THE EFFECTS OF SPEAKER, TRAINING AND TRANSDUCER ON THE RECOGNITION OF TACTILE DIFFERENCES IN COMBINED SPEECH SOUNDS

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ABSTRACT

THE EFFECTS OF SPEAKER, TRAINING AND TRANSDUCER ON THE RECOGNITION OF TACTILE DIFFERENCES IN COMBINED SPEECH SOUNDS

By

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Twenty-four subjects were tested at above tactile threshold levels to determine their ability to differentiate tactually between certain English consonant-vowel combinations. The 24 subjects were divided randomly into four groups of six subjects each. Two of these groups received training to a criterion of at least 75% accuracy, and two of these groups did not receive any training but were only familiarized to some degree with the tactile stimuli. Furthermore, one of the two groups of the trained subjects were trained by using the Bimorph transducer (PZT-5B) and the other group by using the bone receiver transducer (Radioear B-70 A). One of the nontrained groups of subjects received their familiarization by using the Bimorph transducer and the other group received their familiarization using the bone receiver transducer.

The training involved (a) the recognition of the tactile distinctive features established by Haas (1970) of length, intensity, patterns and differing combinations of these parameters; (b) the differentiation between certain test items to a point of at least 75% accuracy. The training was conducted first with the male voice, then immediately followed by the female voice for each separate task in the training.

The procedure used in the familiarization of the above-mentioned twelve subjects on the tactile stimuli was a single presentation of each consonant-vowel combination used in the test during each of the following three separate conditions:

1. Hearing and feeling the combination simultaneously.
2. Seeing a visual representation of the combination and feeling it simultaneously.
3. Seeing a visual representation of the combination, feeling it, and hearing it simultaneously.

This familiarization period was conducted separately for each of the two speakers used in this experiment just prior to the experimental test conducted with that specific speaker's voice. No attempt was made to train the subjects in these two groups to a criterion level as mentioned for the groups of trained subjects. All of the subjects were tested with the stimuli produced by two different speakers, one a male and one a female, both speaking American-English dialect. Each subject responded to two 40 item tests (one for each speaker) of consonant-vowel combinations which were either identical or different from each other. That is, either the vowel or the consonant or both the vowel and the consonant differed between the two combinations in a pair.

The test results found in this experiment indicate that the tactile distinctive features of certain English consonants and vowels maintain their distinctiveness when combined with each other during tactile stimulation.

An analysis of variance was employed to determine whether or not there were any significant effects attributable to speaker variation, stimulator variation, training variation, or interactions between or among any of these preceding variables. The results indicate that the main effect due to speaker variation was the only effect with significance at the 0.05 level of confidence. The only significant two-way interaction at the 0.05 level occurred between the speaker variation and the training variation. The only type of analysis conducted to determine what might account for this difference in the two speakers was to determine the duration and the peak pressure differences for each stimulus pair in each test item for both speakers. These findings demonstrated that the female voice showed a greater degree of duration difference between the consonant-vowel pairs in each test item. This difference would result in greater ease in the recognition of tactile differences between the stimuli in each test item. The peak pressure differences between the stimuli in each test item did not demonstrate a greater difference between the two speakers. Because of the limited number of speakers used in the present study, the findings of speaker differences cannot be generalized to all male and female speakers. The important point to note from these findings is that, at above tactile threshold levels, the vocal characteristics of the speaker may have a significant effect on the observer's utilization of tactile information received.

The effect of training on the differentiation of tactile differences in consonant-vowel combinations does not appear to be of major importance.

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CHAPTER I

INTRODUCTION

As early as 1826, the use of the sense of touch was considered as a means of comunication. At that time, Braille trained the blind to differentiate relief patterns on paper and interpret them as graphemes.

Early attempts were undertaken to use tactile stimulation to aid the hard-of-hearing in communication. Gault (1927), for example, experimented with a 28 year-old deaf female and noted at the end of 200 hours of training that she was able to distinguish tactually about one-half of a 172 monosyllabic word list. Since this early attempt at tactile communication with the hard-of-hearing, many more recent studies have been conducted. The literature denotes different viewpoints as to the usefulness of tactile stimulation. Some of the early writers considered cutaneous stimulation as a substitute for auditory stimulation during communication. On the other hand, more recent literature considers tactile stimulation as a supplement to auditory or visual communication for the hearing-impaired person. For example, Guberina's (1965) verbo-tonal method of aural rehabilitation directs the person to utilize both residual hearing and visual inputs along with tactile sensations to aid in communication.

Work by Pickett (1963) and also Johnson (1963) has shown that cutaneous stimulation when combined with lipreading will aid the hard-of-hearing subject in discrimination. Others, such as Geldard (1957), have suggested a recoding of the speech signal into a "Vibratese language" for use in communication.

In addition to determining the value of this supplemental stimulation, many investigators have considered different types of vibrators, ranging from the diaphragm of a telephone receiver to an elaborate ten channel filtered vocoder with ten separate tactile stimulators, each responsive to a narrow frequency range.

One significant problem encountered with the use of multiple tactile stimulators has been the elevation of the tactile threshold of the signal as found by Sherrick (1964), Pickett (1963) and Gilson (1969). In addition, Sherrick (1964) and Gilson (1969) found that the fewer the number of stimulators used on the hands, the more accurate were the localizations of the signal source.

With the above comments in mind, it is apparent that the use of cutaneous stimulation as a supplemental input for the hard-of-hearing needs further research and experimentation. This research concerns the following topics: (1) tactile stimulus transmission systems to use with a speech signal, (2) effects of different speakers on tactile discrimination of phonemes in combination, (3) ability to recognize very fine tactile differences between different phonemes in combination with each other, (4) usefulness of the skin as an aid in training the hard-of-hearing to make fine discriminations in auditory input.

Statement of the Problem and Purpose of the Study

The present study will seek to determine whether cutaneous tactile discrimination might be useful as a supplement to auditory information in the discrimination of very small speech units. It will determine the tactile differentiation ability on selected consonant-vowel combinations which have been chosen to represent a range of different tactile sensations. This distinctiveness is based on the tactile distinctive features, noted by Haas (1970).

The above will be considered in light of results obtained by the use of two transduction systems and two speakers, one male and one female. The following questions were formulated to define this research:

1. Do the tactile distinctive features of certain English consonants and vowels maintain their distinctiveness when combined with each other during tactile stimulation?

If the above question were true, the following questions would be considered:

2. Do different speakers, i.e., male and female, affect the ability to differentiate tactile distinctive features between different consonant-vowel combinations?

3. Does the type of tactile transducer affect the ability to differentiate tactile distinctive features between different consonant-vowel combinations?

4. Does training on the recognition of tactile distinctive features affect the ability to differentiate tactile distinctive features between different consonant-vowel combinations?

Definitions

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

Electromechanical transducer.--The transducers utilized in this research are of two types. One is a piezoelectric ceramic material called a Bimorph. It has virtually no inertial lag and responds to frequencies from 15 to 20,000 Hz. Its basic construction is a two ceramic plate sandwich-type structure.

The second transducer is a Radioear type B-70 A bone receiver. The frequency response is limited from 100 Hz to 5000 Hz and varying degrees of amplitude of vibration relative to specific frequencies within the above range. Its inertial lag is greater than that of the Bimorph and its frequency range is more limited.

Distinctive features.--The English phonemes may be broken down acoustically into their "inherent distinctive features which are the ultimate discrete signals" separating or differentiating each phoneme from every other phoneme according to Jackobson, Fant and Halle (1952). For example, a listener may judge the presence of nasality or no nasality, or of voicing or no voicing in a perceived utterance. These same types of distinctive features are not encountered tactually. Haas (1970) has determined certain distinctive features for tactile stimulation to take on the form of length, strength, pattern changes, and combinations of these parameters.

CHAPTER II

REVIEW OF THE LITERATURE

History of Investigations Into Cutaneous Speech Reception

The initial investigations into the use of cutaneous stimulation, as an aid to the hard-of-hearing or the deaf, were performed by Gault. Gault (1927) considered tactile stimulation as "hearing through the skin;" and in considering it as a substitute for the hearing handicapped individual, Gault (1924) utilized a non-mechanical type of system, employing a long speaking tube in contact with the palm of the hand of the subject. The experimenter spoke into the 14 foot tube from a separate room, preventing anything other than tactile clues from being received by the subject. He noted that one subject learned to recognize 120 colloquial sentences after only nine presentations. By adding lipreading clues in addition to approximately 60-70 hours of training, Gault noted that the combined input resulted in a range of 30-100 per cent understanding levels for a group of subjects. In general, the gain from lipreading alone to the combined tactile and lipreading situation was about 31.3 per cent for single words and 35.7 per cent for sentences. He attributed this increased discrimination ability to obtaining a feel of the rhythm of the speech in the sentence material. The presence of tactile stimulation for the sounds not easily distinguished by vision accounted for the increase in single-word recognition.

A later modification was an electrical amplifying system with a transmitter that was adjusted to operate at seven volts. It activated six receivers which were similar to those used in a telephone. Six subjects could be stimulated simultaneously by holding the receiver tightly in the hand with the diaphragm of the receiver in contact with the palm of the hand. One major problem noted with this system was that equal areas of contact with the skin's surface could not be maintained with the vibrating surface of the receiver because the pressure against the vibrator could not be controlled. For example, each subject would hold the receiver in his hand with a different amount of muscle tension in the hand.

Bell Telephone Laboratories assisted Gault (1927) in the development of the "Teletactor." The device divided the acoustic energy included within the speech range into five frequency bands. This energy was amplified and presented to the five fingers on a hand of the subject through five vibrators. Each of the vibrators received the output of a band pass filter with the total range of the five filters being from zero to 2600 Hz. The vibrating portion of the "Teletactor" was a narrow reed made of a permalloy and a short steel post (1/16 inch in diameter) which was the only part to come in contact with the skin.

As mentioned earlier, Gault (1927) noted, in experiments with one 28 year-old deaf female, that after 200 hours of practice on the "Teletactor" with sessions lasting one-half to one hour per day, she was able to distinguish approximately half of a 172 monosyllabic word list. It was also found by Gault (1927) that ten of eleven vowel qualities tested could be detected with 83 per cent accuracy after 20 1/2 hours of training with another subject. Gault felt that his type of segmented stimulation aided in the detection of vowel spectrum and that definite patterns of vibration could be felt. Also, in connected speech, the characteristics of rhythm, tempo, accent, and pitch could be detected to aid in recognition. One of the major problems with the above system was that correct tactile identification was reduced significantly when either the speaker or the rate of speaking was changed (Gault, 1927).

One later study using the "Teletactor" involved eight deaf children (Cloud, 1933). It was noted that tactile stimulation aided in tone production and in the recognition of long and short vowels as well as voiced and unvoiced sounds. It helped also in the proper placement of accent in syllables and a smooth speech pattern when compared with children in the same age group who did not have the benefit of the tactile training.

In order to circumvent the problem of the limited frequency response of the skin, Dudley (1936) developed an early version of the present-day vocoder. The speech frequencies were transposed downward and reconstructed by modulating the spectrum of a broad-band source in accordance with the frequency regions and amplitudes of the original signal. This reduced set of signals represented the energy fluctuation in the corresponding set of speech frequency bands. As a result, the transposed signal was transmitted over narrow low frequency bands where the skin is most sensitive tactually.

The next development was a different type of transposition, noted by Keidel (1958), which involved the recording of the stimuli at a rate of 15 inches per second on tape but playing back the speech material at either eight or two inches per second. This method had the effect of shifting the speech frequencies down from their normal 300 Hz to 3000 Hz range to a range of 40 Hz through 400 Hz, a range which is more in accordance with the tactile receptive range of the skin. This stimulus material was transduced by the stimulator Bekesy described in 1955. This stimulator utilized distance to separate the frequency range. That is, a distance of 30 cm separated the lowest frequency of 40 Hz from the highest frequency of 400 Hz;

and each frequency in between excited a different point within the 30 cm distance.

The stimulator consisted of a plastic case around a brass tube with a slit in it, where the forearm was placed in contact with the stimulator. A vibrating piston at one end of the tube produced a wave which travelled from the hand toward the elbow through the fluid-filled tube. Kiedel (1968) noted that subjects were trained to recognize monosyllabic words in relation to either their frequency range or their placement along the 30 cm.

The next refinement in vocoders consisted of a device called FELIX which was developed by Levine, et al. (1951) at the Massachusetts Institute of Technology. Again the speech frequencies were divided into seven bands which also allowed for variations in amplitude relative to the speech signal input. The finger tips of the subject were in contact with the transducer, allowing for contact with one of the more tactually sensitive areas of the body.

One of the more recent developments in vocoders was accomplished in the Speech Transmission Laboratory in Sweden (1963). This vocoder expanded the number of channels to ten with the center frequencies being 210, 400, 580, 830, 1050, 1800, 2250, 3320, 5800, and 7700 Hz. In addition, this system stimulated both hands. The transducers consisted of bone conduction oscillators. The lowest band of frequencies was presented to the little finger of the left hand. The bands of successively higher frequencies proceeded in order through the fingers of the left hand and then to the thumb of the right hand to the little finger of the right hand.

Pickett (1963) indicated that the speech signal was first given a high frequency emphasis of 6 dB per octave by a differentiator, and the specific bands utilized a triangular response curve with a 12 dB per octave slope. The output of each channel was then rectified to obtain a control voltage which modulated the amplitude of a 30 Hz sinusoidal signal. These signals were then amplified, adjusted for the channel's sensitivity, and directed to the above-mentioned bone oscillators. Pickett and Pickett (1963) noted in using the ten channel vocoder that the subject's ability to discriminate between various vowel pairs and consonant pairs varied across a wide spectrum. For example, tactile discrimination between the vowel pairs /e-o/ and /e-ɔ/ was very good and became progressively poorer for the following vowel pairs /i-I/ /u-o/ /o-ɑ/ /ɑ-ʌ/ /o-u/ /ɔ-ʌ/ /i-e/ /e-ɛ/ /ɛ-æ/ /æ-ɑ/. They also found that tactile formant patterns, duration, and tactile masking effects all affect the discrimination ability of the subjects. Also, the identification of long vowels was noted to be better than the identification of short vowels.

When consonant sounds were considered, tactile discrimination was very good for stops and continuants. It was found that distinctions between fricative sounds, detection of nasality, and differentiation between voiced and unvoiced sounds were also good. In general, these authors felt that the skin offered certain capabilities for transmitting speech information which may be useful in complementing speech communication, in situations when only a limited speech signal is received normally.

Johnson (1963) developed a cutaneous speech transmission system. It contained four small loudspeakers (two inches in diameter) which were placed in direct contact with the forearm, except for a thin pellon fabric attached to the front surface of the speakers. When the speaker was activated, an elliptical vibratory pattern was produced on the fabric surface and on the skin with which it came in contact.

Johnson noted that training with this system enhanced the subject's lipreading ability when a combined tactile visual signal was presented to him; but if no training were performed, the subject did not receive any benefit from the added tactile stimulus.

Guberina (1965) described a tactile transmission system employing selective amplification and frequency transposition with a transducer similar to that of a grenade-type bone vibrator held in the palm of the person's hand. Little experimental data have been published to determine the assets of this type of system in conjunction with his verbo-tonal method of auditory training.

Bice (1961) developed a transducer utilizing an insert type receiver which operated on the inertial reaction principle. This system avoided a damping of the signal when the receiver was in contact with the skin. Specifically this device was intended to be used for transmitting coded information. Bice modified the HS-30-U insert-type receiver by loading the diaphragm of the receiver with a 24 gram-force, obtaining greater inertia and a better impedance matching with the tissues of the skin. The frequency response range of the system was from two to 450 Hz for the sensitive body areas with resonant peaks at 27, 88, and 145 Hz. Sherrick (1961) felt that this device was too fragile and was difficult to calibrate exactly. On the other hand, this system made it possible for the first time to position a whole constellation of vibrators on the skin, to allow for wide dispersion and independent external supports, and to maintain the mobility of the observer while thus suited.

A later modification of the same type of stimulator was developed by Sherrick (1965). The frequency response of the system could be shifted upward or downward by altering the mass of the entire system. This was accomplished by reducing or increasing the dimension of the coil of the magnet. The device was strapped to the arm and a plastic button was brought in contact with the skin to act as the stimulator. Geldard (1968) considered this system to be made of "sterner stuff," with relatively larger power and a somewhat more constant performance.

Diespecker (1967) later developed a stimulator system transmitting coded information which contained a double spring-loaded terminal for contact with the skin. A specific set of signals were transmitted, utilizing five transducers placed on different parts of the body. These signals utilized location of stimulator, intensity, and multiple vibrations but not speech. This type of recoded stimulus was advocated by Geldard and identified as "Vibratese language." Geldard (1960) felt that the coded material avoids the problems of the limited frequency range of the skin, the masking effects of any type of multiple vibratory system applied to just the fingers, and the transduction problems of the stimulus materials to a useable form. A 60 Hz sinusoidal signal of varying intensities and durations provides the recoded stimulus signal. This recoded signal is limited only by the speed with which the subjects can handle the coded message.

At the same time that Geldard and Sherrick were working with "Vibratese language," other work was still being pursued with different types of vocoders. Kringlebotn

(1968) was experimenting with a five vibrator tactile vocoder called the "Tactus." The input to this device consisted of speech signals divided into five frequency ranges which provided a spatial pattern of vibration. The signal excites the first vibrator and then is divided between the remaining vibrators successively so that the signal pulse has 1/2, 1/4, 1/8, and 1/16 of the original frequencies in it. Kringleboth experimented with this system, utilizing closed set materials of limited complexity and deaf children as subjects. He found that the system was promising, both as a supplement to lipreading under a teaching condition and as an aid in learning to lipread. This system helped, also, in teaching speech production and in speech correction, along with indicating rhythm in connected speech.

Hisayski Suzuki (1968) described a "Tactphone" at the International Congress on Acoustics. This system used a filter bank analyzer like the vocoder, again with ten channels and a frequency range covering 160 through 6600 Hz. Each band had an equal width in the Mel Scale. The output of the filter was rectified to obtain values of the short time spectrum at the ten frequency bands. The same distribution was used on the ten fingers, as mentioned before, going from left to right on the fingers.

More recently, Haas (1970) used the Clevite Corporation Bimorph transducer, which will be described in detail in the next chapter, to determine the tactile detection threshold of English phonemes and to establish their tactile distinctive features. There was no transformation of the speech signal prior to its transduction by the Bimorph, and upon evaluation it was felt the Bimorph was useful for the presentation of speech materials.

Haas (1970) found the intensities required for tactile detection thresholds for English phonemes. He noted that they have the same relative speech power relationships as acoustical speech signals. That is, vowels have a lower tactile threshold than do consonants. In addition, Haas determined the tactile distinctive features (TDF) of these phonemes on the bases of three dimensions: intensity, duration, and pattern. He found that there was consistency in these features in paired comparisons; but some inconsistencies did occur, suggesting that the three dimensions utilized to describe the TDF were not all inclusive.

As noted earlier, bone conduction oscillators have been used as part of earlier stimulus transduction systems. In most cases, the speech signal was modified in some way prior to its transduction by the bone oscillator. The present study will also utilize both a bone conduction oscillator for transduction and the Bimorph transducer but with no modification of the speech signal other than amplification prior to its transduction by either the bone oscillator or the Bimorph.

Frequency Sensitivity of the Skin

The initial research in the area of tactile communication considered tactile stimulation as a substitute for the auditory system and used it to circumvent any problems present in the auditory system. Through the years, limited success has been demonstrated with many different types of tactile systems, including electrical stimulation. Researchers have become increasingly more aware of the inherent limitations of the cutaneous system and the difficulties in overcoming these limitations. The most apparent problem is the skin's limited responses within the speech range. For example, contemporary authorities feel that the frequency sensitivity range of the skin is between 200 and 400 Hz, with a more limited sensitivity reaching up to 1000 Hz. Specifically, Geldard (1940) felt the maximum sensitivity was at 250 Hz; but because of technical difficulties, no upper limit was stated. Some of the earlier studies by Goodfellow (1933) and Knudsen (1928) had determined the upper limits of the tactile cutaneous frequency response to be 8000 Hz and 4000 Hz respectively. Bekesy (1967) determined the frequency limits to be about 50 through 500 Hz, whereas Kringlebotn (1968) felt the upper limit extended up to 800 Hz. More recently, Sokolyanskiy (1968) has noted responses as high as 2000 Hz which would be helpful in speech interpretation.

Geldard (1960) noted also that many of the early studies performed on the cutaneous frequency range were invalidated because of the failure to control for "subjective intensity" and because of the presence of transients originating from the crude type of instrumentation they used. Goff (1960) appeared to have accounted for these earlier-noted problem areas by assembling bands of equal-loudness stimuli which differed in frequency. Then Goff measured the Δf systematically within each band throughout the obtainable frequency range. She found that below the 70 Hz vibratory rate judgments were very good but that they decreased rapidly in accuracy as the frequency scale was ascended. As a result, the range of 300 through 3000 Hz demonstrated relatively poor discrimination ability. This still leaves some question as to the exact limits; but it is felt, generally, that they are in a region below the speech frequencies.

Geldard (1969) also noted that the skin (due to its overlapping neural network) has an unlimited information processing potential, but very little is known about this potential. Knowledge in this area is limited mainly because the studies performed during the last 30 to 40 years have dealt primarily with two-point limen and single-point location as well as threshold discrimination for different frequencies. Gibson (1968) noted that it is necessary "to determine the perceptual properties of stimuli varied systematically along temporal and spatial dimensions."

Bliss (1963) has pointed out that the determination of the cutaneous system's capabilities relative to the transmission of information has been limited because of our lack of information concerning the appropriateness of the tactile device to utilize fully all the informational capabilities of the cutaneous system.

The unpublished doctoral dissertation of Haas (1970) has documented the literature pertaining to the responses of the skin to speech and pure tone stimuli and has drawn from the literature comparisons between the auditory and tactile input channels. Rather than attempt to repeat this information in detail again, a brief summary of some of the highlights appears in order. Not all of this information is pertinent to the present study, but it does develop a foundation for the present questions asked by this study.

1. Within the literature were found similarities between taction and audition, such as the presence of the traveling wave of energy, and the counterparts of intensity, frequency, duration, localization, neural inhibition and recruitment.

2. The speed of information transmission by the skin is much slower than that of the ear, and there is a

more limited ability to detect fine differences by the skin than is possible by the ear.

Other parameters relative to tactile detection thresholds were discussed by Haas. For example, the finger tip is the most tactually sensitive area of the body; but multiple stimulators in close approximation to each other, such as on the fingers, result in a masking effect and elevate the threshold of tactile perception.

Parameters Affecting Tactile Threshold and Discrimination

The parameters affecting tactile threshold and discrimination are (a) contactor size, (b) pressure, (c) speaker differences, (d) tactile distinctive features.

Contactor Size

The size of the contactor used in a transmission system is known to have an effect on frequency and intensity. Geldard (1940) summarized some of the early findings related to contactor size by noting that changes occurred in the threshold curve as the size of the contactor changes. For example, the larger the contactor's diameter, the lower the threshold becomes for the low frequency sounds. On the other hand, the high frequency sounds are not affected by the size of the contactor.

Verillo (1966) felt that with very small contactors (0.005 and 0.02 cm^2), the threshold curve demonstrated an independence to frequency. He reported on earlier findings of his own and others such as Bekesy (1929), Knudsen (1928), and Sherrick (1953), that showed a very pronounced frequency effect is produced with a very large contactor (2.9 cm^2).

Verillo (1966) reported that the overall shape of the threshold curve obtained with the larger contactor followed a U shape, with its maximum sensitivity at about 250 Hz. Verillo noted that Bekesy (1939) found that in the lower frequencies the threshold curve was flattened, but a break in the shape occurred at approximately 20-40 Hz. At this point the sensitivity increased to a point at 250 Hz. Bekesy reported at the same time that he felt this break in the threshold curve was the result, in part, of temporal summation. The specific curve function, according to Verillo (1966), follows a three dB per octave slope above 40 Hz per doubling of the contactor area, indicating a summation of energy. There was no summation noted for the frequencies of 40 Hz and below. It then can be said there is an inverse relationship present between the vibrotactile threshold and the contactor size; this relationship follows a three dB per octave slope for a doubling of contactor area.

Verillo (1966, pp. 154-55) summarized his findings and the findings of earlier studies related to contactor size by noting three general statements

1. Cutaneous tissue is innervated by at least two receptor systems involved in the transduction of mechanical disturbances.

2. One of the systems summates energy over time and space. It is this system that accounts for the frequency function obtained when large contactors are used to determine vibrotactile thresholds.

3. The other system is not capable of summation and it is this system that produces the flat frequency function when thresholds are determined with a very small contactor. It is this system, also, that accounts for the flat portion of the threshold curve that occurs at low frequencies. As frequency increases, summation occurs in the frequency-sensitive elements and this determines the downward slope of the curve.

Pressure

Cohen and Lindly (1935) found that vibratory thresholds for a single 60 Hz tone were decreased when the pressure applied to the contactor was increased.

Verillo (1966) established that threshold, again using a pure tone stimuli, decreased in direct proportion to the degree of protrusion the contactor had into the skin.

Recently Higgins (1971), in his unpublished doctoral dissertation, noted that the range from five gram-force to 25 gram-force in five gram steps made no difference in the obtained threshold levels for the phonemes /u,ʌ,ɑ,n,b/ when the Bimorph was used as the tactile transducer. He did note that there appeared to be a subjective preference for the 15 gram-force level plus or minus five gram-force. This 15 gram-force level was suggested initially by Geldard and Sherrick (1970) for use by Haas, and it was also found to be the most appropriate level by Higgins.

Speaker Differences

In earlier studies in tactile stimulation using speech, Gault (1927) noted that when the speaker was changed or the rate of presentation was changed, there was a noted effect in the identification ability maintained by the person. On the other hand, Higgins (1971) noted no effect in threshold detection for specific phonemes with two adult speakers, one male and the other female. This area will be considered at an above-threshold level in the present study.

Tactile Distinctive Features

The final area of concern is the earlier work of Haas (1970) and his findings relative to the tactile distinctive features (TDF) of English phonemes. The present study will consider these phonemes in combination with each other, whereas Haas's study considered them only in isolation. He described the TDF on three dimensions and combinations of these dimensions (intensity, duration and pattern) for 33 of the English phonemes. Many of these phonemes had identical TDF or shared three identical features. Table 1 on the following page indicates the results of his findings.

TABLE 1.--Summary table for the tactile distinctive features for 36 English phonemes. All additional discriminations by paired comparisons are in inset boxes.*

	Long: Non-changing	Long: Changing	Short: Non-changing	Short: Changing
Strong	/u/ /ɔ/ /ɑ/	/o/ /e/ /i/ /aɪ/ /ɔɪ/ /l/ /ŋ/	/ʊ/ /ʌ/ /ɛ/ /ɪ/ /w/	
Strong (on border between Short Non-changing and Short Changing)			/ɝ/	/ɝ/
Strong (inset boxes)	none	ŋ-o	ɝ-ɪ, ɝ-ʌ, ɝ-w, ɝ-ʊ, ɝ-ɛ, w-ʌ, w-ɛ	none
On border between Strong and Weak		/æ/		/au/
Weak	/m/ /n/ /ʒ/	/z/ /ð/ /tʃ/	/j/ /v/ /b/ /d/ /p/ /t/ /k/ /g/	
Weak (on border between Short Non-changing and Short Changing)			/dʒ/	/dʒ/
Weak (inset boxes)	none	æ-ð, æ-z, tʃ-ð, tʃ-z	p-g, p-dʒ, p-j, p-d, p-k, p-v, j-k, j-g, j-t, t-v	au-dʒ

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

Haas also noted that the following sounds /s,θ,ʃ, f/and/h/ were not described in light of the TDF for one of two reasons: equipment limitations or the inability of these sounds to develop enough energy when transduced to be detectable by the subjects in light of a basic threshold level of 1.6 volts for zero dB.

The TDF were determined by at least five out of six of Haas' subjects selecting the same set of features for an individual phoneme. The validity of the dimension of intensity was supported by the threshold data obtained on the phonemes. The data indicated that the vowel sounds had significantly lower threshold values than the consonant sound. This same finding has been noted acoustically for these two types of sounds.

Duration was not tested directly for validity but spectrographic analysis dichotomized the short and long sounds from each other, and tactually the subjects indicated this same breakdown with the exception of the /ɑ,u/ phonemes. These sounds were noted spectrographically to be longer in duration than the /I,n,æ,m,3,ɔ,e,o,u/ which were consistently judged as long by the subjects.

The dimension of pattern also provided additional tactile information which distinguished sounds from one another.

Some lack of agreement was noted in the TDF for the /3,au,æ,dʒ/ with additional discriminations being noted when paired comparisons between the different phonemes were made. For example, the /ʒ/ and the /p/ were consistently judged as "different" under a paired comparison. These observations indicate that the three dimensional TDF criteria may not be an adequate description of the TDF of the sounds tested. Within paired comparisons between sounds having the same TDF's, 42 per cent of the trials by paired comparisons resulted in a response of "different." Haas noted that the resolving power of the three dimensional TDF set is not an absolute picture of the sound. On the other hand, no other study has considered in such detail the parameters of cutaneous stimulation for speech sounds. It has also shown that there are discernible differences among sounds utilizing cutaneous stimulation but that the degree of differentiation in units other than isolated units needs to be considered. It should also be mentioned that the above findings relate to a specific tactile transduction system and quite different findings might result if a different type of tactile transduction system were utilized.

CHAPTER III

SUBJECTS, EQUIPMENT, MATERIALS AND PROCEDURES

Subjects

In this study 24 experimental subjects in the age range from 21 to 35 years were utilized. None of the subjects had known (clinically significant) hearing losses. None had known pathological conditions of the skin or of the central nervous system.

Equipment

The following test equipment constituted the major instrumentation employed for this study.

Tape Recorder I (Ampex AG440-B) 7.5 ips.
Tape Recorder II (Ampex AG 600) 7.5 ips.
Tape Recorder III (Ampex AG 601) 7.5 ips.
Microphone (Electrovoice 635 A)
Level Recorder (Bruel and Kjaer 2305)
Audio Oscillator (Hewlett Packard 4204 A)
Sound Proof Test Room (Industrial Acoustic Company, Inc., Single Walled Room Series 402)
Sound Proof Test Room (Industrial Acoustic Company, Inc., Double Walled Room Series 1600 ACT)
Magnetic Recording Tape (Type 201 Scotch Brand)
Speech Audiometer I (Grason Stadler Model 162)
Audiometer II (Beltone Model 15 C)
Tactile Stimulus Transmission System with Piezoelectric Ceramic Bimorph (Clevite Corp.)
Bone Receiver Tactile Transmission System Type B-70 A (Radioear Corp.)

Materials

A magnetic taped sequence of recorded English consonant-vowel combinations comprised the stimulus material for the familiarization portion of Experiments I and II. These same consonant-vowel combinations were paired in different ways to form the test portion of the tape. The specific matrices from which the pairs were obtained are presented in Appendix 1. The specific order of presentation can be noted in Appendix 2. The familiarization order was established by selecting the first combination from the vertical (V) side of matrix I and the fifth combination from the horizontal (H) side of the matrix, following this order: V1,H5,V2,H4,V3,H3,V4,H1,V5,H1. The order of the test pairs was established by matching the first combination on the vertical side of matrix I and II (V1) with the first combination on the horizontal side (H1) and proceeding across the horizontal side of the matrix matching the first vertical combination with all the horizontal combinations. In addition, the pairs were formed alternately so that the vertical combination of the pair was not always first. An example of the above combination for the first vertical combination with the horizontal row would be (V1 H1) (H2 V1) (V1 H3) (H4 V1) (V1 H5).

Two different orders of the paired combinations were recorded. The first was Form A which is noted in Appendix 2. This form resulted from the paired combinations formed in the above paragraph. Form B was established by beginning the sequence with the twentieth pair of combinations in Form A and following the sequence up to the fortieth pair, then the first 20 pairs were placed at the end of the list in their same sequence, one through 20. A total of 40 pairs of consonant-vowels were formed from the two matrices presented in Appendix 1. Twenty-five were from the matrix with the different vowels or matrix I, and 15 were from the matrix with the same vowels, or matrix II. Ten combinations were eliminated from the second matrix because they were duplicates of other combinations, with order reversal constituting the only difference.

The training tape consisted of nine different discrimination tasks with increasing difficulty. The first three parameters included the recognition of differences in length (speech noise), intensity /u/, and changing or nonchanging patterns /n/ /z/. From this point, the above parameters were combined with each other to form the following comparisons: weak short/ strong long /p/ /e/; long weak/strong short /m/ /I/; strong nonchanging/weak changing /u/ /z/. The last three parameters consisted of consonant-vowel combinations which differed on certain parameters. They were as follows: a vowel difference only /pI/ /pæ/ ; a consonant difference only /pæ/ /læ/; a difference between the consonant and the vowel within the two combinations /dʒI/ /læ/. These specific materials were selected for training to develop an increasingly more difficult task which included all the parameters involved in the test situation and involved a discrimination task similar to that in the test situation.

Preparation of Materials

The test tape and the training tape were prepared in the following manner.

Test Tape

The master tape of the 15 consonant-vowel combinations was recorded in a single-walled sound treated booth (IAC series 402). The recording was performed by two speakers, one male and the other female, both speaking American English dialects. The stimulus materials were recorded on tape recorder I employing an Electrovoice 635 A microphone. The above-mentioned combinations were uttered as naturally as possible; but an attempt was made to monitor the loudness through a VU meter, connected to the tape recorder, to a constant level. The duration of each combination varied from approximately 515 msec. to approximately 697 msec.

The master tape was then re-recorded through a tape recorder II monitoring the level of the peaks with the level recorder (Bruel and Kjaer model 2305) to obtain equal peak intensities for all consonant-vowel combinations. The final readout of the level recorder indicated that all the combinations were within a three dB range of each other. That is, the lowest recorded combination was only three dB below the highest recorded combination. Once a predetermined level was obtained on the level recorder for a specific combination, multiple recordings were made of that specific combination to form all the required paired combinations for the test tape and the single utterances for the familiarization procedure. This meant, for example, that the combinations with the /I/ vowel were recorded at least eight times, allowing for any damage to the tape recordings while splicing them into their predetermined sequence. The combinations with the /æ/ vowel were recorded at least 13 times for the same reason. This procedure was performed by playing back the master tape on tape recorder I. The output was connected to tape recorder II; the level recorder was connected to the output of tape recorder II to monitor the recording level peaks. All levels were kept well below the VU zero point on tape recorder II to avoid any further distortion in the re-recording of the stimuli.

The different consonant-vowel combinations were then spliced out separately from the re-recorded tape. They were combined into the different pairs noted in Appendix 2 under Form A to form an ordered master copy of the test tape. One copy of the ordered master copy was re-recorded again, monitoring the peak levels to be as close as possible to each other. The results were similar to the previous recording, the levels being within four dB of each other. Form B was recorded from the ordered master copy, resulting in the order noted in Appendix 2 under Form B. This re-recording resulted in a splice-free test tape, except for the spliced-in lead tapes. A calibration tone was recorded at the beginning of the tapes, monitored to a level of the highest recorded consonant-vowel combination.

The master version of the consonant-vowel pairs were played to four persons to determine whether any distortions were present prior to the above-mentioned recording. No distortions were found to be present. The listening task was conducted under earphones from the output of the tape recorder II.

The specific time intervals utilized in the test tape were as follows: one second between the two consonant-vowel stimuli and three seconds between each consecutive pair of consonant-vowels. The familiarization portion of the test tape utilized a three second interval between each consonant-vowel presentation. Three seconds of lead tape were allowed at the beginning of each test form to enable the subject to be signaled at the start of the test and to be ready for the first set of stimuli.

Training Tape

The same recording procedure was utilized in the development of the training tape. The specific materials were recorded and reproduced in the same manner, with the exception that the consonant-vowel pairs were again reproduced from the master tape of the test pairs. The same time intervals were used between stimulus pairs in the training tape as were used in the test tape to duplicate the test condition in training. A slightly larger range in peak levels was noted in the training tape. It was about 2-5 dB from the lowest to the highest peak in any given parameter for either speaker on the training tape.

The individual stimuli were spliced together to form the training tape with all the possible combinations of the two stimuli in the parameter. For example, in the training portion for intensity the (u) sound was used in both the male and female portions of the training. There was one pair of weak stimuli, one pair of strong stimuli, and two pair of one weak and one strong stimuli with their orders reversed. This same sequence was presented for both speakers on the training tape with the male speaker first and the female speaker second.

Tactile Stimulus Transmission System

Two systems were used in this study. One was a Bimorph transducer and the other, a bone receiver transducer. A description of these systems follows.

Bimorph

The same type of Bimorph transducer (Clevite Corporation) utilized by Haas (1970) was used in the present study. It consists of a piezoelectric ceramic Bimorph element commercially available from the Clevite Corporation of Bedford, Ohio. It has a broad frequency response, almost no inertial delay of transmitted signals, and it is easily coupled to the skin. The specific Bimorph vibrator employed in this study (PZT-5B) measures: length = 31mm, width = 3.1mm and thickness = 0.5mm. The specifications are reported in Appendix 3. The Bimorph utilizes flexure responsive piezoelectric elements as transducers for mechanical output as a function of electrical input.

The Bimorph responds flexurally to an input signal because of the oppositely polarized ceramic plates. Oppositely directed transverse strains are produced, resulting in a bending or deflection of the free end of the Bimorph. The motion sensitivity is determined by the deflection per unit of applied voltage. An upper limit of 260 volts is specified for the above Bimorph; beyond this limit, destruction of the vibrator could be produced. The Bimorph is held in place by two brass plates forming a clamp on the top and bottom surfaces.

The area which actually is in contact with the skin is a Lucite rod which has been secured to the outmost end of the Bimorph by a small flat head screw. The screw was glued to the Bimorph and allowed for different sized contactors to be attached to the Bimorph. The present experiment used a rod with a diameter of 3.1mm. This was the rod utilized by Haas (1970) when the tactile distinctive features were first obtained with the Bimorph.

The housing of the Bimorph is a plexi-glass structure, noted in Figure 1, involving an 28.9 cm high post mounting for the dynamometer. This was utilized to determine the force exerted by the third finger of the subject's right hand on the Bimorph. This force was measured at the second phalanges joint of the finger. The dynamometer, scaled in gram-force, was suspended from the above-mentioned post and coupled to a finger cradle at the lower end by a 6.6 cm string. This arrangement allowed for the direct reading of the force applied to the cradle by the finger and an indirect indication of the force applied to the Lucite tip attached to the free end of the Bimorph noted in Figure 2. The rod's end rested above the surface of the hand rest portion of the Bimorph housing by 3.1 mm. This allowed the finger to be lowered in the cradle rest to touch the end of the rod and then adjusted to the

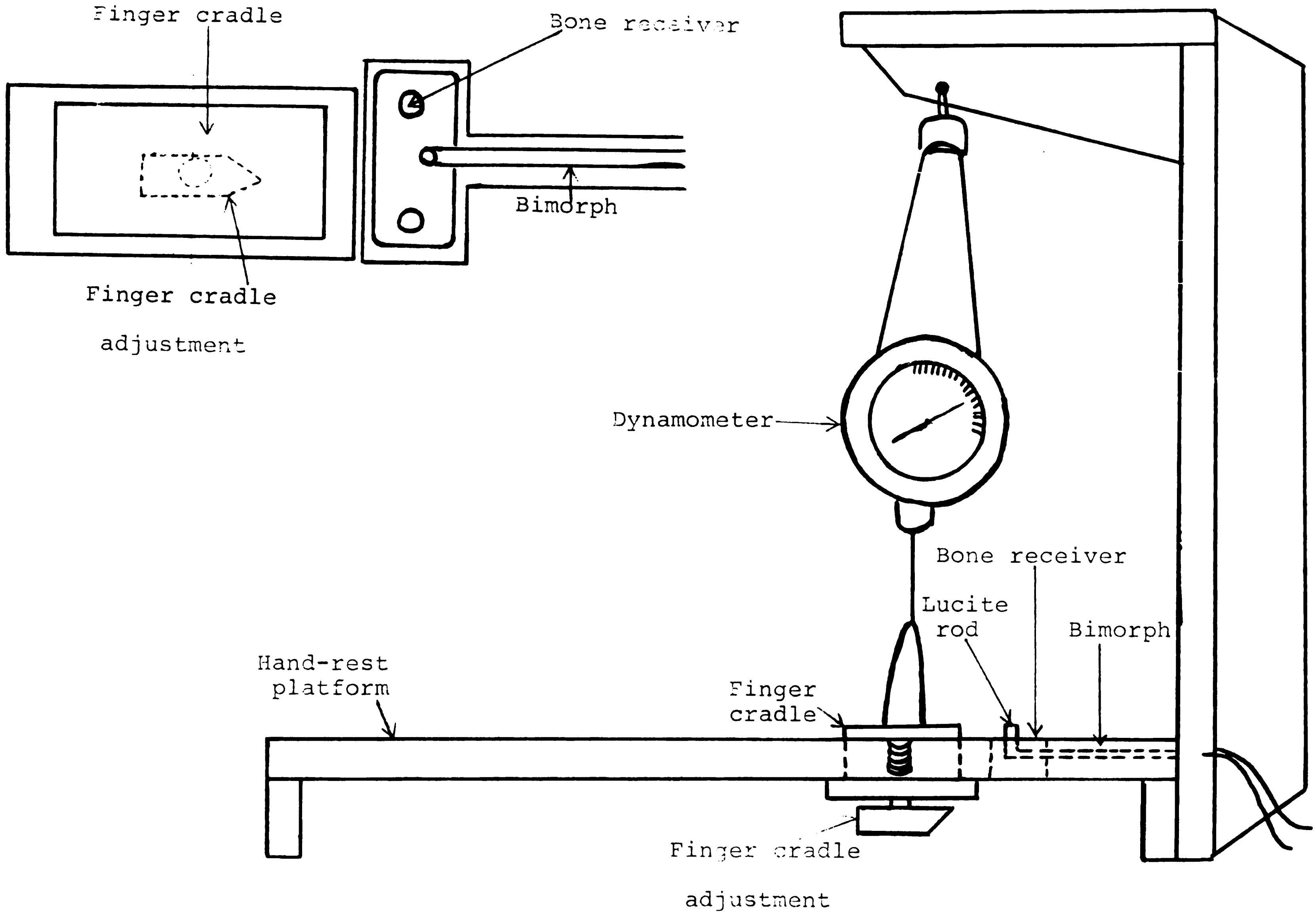

FIGURE 1.--Plexi-glass housing.

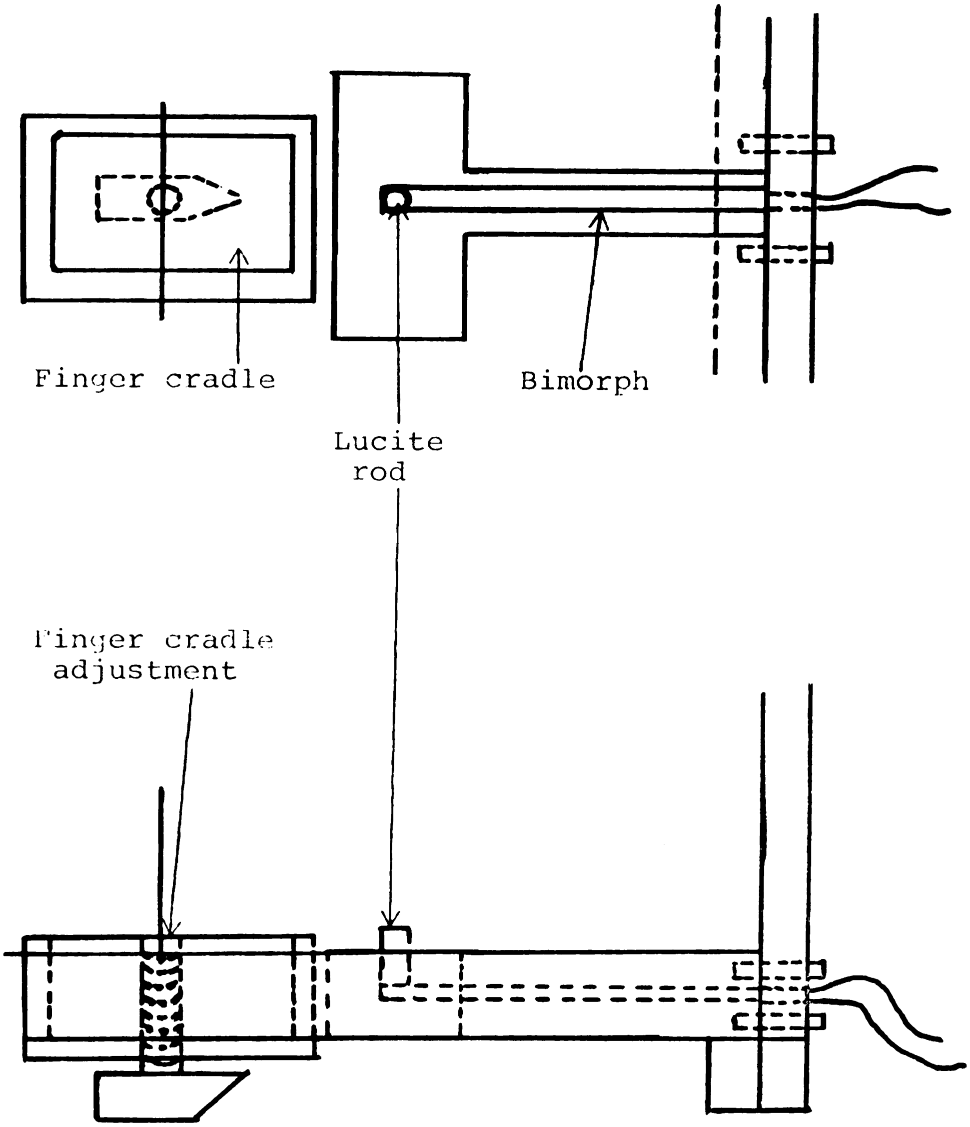

FIGURE 2.--Mounting for the Bimorph.

desired force against the cradle and, in turn, the end of the rod. The upper limit of the grams of force that could be exerted against the cradle was 40 gram-force. The point of coupling the rod to the finger was the innermost concentric fingerprint line of the third finger of the right hand. The desired force noted for the present experiment was a 15 gram-force as read on the dynamometer and starting from the above-noted beginning point of contact between the finger and the Lucite rod. This amount of force exerted by the finger was found to be the most desirable in two previous studies by Haas (1970) and Higgins (1971).

The mass of the Lucite rod does not affect the performance characteristics of the Bimorph as noted by Haas and the manufacturer of the Bimorph. On the other hand, the finger tip mass when loading the Bimorph with 15 gram-force does affect the interaction between the deflection rate and voltage. The resonance frequency is not affected, according to the manufacturer's specification.

<u>Bone Oscillator</u>

The second stimulator utilized was a bone receiver (Radioear B-70 A) which was housed in the above-mentioned plexi-glass structure noted in Figure 3. A hole was made perpendicular to that used by the Bimorph to accommodate the bone receiver. Therefore, only one of the stimulators was housed at any given time. The same dynamometer was

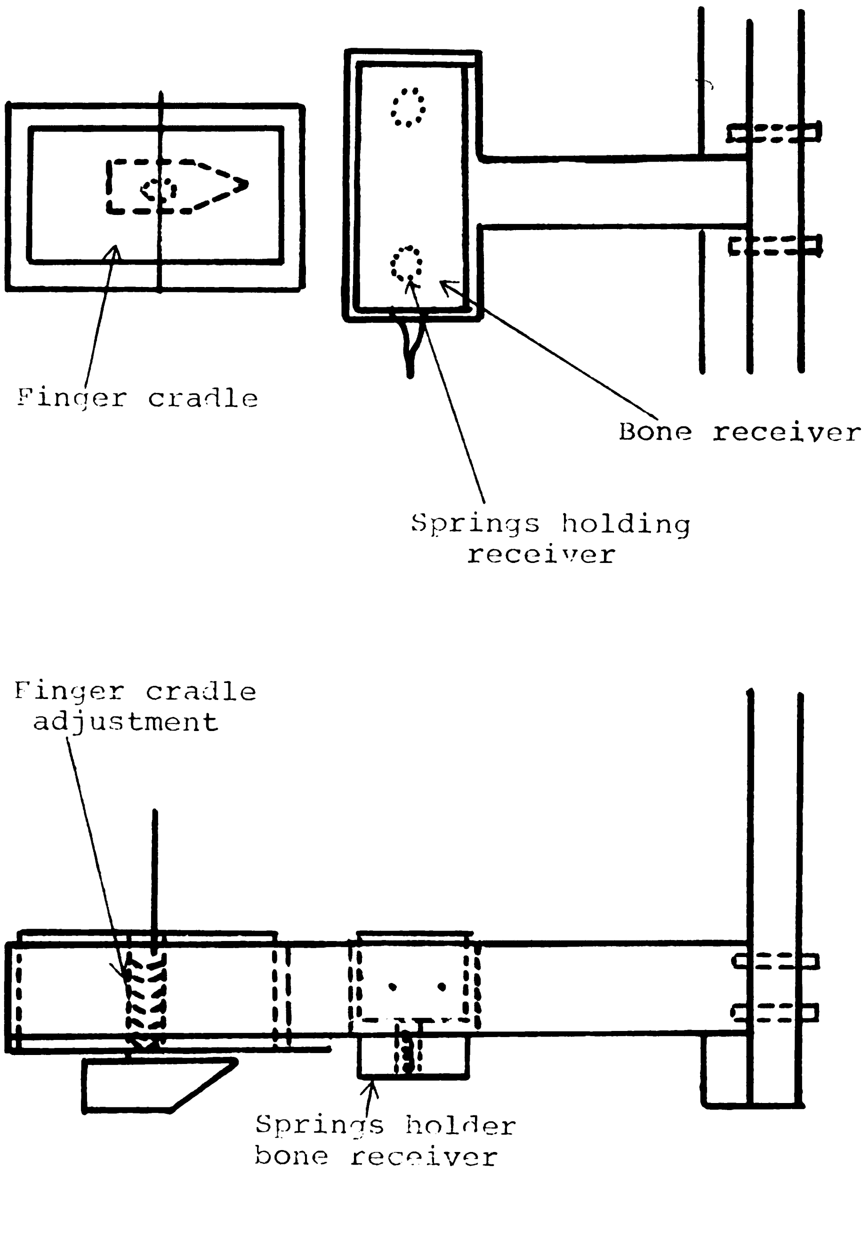

FIGURE 3.--Mounting for the bone receiver.

able to determine the amount of force exerted on the surface of the bone receiver. The specific frequency response of the bone receiver is presented in Appendix 4. The receiver's characteristics were obtained on an artificial mastoid (Beltone M5A) by inputing 0.14 volts (RMS) into the bone receiver.

The surface of the bone receiver also extended above the surface of the hand rest portion of the housing in a manner similar to that of the Bimorph. The bone receiver was held in place by two spring mountings connected to the back of the bone receiver. These mountings did not allow the bone receiver to come in direct contact with the plexi-glass structure, thus avoiding any dampening effect the mass of the housing may have had on the bone receiver.

The stimulus material was played-back on tape recorder III. This signal was then routed to the speech audiometer I (Grason Stadler model 162) and, finally, to either of the tactile transducers which were under test. The system allowed the test signal to be presented to the tactile stimulator and a white noise simultaneously to the earphones (TDH-39) of the speech audiometer to mask out any auditory clues the subject might receive from the transmission system. When a combined auditory and tactile signal was desired as in Experiments I and II, the auditory test signal could be directed to the earphones and the tactile stimulator simultaneously.

The intensity of the stimulus material was controlled by the attenuator of the speech audiometer I. That is, Channel One controlled the intensity of the test signal to both the earphones and the tactile stimulator. Channel Two controlled the intensity of the white noise to the earphones when no auditory signal was desired and the stimulator noise was to be masked while testing. The upper limit at which the test stimulus material could be presented was determined by the peak-to-peak voltage limits of the Bimorph and the bone receiver, these being 260 volts and two volts, respectively.

There was a slight modification in the test equipment for the trained group. Since no auditory input of the test signal was necessary during their training or testing, it was felt that a different source of white noise would be used. The reason for the change was so that a lower level of white noise could be utilized, a level which was more comfortable for the subjects but still allowed no acoustical emissions from either of the tactile transmission systems to be heard by the subjects. The subjects in Experiments I and II did mention that the noise level was annoying after a period of time. The second source of white noise was obtained from audiometer II (Beltone 15 C). To avoid the auditory signal from being heard when speech audiometer I was used, the S/N ratio at the earphones worn by the subject had to be at least -10 dB to mask out the signal.

Calibration of Equipment

Speech audiometer I utilized in this study was calibrated prior to the testing of subjects and calibrated routinely during the period of conducting this study. The calibration was conducted by making voltage measurements across the electrical terminals of the Bimorph and the bone receiver with a 1000 Hz tone being played through the system. The earphones were calibrated utilizing the white noise from the speech audiometer and noting the output at the earphones with a sound level meter (Bruel and Kjaer model 2203) connected to an octave band filter (Bruel and Kjaer model 1613). That is, a noise level of 94 dB Lp was required at the earphones to mask out the noise of the tactile stimulators and mask out any speech signal present in the earphones that could be heard by the subject. Also, this type of measurement gave a means of checking the level of the test stimulus when presented through the earphones during the familiarization period. The white noise was monitored to a VU zero point on speech audiometer I and then the readings were made at the earphones with the sound level meter. This same procedure was utilized to check the masking noise level developed by audiometer II. It was found that only 81 dB Lp was required to mask out any auditory signal from either stimulus transmission system. This level was found to be more acceptable to the subjects tested in the last two experiments.

Procedures for the Experiments

This study consisted of four different types of experiments numbering I, II, III, and IV. All of the experimental sessions were conducted in a sound treated room (IAC double walled room series 1600 ACT). The subject was seated comfortably on the left side of a table upon which the housing for the tactile transmission system was resting. Also on the table was a foam rubber pad of the same height as the Bimorph housing platform. This arrangement allowed the subject's right hand, palm down, to be placed on the handrest portion of the housing and the lower portion of the arm to rest on the foam rubber pad. The middle finger was placed in the finger cradle with a metal brace strapped to it to maintain a relatively stiff and straight extension of the second and third phalanges joints. The tip of the finger was extended over the Lucite rod on the Bimorph. The coupling was made at the innermost concentric fingerprint line. The finger and hand were secured into position by a single strap of adhesive tape placed over the finger and pressed against the plexi-glass housing on both sides. The finger cradle was elevated to remove coupling with the contactor. The cradle was then lowered to a point where the subject could just begin to detect contact with the rod. A reading was then made on the dynamometer, and the cradle was lowered to a point which was indicated on the dynamometer as an additional 15 gram-force. This amount of force applied to the cradle and indirectly to the Bimorph was found to be the most appropriate level in the previous studies by Haas (1970) and Higgins (1971).

To avoid any perceived auditory signal emanating from the transducer and the subject in discerning any difference between the pairs of consonant-vowels during the test condition and the visual tactile mode of familiarization, white noise at 94 dB Lp was delivered to the earphones (TDH-39) from speech audiometer I. The noise was generated from Channel One of the audiometer. A sound pressure analysis of all the speech sounds emanating from the Bimorph transducer indicated that a maximum level of 28 dB Lp was occurring at 20 volts peak-to-peak for a 1000 Hz tone. A 64 dB Lp was found for the bone receiver at 1.6 volts peak-to-peak.

Experiment I

The purpose of the experiment I was to determine whether there were discernible differences between certain consonant-vowel combinations spoken by two different speakers, utilizing the Bimorph as the tactile transducer system. The combinations were formulated with the previously determined tactile distinctive features for separate English phonemes of Haas (1970) kept in mind to acquire different degrees of tactile distinctiveness.

Prior to each test session, the pre-recorded calibration tone was used to adjust the output gain for speech audiometer I to a level of zero on the VU meter of the audiometer. The test session for each of the two speakers was initiated by a practice session utilizing three different modes of input stimulation. Mode One involved hearing the stimulus while simultaneously feeling the stimulus. Mode Two involved visual and tactile stimulation during which the subject could view a written representation of the tactile stimulation and at the same time he could feel the tactile stimulation, Mode Three involved hearing, seeing and feeling the stimulus simultaneously.

The familiarization portion of the test tape was played with each stimulus occurring at three-second intervals. Mode One was presented, and the tape was rewound and played again for the second and third modes of presentation. The familiarization process was completed within five minutes.

The instructions given to the subject were as follows:

> The purpose of this task is to have you become familiar with the different sensations of ten sound combinations. There are three ways these sound combinations will be presented to you. They are: hearing and feeling at the same time, seeing and feeling at the same time, and hearing, seeing, and feeling at the same time. Your task during this brief familiarization period is to become aware of what the different tactile sensations feel like. One stimulus will be presented every three seconds, and the above-mentioned order will be followed of hearing and feeling, seeing and feeling, and finally all three together. Do not try to learn any type of association between the sensation you feel and the visual or auditory representation. Just become familiar with what a tactile sensation of a sound combination feels like. Also, during the seeing and feeling presentation, a noise will be presented to you through the earphones you will be wearing to mask out any sound from the tactile transmission system.

Following the familiarization process, the test condition was conducted. The subject felt the 40 pairs of consonant-vowel combinations presented according to Form A listed in Appendix 2. After the presentation of each pair, the subject indicated verbally whether the tactile stimuli felt the same or different. At the end of 20 presentations there was a short rest period of 30 seconds during which the masking noise was turned off and no tactile stimulus was presented.

The above familiarization period and test conditions were all presented tactually at 5.8 volts peak-to-peak and auditorily at 70 dB Lp through the earphones (TDH-39).

The above-mentioned procedures were repeated for the second speaker condition. The speakers were presented alternately to the different subjects. That is, the odd-numbered subjects (1,3,5) received the female speaker first and the male speaker second. The even-numbered subjects (2,4,6) received the reverse order, that being the male speaker first and the female speaker second.

The following instructions were read by the subjects before the test condition was begun:

> The purpose of this task is to determine how well you can discern any difference between pairs of successive tactile sensations. You will receive a stimulus, a one second interval of no stimulus, and then a second stimulus of the pair. Please say aloud: 'Same' if you judge the sensations as identical; or 'Different' if you judge the sensations as not the same. Between pairs of sensations there will be a three-second interval for your response. Also, there will be a noise on continuously during this portion of the test coming from the earphones you will be wearing. This is to mask out any auditory sound emanating from the tactile stimulator which might give you a clue as to a difference between the sensations.

The above procedure was repeated with the stimulus being produced by the second speaker. That is, the subject was presented with the familiarization portion of the experiment with the new speaker and the test portion of the experiment with the second speaker utilizing Form B of the test material to avoid any learning occurring from one speaker to the next. The response forms utilized by the experimenter during the testing sessions are presented in Appendix 11.

Experiment II

Within one week following experiment I experiment II was conducted. The purpose of the second experiment was also to determine whether there were discernible differences between the same consonant-vowel combinations spoken by the two different speakers utilizing the bone receiver (Radioear B-70 A) as the tactile transducer system. Form A of the test list was utilized during this test procedure again for the first speaker and Form B for the second speaker.

The same procedures were followed for this experiment as were used in the first experiment. The abovementioned familiarization period and test condition were all presented tactilely at 2.0 volts peak-to-peak and auditorily at 70 dB Lp through the earphones (TDH-39).

Experiment III

The purpose of experiment III was to determine whether training the subjects in the tactile recognition of the similarities and differences on the bone receiver (Radioear B-70 A), as opposed to familiarization only with the tactile stimulus, affected the experimental results. The same testing procedure was followed in experiment III as was noted in experiments I and II. The major difference was the training of the six subjects, utilizing continuous reinforcement during the training. The training involved a series of nine parameters of TDF from length, intensity, and pattern changes, plus combinations of these parameters; finally the training involved the recognition of consonant-vowel combinations which are different from each other.

A copy of the training score sheet utilized with both speakers is presented in Appendix 12. This procedure was identical to the test task.

The following instructions were read by the subject before the training was conducted:

> The purpose of this training task is to develop a certain level of proficiency in the recognition of tactually different stimuli, prior to testing this newly acquired ability. The tactile training stimuli will be presented to you in pairs with a one-second interval between the two stimuli. That is, you will receive a stimulus, a one-second interval of no stimulus, then a second stimulus of that pair. Please say aloud: 'Same' if you judge the sensations as identical: or 'Different' if you judge the sensations as not the same. After you have stated your judgment of each pair, look to the window to your left. A printed card will be displayed, indicating the correct response. This will occur after each pair of stimuli are presented.
>
> There will be nine parameters such as length, strength, pattern changes and combinations of these on which you will be trained. Prior to the training on each parameter, the dimensions will be explained to you and four different examples of it will be presented to you, with the correct identification presented after each example. Do not respond verbally to this portion of the training procedure but do attempt to recognize the similarities and differences.

During the training a randomly selected series of four pairs was presented involving the above-mentioned parameters. The subject made a selection of "Same" or "Different" and the experimenter recorded whether or not the response the subject made to the stimulus pair was correct. Then he would indicate to the subject visually what the correct response should be, regardless of whether or not the subject had made the correct response. This same procedure was continued for the male speaker until a point where 75 per cent or higher recognition was obtained on a set of four pairs. This same procedure was then conducted with the female speaker on the training tape. The order of presentation varied with each set of four pairs to avoid any learning of the pattern of presentation.

Following the above training, a few minutes' rest period was given, during which the test tape was set up and the signal calibrated to VU zero on the speech audiometer I. Then the same test procedure noted in Experiment I was conducted.

The training and testing were all conducted tactually at 2.0 volts peak-to-peak at a dial setting of 70 dB on the speech audiometer I for the calibration tone on the two tapes. A masking noise of 82 dB Lp was presented to the earphones (TDH-39) connected to the audiometer II to mask the noise emission from the bone receiver tactile transmission system.

Experiment IV

Within one week following experiment III experiment IV was conducted with six different subjects. The purpose of this fourth experiment was to determine whether training the subjects in tactile recognition of the similarities and differences utilizing the Bimorph as opposed to only a familiarization with the tactile stimulus affected the experimental results. The same procedures were followed in this experiment as were noted in Experiment III.

The training and testing were all conducted tactually at 5.8 volts peak-to-peak at a dial setting of 70 dB on speech audiometer I for the calibration tone on the two tapes. A masking noise of 82 dB Lp was presented to the earphones (TDH-39) of audiometer II to mask the noise emission from the Bimorph tactile transmission system.

CHAPTER IV

RESULTS AND DISCUSSION

The questions asked in this study were as follows:

1. Do the tactile distinctive features of certain English consonants and vowels maintain their distinctiveness when combined with each other during tactile stimulation?

If the above question were true, the following questions would be considered.

2. Do different speakers (i.e., male and female) affect the ability to differentiate tactile distinctive features between different consonant-vowel combinations?

3. Does the type of tactile transducer affect the ability to differentiate tactile distinctive features between different consonant-vowel combinations?

4. Does training on the recognition of tactile distinctive features interact with the ability to differentiate tactile distinctive features between different consonant-vowel combinations?

To facilitate the analysis of the data, each pair of the consonant-vowel stimuli presented to the subjects was considered to be in the form of a true/false question with a total of 40 questions. Each combination was presented twice to the same subject, once being produced by the female and once by the male speaker. For example, if the pair was identical /læ - læ/ or tactually the same, the subject was expected to say "same." If the pair was not identical /dʒI - læ/ or contained tactually different elements, the pair was considered different and the subject was expected to say "different."

Results

Maintenance of Tactile Distinctiveness of Certain Sounds

Question One asked "Do the tactile distinctive features of certain English consonants and vowels maintain their distinctiveness when combined with each other during tactile stimulation?" The correct responses for the 40 items on the test ranged from nine to 33 for both speakers, with a mean of 21.91 for the total group of subjects. This is graphically displayed in Figure 4. The mean number of correct responses for the male and female speakers separately were 20.08 and 23.74, respectively. These are graphically displayed in Figures 5 and 6. It can be noted from the above range of scores that very fine tactile differences can be recognized with a moderate degree of accuracy across the variables of two different speakers, two types of tactile transducer systems, and trained and untrained subjects.

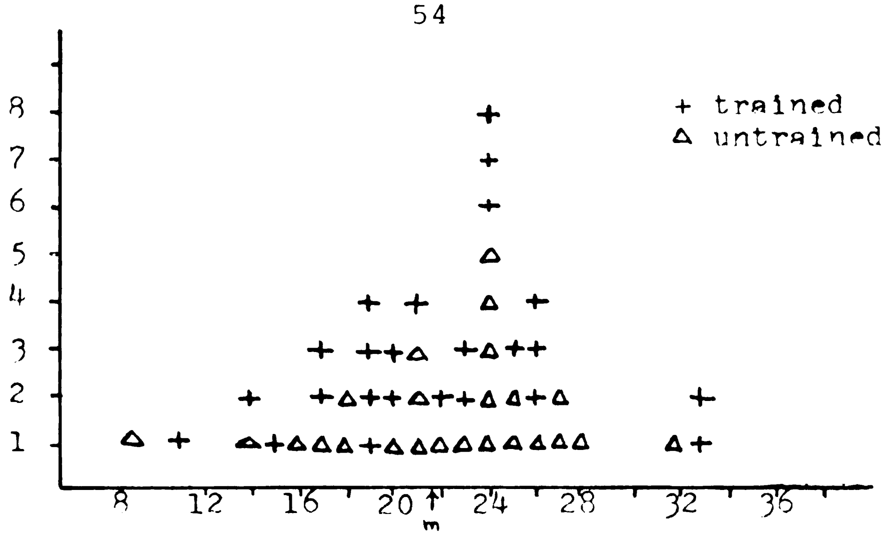

FIGURE 4.--Frequency distribution for the different test scores for all the subjects tested with both speakers.

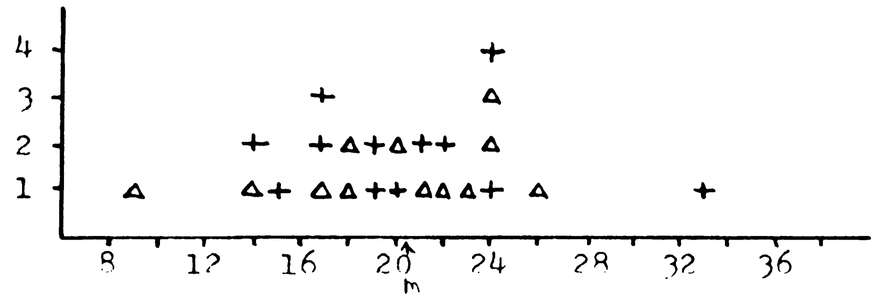

FIGURE 5.--Frequency distribution for the different test scores for all the subjects receiving only the male speaker.

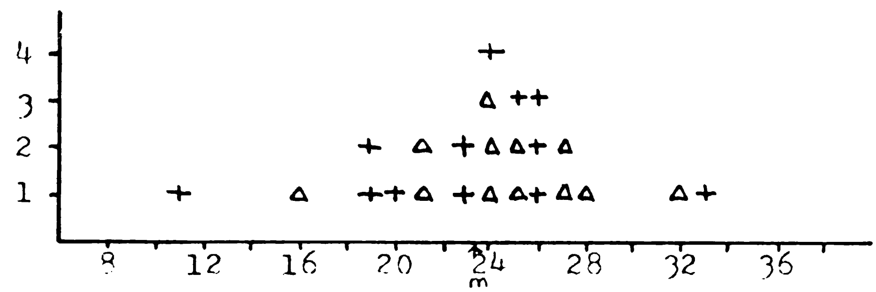

FIGURE 6.--Frequency distribution for the different test scores for all the subjects receiving only the female speaker.

The probability of guessing correctly or incorrectly on each of the 40 test items is 0.5. The probability factor was considered in relation to the distribution of the test scores. The determined critical value levels for deciding which responses were above and below chance if a confidence level of 5 per cent is chosen are 13.8 for the low end (number wrong) and 26.19 for the high end (number correct). Two subjects performed below 13.8 and five subjects performed above 26.19, thus representing seven subjects out of the total of 24 subjects. The scores obtained by these seven subjects could have occurred by chance five times out of 100, whereas the remaining 17 subjects were performing at a greater chance level of occurrence than 5 per cent.

Effects of Speaker, Stimulator and Training

The significance of the answer to the next three questions in this experiment were determined by analysis of variance with a three factor design with repeated measures on the factor of speaker (Winer 1962). The results of this analysis are listed in Table 2.

Each subject's two test scores (one for each speaker) were analyzed as a group in order to determine whether or not these three factors were significant as main effects or in combination with each other. The factors included speaker, stimulator, and training.

TABLE 2.--Analysis of variance.

Source	d/f	Sums of Squares	Mean Squares	F-Ratio
S	1	80.083	80.083	2.081
T	1	3.000	3.000	0.077
G	1	161.333	161.333	84.556*
O:ST	20	769.500	38.475	
ST	1	0.084	0.084	0.002
SG	1	6.751	6.751	3.538
TG	1	16.334	16.334	8.560*
G(O:ST)	20	38.116	1.908	
STG	1	6.748	6.748	3.536

*4.350 required for significance at the 0.05 level of confidence.

S = Stimulator
T = Training
G = Sex of Speaker
O = Observations

Question Two asks "Do different speakers (i.e., male and female) affect the ability to differentiate tactile distinctive features between different consonant-vowel combinations?" The analysis of variance for the main effect of speaker was found to be significant at the 0.05 level of confidence. That is, the two speakers used in this study demonstrated a very different influence on the subjects tested in this study. This can be illustrated graphically in Figures 7, 8, and 9. Figure 7 portrays the difference produced by speakers and training. Figures 8 and 9 portray the influence of the speakers in the same manner as in the

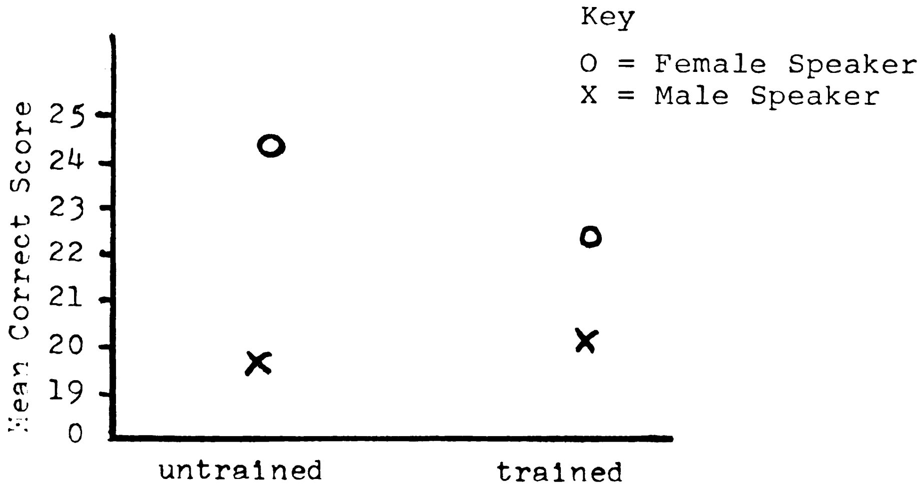

FIGURE 7.--Mean scores for all subjects tested with either transducer.

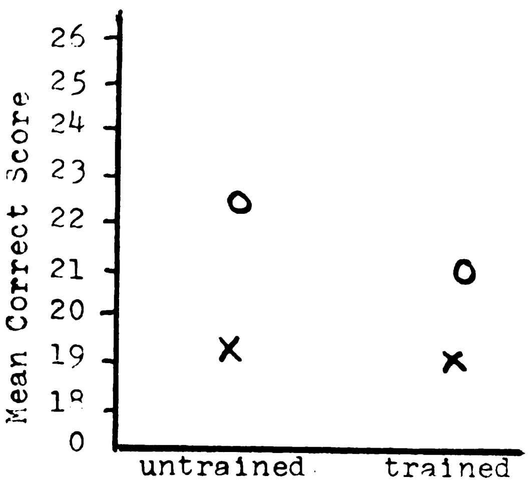

FIGURE 8.--Mean scores for all subjects tested on the Bimorph transducer.

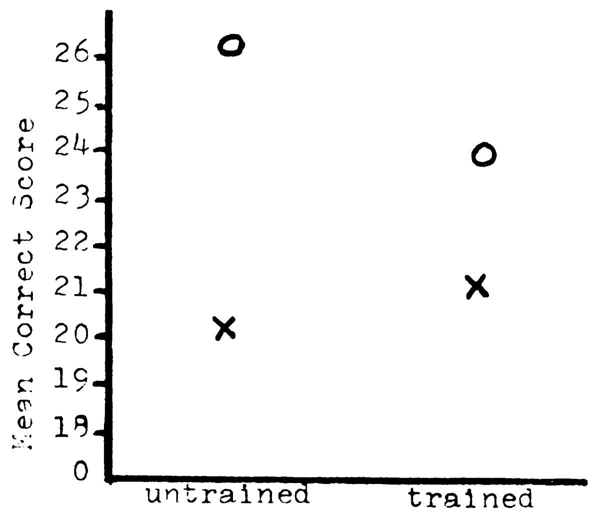

FIGURE 9.--Mean scores for all subjects tested on the bone receiver transducer.

previous figures, but to the different stimulus transduction systems used in the study. It can be noted that the female voice seemed to elicit higher mean correct scores than did the male voice.

Question Three asks "Does the type of tactile transducer affect the ability to differentiate tactile distinctive features between different consonant-vowel combinations?" The analysis of variance for the main effect of stimulators did not indicate any significant difference at the 0.05 level of confidence. It can be seen graphically by comparing Figures 8 and 9 that there is a difference in the results obtained with the two tactile transduction systems, but that this difference is not significant.

Question Four asks "Does training on the recognition of tactile distinctive features interact with the ability to differentiate tactile distinctive features between different consonant-vowel combinations?" The analysis of variance for the main effect of training was not found to be significant at the 0.05 level of confidence. This is illustrated graphically in Figure 7. There is some slight improvement noted for the stimuli involving the male speaker presented to the trained subjects but a decrease in performance occurred with stimuli involving the female speaker presented to the trained subjects.

There was only one significant two-way interaction found in the analysis. This was between training and the speakers. Figure 7 again illustrates this interaction between the two conditions. For example, training seemed to have an adverse effect for the female speaker, whereas for the male speaker there was some slight improvement with training. Also, it was noted earlier, in both trained and untrained conditions, the female speaker stimuli produced higher mean correct scores than did the male speaker stimuli.

Discussion

From the above findings, there would appear to be a difference produced by the two speakers. This difference was considered in light of duration differences between the two stimuli in each test item. To produce a recognizable difference for duration between the two consonant-vowel combinations in each test item, a minimum of 99 msec was required. Twenty-six of the total of 40 items in the experimental test met this criterion for the female voice, but only 12 for the male voice were found (Table 3). For example, in the test item /dʒI-læ/ the male voice demonstrated no duration differences between the two consonant-vowel combinations, whereas for the female voice there was a 233 msec difference between the two consonant-vowel combinations. If peak pressure differences are considered for each test item across the two speakers, only six test items for the female voice demonstrated a peak pressure

TABLE 3.--Duration and peak pressure differences between the consonant-vowel combinations in each test item for both speakers.

Test Items	Duration differences between combinations (msec).		Peak pressure differences between combinations (dB).	
	Male	Female	Male	Female
lɪ læ	0	199	0.5	0.05
pæ lɪ	66	166	0.5	1.0
lɪ bæ	33	99	1.0	3.0
dʒæ lɪ	49	99	1.0	0.5
lɪ mæ	33	199	0.5	0.5
pɪ læ	133	233	0.5	0.0
pæ pɪ	83	199	0.0	1.0
pɪ bæ	166	133	1.0	2.0
dʒæ pɪ	199	199	0.0	0.0
pɪ mæ	133	266	0.0	0.0
læ bɪ	0	233	0.0	0.0
bɪ pæ	66	133	0.0	1.0
bæ bɪ	66	133	0.0	2.0
bɪ dʒæ	99	133	0.5	0.0
mæ bɪ	33	233	0.0	0.0
dʒɪ læ	0	233	1.0	1.0
pæ dʒɪ	99	33	0.5	2.0
dʒɪ bæ	33	99	0.0	1.0
dʒæ dʒɪ	0	133	0.0	0.0
dʒɪ mæ	33	166	1.0	1.0
mɪ læ	66	99	1.0	0.5
pæ mɪ	133	33	1.0	1.0
mɪ bæ	66	33	0.5	2.0
dʒæ mɪ	66	0	1.5	0.0
mɪ mæ	99	233	1.0	0.5
læ læ	0	33	0.0	0.0
pæ læ	99	66	0.0	0.5
læ bæ	33	133	0.0	0.5
dʒæ læ	33	99	0.0	1.0
læ mæ	33	66	0.0	0.0
pæ pæ	0	0	0.0	0.0
pæ bæ	99	33	0.0	2.0
dʒæ pæ	133	33	0.5	2.0
pæ mæ	133	199	2.0	1.5
bæ bæ	0	0	0.0	0.0
dʒæ bæ	33	199	1.0	1.5
bæ mæ	0	99	0.0	1.0
dʒæ dʒæ	0	0	0.0	0.0
mæ dʒæ	0	33	1.0	1.0
mæ mæ	0	0	0.0	0.0

difference between the two consonant-vowel combinations of 2 dB or greater and only one was found for the male voice. For example, the test item /pæ - dʒI/ demonstrated a 2 dB peak pressure difference between the two consonant-vowel combinations for the female voice, but only a 0.5 dB difference in peak pressure was found for the male voice.

These duration and pressure differences between the two speakers used in this study might account for the significant main effect found for speaker in the analysis of variance. One other difference between the two speakers which might be involved in this main effect of speaker is the fundamental frequency of the two speakers which was found to be 106 Hz for the male voice and 192 Hz for the female voice. On the other hand, this difference may be indicative only of how the subjects in this study responded to these two particular male and female speakers, but could not be generalized. Considering the findings of Higgins (1971) the sex of the speaker did not have a major effect on the tactile reception threshold levels for phonemes (except for the /b/ phoneme, as uttered by a female child speaker). The findings of the present study indicate that at an above-threshold level, the vocal characteristics, particularly duration, for the speaker have an effect on how subjects will differentiate tactile differences in speech signals. However, the determination of these vocal characteristics is not within the scope of this study nor will an answer to this question be sought in the present study. It should be added that Gault (1927) found a 20 per cent drop in performance with a change in the speaker in tactile identification of familiar words and phrases. In addition, changes in the speaker's tempo or rhythm also affect the tactile recognition of words or phrases, according to Gault (1927).

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

A total of 24 subjects was tested at above tactile threshold levels to determine their ability to differentiate tactually between certain English consonant-vowel combinations. The 24 subjects were divided randomly into four groups of six subjects each. Two of these groups received training to a criterion of at least 75 per cent accuracy, and two of these groups did not receive any training but were only familiarized to some degree with the tactile stimuli. Furthermore, one of the two groups of the trained subjects were trained by using the Bimorph (PZT-5B) and the other group by using the bone receiver transducer (Radioear B-70 A). Also, one of the non-trained groups of subjects received their familiarization by using the Bimorph transducer and the other group received their familiarization using the bone receiver transducer.

The training involved: (a) the recognition of the tactile distinctive features established by Haas (1970) of length, intensity, patterns, and differing combinations of these parameters; (b) the differentiation between certain test items to a point of at least 75 per cent accuracy. The training was conducted first with the male voice, then immediately followed by the female voice for each separate task in the training.

The procedure used in the familiarization of the above-mentioned twelve subjects on the tactile stimuli was a single presentation of each consonant-vowel combination used in the test during each of the following three separate conditions:

1. Hearing and feeling the combination simultaneously.
2. Seeing a visual representation of the combination and feeling it simultaneously.
3. Seeing a visual representation of the combination, feeling it, and hearing it simultaneously.

This familiarization period was conducted separately for each of the two speakers used in this experiment just prior to the experimental test conducted with that specific speaker's voice. No attempt was made to train the subjects in these two groups to a criterion level as mentioned for the two groups of trained subjects. All of the subjects were tested with the stimuli produced by two different speakers, one a male and one a female, both speaking American-English dialect. Each subject responded to two 40-item tests (one for each speaker) of consonant-vowel combinations which were either identical or different from each other. That is, either the vowel or the consonant or both the vowel and the consonant differed between the two combinations in a pair.

An analysis of variance was employed to determine whether or not there were any significant effects attributable to speaker variation, stimulator variation, training variation, or interactions between any of these preceding factors. The results indicate that the main effect due to speaker variation was the only effect with significance at the 0.05 level of confidence. The only significant two-way interaction at the 0.05 level occurred between the speaker variation and the training variation. The only type of analysis conducted to determine what might account for this difference in the two speakers was to obtain the duration and peak pressure differences for each stimulus pair in each test item for both speakers. These findings demonstrated that the female voice showed a greater degree of duration difference between the consonant-vowel pairs in each test item. This difference would result in greater ease in the recognition of tactile differences between the stimuli in each test item. The peak pressure differences between the stimuli in each test item did not demonstrate a great difference between the two speakers. Because of the limited number of speakers used in the present study, this finding of speaker differences cannot be generalized to all male and female speakers. The question of vocal characteristics is beyond the scope of the present study. The important point to note from these findings is that, at above tactile threshold levels, the vocal characteristics of the speaker may have a significant effect on the observer's utilization of the tactile information received. Changes in the speakers' vocal characteristics were noted by Gault (1927) to reduce the subject's tactile reception ability. In addition, training with the tactile distinctive features with a specific speaker may not necessarily transfer to a second speaker.

The results of this study support the concept of Haas's (1970) tactile distinctive features and these (TDF) are applicable to tactile transducers other than the Bimorph (PZT-5B), such as a bone receiver (Radioear B-70 A).

The effect of training on the differentiation of tactile differences in consonant-vowel combinations does not appear to be of major importance, because it will probably vary in its value from speaker to speaker. The subject who is just familiarized with the speech material with a speaker, depending on the vocal characteristics of the speaker, might perform better than a subject who is trained to a specific criterion level of tactile recognition with the same speaker and the same material when a new speaker presents the same speech material.

Conclusions

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

1. The tactile distinctive features of certain English consonants and vowels maintain their distinctiveness when combined with each other during tactile stimulation.

2. Different speakers, i.e., male and female, will affect the ability to differentiate tactile distinctive features between consonant-vowel combinations and will have different effects on the value of training with tactile speech stimuli.

3. The two types of tactile transducers used in this study (Bimorph PZT-5B and the bone receiver Radioear B-70 A) do not perform differently from each other to a significant degree in allowing subjects to differentiate between different consonant-vowel combinations.

4. Training subjects on the recognition of tactile distinctive features to a certain criterion level does not appear to aid their ability to differentiate between different consonant-vowel combinations.

5. There are no significant interactions attributable to the type of stimulator utilized and the training, the type of stimulator and the speaker, or in the three-way interaction of the stimulator training and speaker.

Recommendations

In light of the findings of the present study, the following recommendations for additional research are made:

1. A study should be conducted to determine whether or not there exists specific vocal characteristics of the speaker that facilitates tactile recognition of speech stimuli.

2. A study should be conducted to determine whether or not the tactile distinctiveness found in the present study, using a broad frequency range system, maintains its distinctiveness when a narrow frequency range system (such as the frequency range of a hearing aid) is utilized for presentation of the stimuli.

3. A study should be conducted to determine whether or not the tactile transduction systems utilized in the present study would demonstrate a greater sensitivity if they are housed in a different manner, and in contact with the subject's body, without the resting force on the stimulator experienced with the present system.

4. A study should be conducted to determine the degree of improvement that tactile information adds to auditory information under differing degrees of signal-to-noise interference with speech information.

LIST OF REFERENCES

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Bekesy, G. von., Experiments in Hearing. New York: McGraw-Hill Book Co. (1960).

__________, "Ueber die Vibrationsempfinding." AKUST 2, No. 4, 316 (1939).

__________, Sensory Inhibition. Princeton, N.J.: Princeton University Press (1967).

Bice, R. C., "Electromechanical Transducer for Vibrotactile Stimulation." Rev. Sci. Intr. 32, 856-857 (1961).

Bliss, James C. Chapter 24, from Bennett, E., J. Degan, and J. Spiegel (Editors). Human Factors in Technology. New York: McGraw-Hill Book Co., 368-375 (1963).

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

Cohen, Louis H. and Stanley B. Lindley, "Studies in Vibratory Sensibility." Amer. J. of Psych. 51, 44-63 (1938).

Dudley, H. W., "The Vocoder." Bell Laboratory Record. 18, 122-126 (1936).

Diespecker, D. D., "Vibrotactile Learning." Psychonomic Science. 9, No. 2, 107-108 (1967).

Gault, R. H., "Progress in Experiments on Tactual Interpretation of Oral Speech." J. of Abnormal and Social Psych. 19, 155-159 (1924).

__________, "Hearing Through the Sense Organs of Touch and Vibration." J. Franklin Institute. 204, 329-358 (1927).

__________, "On the Identification of Certain Vowel and Consonantal Elements in Words by their Tactual Qualities and by their Visual Qualities as Seen by the Lipreader." J. of Abnormal and Social Psych. 22, 33-39 (1927).

Geldard, Frank A., "The Perception of Mechanical Vibration: One History of a Controversy." J. Gen. Psych. 22, 243-269 (1940).

__________, "Adventures in Tactile Literacy." Amer. Psychologist. 12, 115-125 (1957).

__________, "Some Neglected Possibilities of Communication." Science. 131, 1583-1588 (1960).

__________, "Cutaneous Channels of Communication." Sensory Communication. Edited by W. A. Rosenblith. Cambridge, Mass.: The M.I.T. Press (1961).

__________, "Pattern Perception by the Skin." The Skin Senses. Edited by D. R. Kenshalo. Springfield, Ill.: Charles C. Thomas (1968).

__________, "Vision, Audition, and Beyond." Contributions to Sensory Physiology. Edited by William D. Neff. New York: Academic Press, 1-16 (1969).

__________ and C. E. Sherrick, "Telephone Conversation, 1970." noted by Haas. Unpublished Ph.D. dissertation, Michigan State University (1970).

Gibson, Robert H., "Electrical Stimulation of Pain and Touch." The Skin Senses. Edited by D. R. Kenshalo. Springfield, Ill.: Charles C. Thomas (1968).

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

Goodfellow, Louis D., "An Empirical Comparison of Audition, Vision, and Touch in the Discrimination of Short Intervals of Time." Amer. J. of Psych. 46, 243-258 (1934).

Goff, Genevieve D., "Differential Discrimination of Frequency of Cutaneous Mechanical Vibration." J. Exper. Psych. 74, No. 2, 290-298 (1967).

Guberina, P., "Deaf Patients Learn to Listen on a New Wave-Length." J. of Rehabilitation. 31, 20-21 (1965).

Haas, William H., "Vibrotactile Reception of Spoken English Phonemes." Unpublished Ph.D. dissertation, Michigan State University (1970).

Higgins, Jerry M., "The Effects of Speaker and Pressure Variation on the Vibrotactile Reception of Selected Spoken English Phonemes." Unpublished Ph.D. dissertation, Michigan State University (1971).

Hisayoshi, Suzaki, R. Kagami, and T. Takahashi., "Tactphone as an Aid for the Deaf." Sixth International Congress on Acoustics: Tokyo, Japan. Aug. 21-28, A-5-2 (1968).

Jakobson, R., C. G. Fant, and M. Halle., Preliminaries to Speech Analysis. Cambridge, Mass.: The M.I.T. Press (1963).

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

Kiedel, W. D., "Note on a New System for Vibratory Communication." Perceptual and Motor Skills. 8, 250 (1958).

Knudsen, V. O., "Hearing with the Sense of Touch." J. Gen. Psych. 1, 320-352 (1928).

Kringlebotn, M., "Experiments with some Visual and Vibrotactile Aids for the Deaf." Amer. Annals of the Deaf. 113, 311-317 (1968).

Levine, et al., FELIX. Massachusetts Institute of Technology (1949-1951).

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

__________ and Pickett, B. H., "Communication of Speech Sounds by a Tactual Vocoder." J. of Speech and Hearing Research. 6, 207-222 (1963).

Sherrick, C. E., "Variables Affecting Sensitivity of the Human Skin to Mechanical Vibration." J. of Experimental Psych. 45, 237-242 (1953).

__________, "Effects of Double Simultaneous Stimulation of the Skin." The Amer. J. of Psych. 77, 42-53 (1964).

__________, "Simple Electromechanical Vibration Transducer." Rev. of Sci. Instrumentation. 36, 1893-1894 (1965).

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

Speech Transmission Laboratory, Stockholm, Sweden. Report No. 27, March (1963).

Verillo, Ronald T., "A Duplex Mechanism of Mechanoreception." The Skin Senses. Edited by D. R. Kenshalo. Springfield, Ill.: Charles C. Thomas, 139-159 (1968).

__________, "Effect of Contractor Area on the Vibrotactile Threshold." J. of Acoustical Soc. of America. 35, 1962 (1963).

Winer, B. J., Statistical Principles in Experimental Design. New York: McGraw-Hill Book Co. (1962).

APPENDICES

APPENDIX 1

MATRICES OF CONSONANT-VOWEL COMBINATIONS

Matrix I

Vertical \ Horizontal	1 læ	2 pæ	3 bæ	4 dʒæ	5 mæ
1 lɪ	0* 5 c v	6 5	6 5	5 5	4 5
2 pɪ	6 5	0 5	0 5	1 5	2 5
3 bɪ	6 5	0 5	0 5	1 5	2 5
4 dʒɪ	5 5	1 5	1 5	0 5	3 5
5 mɪ	4 5	2 5	2 5	3 5	0 5

Matrix II

Vertical \ Horizontal	1 læ	2 pæ	3 bæ	4 dʒæ	5 mæ
1 læ	0* 0 c v	6 0	6 0	5 0	4 0
2 pæ	6 0	0 0	0 0	1 0	2 0
3 bæ	6 0	0 0	0 0	1 0	2 0
4 dʒæ	5 0	1 0	1 0	0 0	3 0
5 mæ	4 0	2 0	2 0	3 0	0 0

*The numbers inside the boxes indicate the degree of difference the consonants and vowels have from each other. A difference across one distinctive feature parameter is given a value of two, and a difference which does not completely cross a parameter line is given a value of one. Table 1 can be used to determine the above-mentioned degrees of difference.

APPENDIX 2

FAMILIARIZATION LIST AND TEST FORMS A AND B

TEST LISTS

FORM A						FORM B					
1	lI	læ	21	mI	læ	1	mI	læ	21	lI	læ
2	pæ	lI	22	pæ	mI	2	pæ	mI	22	pæ	lI
3	lI	bæ	23	mI	bæ	3	mI	bæ	23	lI	bæ
4	dʒæ	lI	24	dʒæ	mI	4	dʒæ	mI	24	dʒæ	lI
5	lI	mæ	25	mI	mæ	5	mI	mæ	25	lI	mæ
6	pI	læ	26	læ	læ	6	læ	læ	26	pI	læ
7	pæ	pI	27	pæ	læ	7	pæ	læ	27	pæ	pI
8	pI	bæ	28	læ	bæ	8	læ	bæ	28	pI	bæ
9	dʒæ	pI	29	dʒæ	læ	9	dʒæ	læ	29	dʒæ	pI
10	pI	mæ	30	læ	mæ	10	læ	mæ	30	pI	mæ
11	læ	bI	31	pæ	pæ	11	pæ	pæ	31	læ	bI
12	bI	pæ	32	pæ	bæ	12	pæ	bæ	32	bI	pæ
13	bæ	bI	33	dʒæ	pæ	13	dʒæ	pæ	33	bæ	bI
14	bI	dʒæ	34	pæ	mæ	14	pæ	mæ	34	bI	dʒæ
15	mæ	bI	35	bæ	bæ	15	bæ	bæ	35	mæ	bI
16	dʒI	læ	36	dʒæ	bæ	16	dʒæ	bæ	36	dʒI	læ
17	pæ	dʒI	37	bæ	mæ	17	bæ	mæ	37	pæ	dʒI
18	dʒI	bæ	38	dʒæ	dʒæ	18	dʒæ	dʒæ	38	dʒI	bæ
19	dʒæ	dʒI	39	mæ	dʒæ	19	mæ	dʒæ	39	dʒæ	dʒI
20	dʒI	mæ	40	mæ	mæ	20	mæ	mæ	40	dʒI	mæ

APPENDIX 3

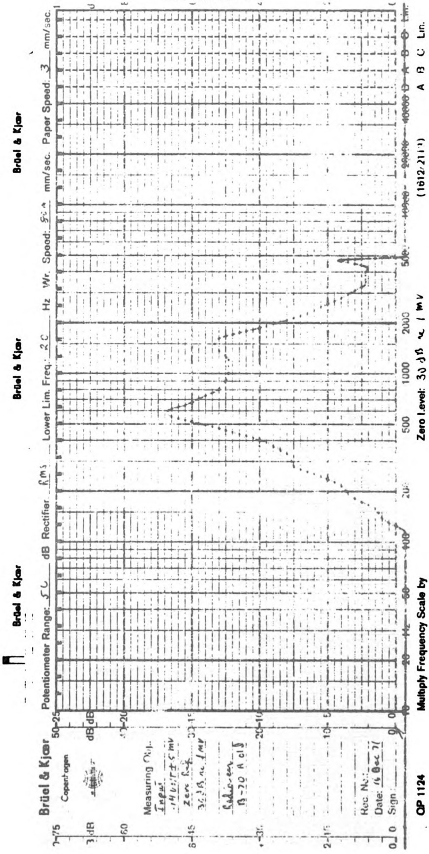
SPECIFICATIONS OF THE BIMORPH TRANSDUCER

Bimorph Model	Size (Inches)	Voltage (Volts)
PZT-5B	1/8 x 1.25	260

The PZT-5B Bimorph transducer was chosen for the previous and present studies because of its high voltage limit. This transducer provides relatively flat frequency response characteristics from 15 to 20,000 Hz (Clevite Corporation: Bedford, Ohio). The resonant frequency is in the range of 300 k Hz.

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

APPENDIX 4



FREQUENCY RESPONSE OF THE BONE RECEIVER

APPENDIX 5

RESPONSE CHARACTERISTICS OF THE RECORDING EQUIPMENT AND THE STIMULUS TRANSMISSION TAPE RECORDER

Electrovoice 635-A Microphone. The Electrovoice 635-A microphone used in this study conformed to the manufacturer's standards of a variation of ± 2 dB from 100 to 15,000 Hz. This response was measured with the following procedure: The Electrovoice 635-A microphone was placed in the hearing aid test box (type 4212), at zero degree incidence to the regulating microphone. The output from the microphone being tested was fed into the microphone amplifier (Bruel and Kjaer type 2604). A 60 dB signal generated from a beat frequency oscillator (Bruel and Kjaer type 1022) was directed into the hearing aid test box sound field and was used together with the amplifier section of the audio frequency spectrometer (Bruel and Kjaer type 2112) and a graphic level recorder (Bruel and Kjaer type 2305) to record the frequency response curve of the Electrovoice 635-A microphone.

Ampex AG 440-B Tape Recorder. The frequency response of this recorder was the same as stated in the manufacturer's specifications, i.e., ± 2 dB from 50 to 15,000 Hz. The frequency response characteristics of this tape recorder were determined by using the Ampex (7.5 ips) precision alignment tape (NAB).

APPENDIX 5 Continued

Ampex AG 600 Tape Recorder. The frequency response of this recorder was the same as stated in the manufacturer's specifications, i.e., ± 2 dB from 50 to 12,000 Hz. The frequency response characteristics of this tape recorder were determined by using the Ampex (7.5 ips) precision alignment tape (NAB).

Ampex AG 601 Tape Recorder. The frequency response of this recorder was the same as stated in the manufacturer's specifications, i.e., ± 2 dB from 50 to 12,000 Hz. The frequency response characteristics of this tape recorder were determined by using the Ampex (7.5 ips) precision alignment tape (NAB).

APPENDIX 6

EQUIPMENT CALIBRATION

The speech audiometer (Grason Stadler model 162) was calibrated to the Bimorph (PZT-5B) and the bone receiver (Radioear B-70 A) by taking voltage measurements across the electrical terminals of both tactile transducers. The oscilloscope (Tektronic 561A) was used in making the measurements. The stimulus tone was a 1000 Hz calibration tone from the test tape used in this experiment.

The measurements were as follows for the two stimulators:

Attenuator Dial Setting	Voltage Readings for the Bimorph	Voltage Readings for the Bone Receiver
50 dB	6.90 v	0.162 v
60 dB	22.00 v	0.510 v
70 dB	70.00 v	1.600 v
80 dB	230.00 v	5.300 v

The linearity of the speech audiometer (Grason Stadler model 162) audiometer dial was evaluated utilizing the sound level meter (Bruel and Kjaer type 2204 S) together with the artificial ear (Bruel and Kjaer type 4152). The earphone (TDH-39), 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.

APPENDIX 6 Continued

The measurements for a 1000 Hz tone at 10 dB intervals from 100 dB HL to 30 dB HL all indicated a 10 dB change ± 1 dB.

Measurements of masking noise for both earphones were within ± 1 dB of each other for both the Grason Stadler speech audiometer and the Beltone model 15 C audiometer.

APPENDIX 7

TEST SCORES (RAW DATA) WITH THE BIMORPH

Bimorph Transducer

Items		Trained Subjects Male and Female Voice												Untrained Subjects Male and Female Voice											
		1		2		3		4		5		6		7		8		9		10		11		12	
		f	m	f	m	f	m	f	m	f	m	f	m	f	m	f	m	f	m	f	m	f	m	f	m
lɪ	læ	0	0	0	1	0	1	0	1	1	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0
pæ	lɪ	0	1	0	0	0	1	1	0	0	1	1	0	1	1	0	0	1	0	1	1	1	1	1	1
lɪ	bæ	1	1	1	1	1	1	0	1	0	0	1	1	1	1	1	0	1	1	1	0	0	1	1	1
dʒæ	lɪ	0	0	0	0	1	1	1	1	0	1	1	1	1	0	0	0	0	1	0	0	0	1	1	1
lɪ	mæ	0	0	0	1	1	0	0	0	1	1	0	0	1	0	0	0	0	0	0	1	1	1	1	0
pɪ	læ	1	0	1	1	1	0	1	1	1	1	0	0	1	0	1	1	1	1	1	0	1	0	1	1
pæ	pɪ	1	1	1	0	1	1	1	1	1	1	0	0	1	0	1	0	1	0	0	1	0	0	1	0
pɪ	bæ	0	0	0	1	1	0	0	1	0	1	1	1	0	1	1	0	1	1	1	1	0	1	1	0
dʒæ	pɪ	0	0	0	1	1	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	1
pɪ	mæ	1	0	1	1	0	0	0	1	1	0	1	0	1	1	1	1	0	0	1	0	1	0	1	1
læ	bɪ	1	1	1	0	1	1	0	0	1	1	1	1	1	0	1	0	1	1	1	1	1	0	1	0
bɪ	pæ	0	1	0	0	0	0	1	0	1	1	0	1	1	0	0	0	1	1	1	0	1	0	0	1
bæ	bɪ	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	1	0	1	1	0	0
bɪ	dʒæ	0	1	1	0	0	0	1	0	1	1	1	0	0	1	0	1	1	0	0	1	0	0	0	0
mæ	bɪ	0	1	1	0	1	1	1	0	1	1	1	1	1	1	0	0	0	1	0	0	0	1	1	0
dʒɪ	læ	0	0	0	1	0	1	0	0	1	1	1	0	1	0	1	0	1	1	0	1	0	0	1	1
pæ	dʒɪ	1	0	0	1	0	1	1	1	0	1	1	0	1	0	0	0	1	1	0	1	1	0	1	0
dʒɪ	bæ	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	1	1	1
dʒæ	dʒɪ	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0
dʒɪ	mæ	1	1	1	0	0	1	0	1	1	0	1	1	1	0	0	0	1	1	0	1	0	0	1	1
mɪ	læ	1	1	0	0	1	1	0	1	1	0	1	0	1	1	0	0	1	1	0	1	1	0	1	1
pæ	pɪ	1	0	0	0	0	0	1	0	1	0	1	0	1	0	0	0	0	1	1	1	1	1	1	1
mɪ	bæ	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0
dʒɪ	mɪ	1	0	1	0	1	1	1	1	1	1	1	0	1	0	0	0	1	1	1	0	1	0	1	1
mɪ	mæ	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	1
læ	læ	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	1	1
pæ	læ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1	1
læ	læ	0	1	1	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	1
dʒæ	læ	0	0	0	0	1	1	1	1	1	0	0	0	1	1	0	0	0	1	0	1	0	0	1	0
læ	mæ	1	1	0	0	1	0	1	1	0	0	0	0	0	1	0	0	1	1	0	1	1	1	1	0
pæ	pæ	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	0	0	1	0	1	1	1	0	0
pæ	bæ	0	1	1	1	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	1	1	0	0	1
dʒæ	pæ	0	0	1	1	1	1	0	0	1	0	0	0	0	0	1	0	0	0	0	1	1	0	0	1
pæ	mæ	0	0	0	0	1	0	0	1	0	1	0	1	0	1	1	0	0	1	1	0	1	1	1	1
bæ	bæ	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	1	0	0	1	1	0
dʒæ	bæ	1	0	0	0	1	1	0	1	0	1	0	0	0	0	1	0	0	0	1	0	1	1	1	1
bæ	mæ	0	0	1	0	1	0	1	1	1	0	1	0	1	0	1	0	0	1	1	0	1	0	1	0
dʒæ	dʒæ	0	0	1	0	0	1	1	1	0	1	1	0	0	0	1	0	0	0	0	0	1	1	1	0
mæ	dʒæ	1	1	0	0	1	0	1	0	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1	0
mæ	mæ	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	1	0	0	0	1	1	0

0: response of "same" by the subject.
1: response of "different" by the subject.

APPENDIX 8

TEST SCORES (RAW DATA) WITH THE BONE RECEIVER

Items — Bone Receiver Transducer

Items		Trained Subjects Male and Female Voice												Untrained Subjects Male and Female Voice											
		13		14		15		16		17		18		19		20		21		22		23		24	
		f	m	f	m	f	m	f	m	f	m	f	m	f	m	f	m	f	m	f	m	f	m	f	m
lɪ	læ	1	0	0	0	1	0	1	1	1	1	0	1	0	0	0	0	1	0	1	1	0	0	0	1
pæ	lɪ	0	1	0	1	0	1	0	0	1	1	1	1	0	0	1	1	0	0	1	0	1	0	1	0
lɪ	bæ	1	1	0	0	0	0	1	0	1	1	0	1	1	1	1	1	0	1	1	1	0	0	1	0
dʒæ	lɪ	1	0	0	1	1	1	0	0	1	1	1	0	1	0	1	1	1	0	0	1	1	0	0	0
lɪ	mæ	1	0	1	0	1	1	0	0	1	1	0	1	1	0	1	1	1	1	1	0	1	0	1	1
pɪ	læ	1	0	0	0	0	0	1	1	1	1	1	1	0	0	1	1	0	0	1	1	0	1	1	1
pæ	pɪ	1	0	1	0	1	1	0	0	1	1	0	0	0	0	1	0	1	0	1	0	1	0	1	1
pɪ	bæ	0	0	0	0	0	0	1	0	1	1	1	1	0	0	1	1	0	1	1	1	0	1	0	0
dʒæ	pɪ	0	0	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	0	1	1	1	0	0	0
pɪ	mæ	1	0	0	0	1	1	0	0	1	1	0	0	1	0	1	1	1	0	1	0	1	0	1	0
læ	bɪ	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	0	1
bɪ	pæ	1	1	1	0	1	0	0	0	1	1	1	0	1	0	1	0	1	0	1	0	1	1	1	1
bæ	bɪ	1	0	0	0	0	1	0	1	1	1	0	0	0	0	1	0	1	0	1	0	0	1	0	1
bɪ	dʒæ	1	1	0	0	1	1	0	1	1	1	0	0	0	0	1	0	1	0	0	0	1	1	1	1
mæ	bɪ	0	0	0	0	1	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	0
dʒɪ	læ	1	1	0	0	1	1	1	1	1	1	1	0	0	1	0	1	0	1	1	1	1	1	0	0
pæ	dʒɪ	0	0	0	1	0	1	1	1	1	1	0	1	0	0	0	0	0	1	1	1	1	0	1	0
dʒɪ	bæ	1	1	0	0	1	1	1	0	1	1	0	0	1	1	0	0	1	0	1	1	0	1	0	1
dʒæ	dʒɪ	0	0	0	0	1	0	1	1	1	1	0	1	1	0	1	0	1	1	1	1	1	1	1	1
dʒɪ	mæ	1	0	1	0	0	0	0	0	1	1	1	0	1	0	0	0	1	0	1	0	1	1	0	0
mɪ	læ	1	1	0	0	1	1	1	1	1	1	1	0	0	0	0	1	0	1	1	1	1	1	0	0
pæ	mɪ	1	0	1	1	1	1	1	1	0	1	0	1	0	1	1	1	0	0	0	1	0	1	1	0
mɪ	bæ	1	1	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
dʒæ	mɪ	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	0	0
mɪ	mæ	1	1	0	0	0	1	1	1	1	1	1	0	0	0	1	0	1	1	0	0	1	0	1	1
læ	læ	1	0	1	1	0	0	0	0	0	0	0	1	0	1	1	1	1	1	0	0	0	0	1	1
pæ	læ	0	0	0	0	1	1	1	0	1	0	1	1	0	0	1	1	1	0	1	0	1	0	1	0
læ	bæ	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	1	0	1	1	1	1	1	0	0
dʒæ	læ	0	1	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	1	0	1	0	1	0	1
læ	mæ	0	0	0	0	1	0	1	0	1	0	1	0	1	0	1	1	1	1	1	1	1	0	1	1
pæ	pæ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	1
pæ	bæ	0	1	1	0	1	0	1	0	1	0	1	0	0	0	1	1	1	1	1	1	1	1	0	0
dʒæ	pæ	1	1	0	0	1	0	0	0	1	0	1	0	1	0	1	1	1	1	1	0	1	1	1	0
pæ	mæ	0	0	0	1	0	1	1	0	0	0	0	0	1	1	1	1	1	0	1	0	0	1	1	0
bæ	bæ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	1
dʒæ	bæ	1	1	1	1	0	0	0	0	0	1	0	1	0	0	0	1	0	0	1	1	1	1	0	1
bæ	mæ	1	0	0	1	0	0	1	0	1	1	1	0	1	0	1	1	1	0	0	1	1	0	1	1
dʒæ	dʒæ	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0
mæ	dʒæ	1	0	0	0	0	1	0	0	0	0	0	0	1	0	1	0	1	1	1	1	1	0	1	1
mæ	mæ	0	0	0	0	0	1	1	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	0

0; response of "same" by the subject.
1; response of "different" by the subject.

APPENDIX 9

TOTAL NUMBER OF CORRECT RESPONSES FOR EACH SUBJECT

Trained Bimorph Subject No.	Speakers: Male		Female	
1	17		20	
2	17		19	
3	21		26	Grand
4	22		19	Mean 20.4
5	24		23	
6	14		23	
Group mean	19.16	Group mean	21.6	

Trained Bone Receiver Subject No.	Speakers: Male		Female	
13	19		26	
14	15		11	
15	24		25	Grand
16	19		26	Mean 22.9
17	33		33	
18	20		24	
Group mean	21.66	Group mean	24.16	

Untrained Bimorph Subject No.	Speakers: Male		Female	
7	17		25	
8	9		16	
9	26		21	Grand
10	21		21	Mean 20.8
11	18		24	
12	23		27	
Group mean	19.16	Group mean	22.5	

Untrained Bone Receiver Subject No.	Speakers: Male		Female	
19	14		24	
20	22		27	
21	18		25	Grand
22	24		32	Mean 23.5
23	24		28	
24	20		24	
Group mean	20.33	Group mean	26.66	

APPENDIX 10

TOTAL NUMBER OF CORRECT RESPONSES FOR THE EXPERIMENTAL TEST FOR EACH SUBJECT (TRAINED OR NONTRAINED) WITH THE BIMORPH STIMULATOR WITH BOTH SPEAKERS

Group of Subjects Trained		Group of Subjects Nontrained	
Subject No.	Score	Subject No.	Score
1	37	7	42
2	36	8	25
3	47	9	47
4	41	10	43
5	47	11	43
6	37	12	50
Group Mean	40.83	Group mean	41.66
Grand mean 41.24			
BONE RECEIVER STIMULATOR			
13	45	19	38
14	26	20	49
15	49	21	43
16	45	22	56
17	66	23	52
18	44	24	44
Group Mean	45.83	Group mean	47.0
Grand mean 46.41			

Grand mean for the total number of correct responses for the experimental test for each subject trained and tested with either stimulator and with both speakers.
Grand mean 43.33

Grand mean for the total number of correct responses for the experimental test for each subject untrained on either stimulator but familiarized tactilely with both speakers.
Grand mean 44.33

APPENDIX 11

SUBJECT RESPONSE FORMS A AND B

SUBJECT RESPONSE FORM #1 NAME: ______________

Date: ______________ Subject #: ______________

Form: A

RESPONSE FORM FOR PAIRED COMPARISONS

Pair		S/D*
lI	læ	
pæ	lI	
lI	bæ	
dʒæ	lI	
lI	mæ	
pI	læ	
pæ	pI	
pI	bæ	
dʒæ	pI	
pI	mæ	
læ	bI	
bI	pæ	
bæ	bI	
bI	dʒæ	
mæ	bI	
dʒI	læ	
pæ	dʒI	
dʒI	bæ	
dʒæ	dʒI	
dʒI	mæ	

Pair		S/D
mI	læ	
pæ	mI	
mI	bæ	
dʒæ	mI	
mI	mæ	
læ	læ	
pæ	læ	
læ	bæ	
dʒæ	læ	
læ	mæ	
pæ	pæ	
pæ	bæ	
dʒæ	pæ	
pæ	mæ	
bæ	bæ	
dʒæ	bæ	
bæ	mæ	
dʒæ	dʒæ	
mæ	dʒæ	
mæ	mæ	

APPENDIX 11 Continued

SUBJECT RESPONSE FORM #1 NAME: ______________

Date: ______________ Subject #: ______________

Form: B

RESPONSE FORM FOR PAIRED COMPARISONS

Pair		S/D
mI	læ	
pæ	mI	
mI	bæ	
dʒæ	mI	
mI	mæ	
læ	læ	
pæ	læ	
læ	bæ	
dʒæ	læ	
læ	mæ	
pæ	pæ	
pæ	bæ	
dʒæ	pæ	
pæ	mæ	
bæ	bæ	
dʒæ	bæ	
bæ	mæ	
dʒæ	dʒæ	
mæ	dʒæ	
mæ	mæ	

Pair		S/D*
lI	læ	
pæ	lI	
lI	bæ	
dʒæ	lI	
lI	mæ	
pI	læ	
pæ	pI	
pI	bæ	
dʒæ	pI	
pI	mæ	
læ	bI	
bI	pæ	
bæ	bI	
bI	dʒæ	
mæ	bI	
dʒI	læ	
pæ	dʒI	
dʒI	bæ	
dʒæ	dʒI	
dʒI	mæ	

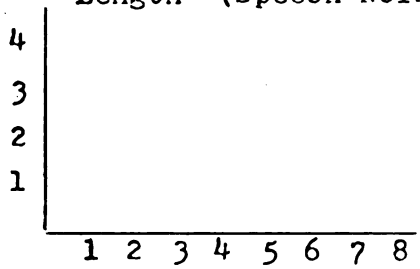
APPENDIX 12

TRAINING SCORE SHEET

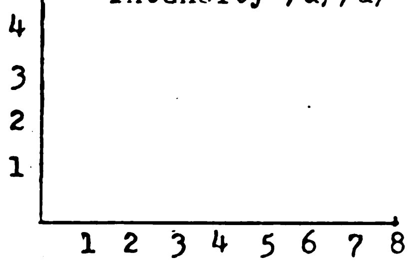
Name________________ Stimulator____________

Speaker male: +
female: 0

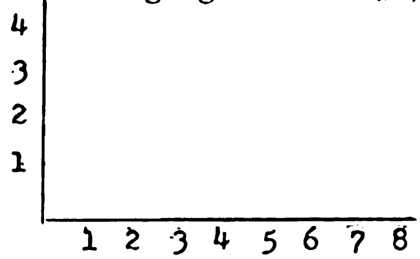
Length (Speech Noise)



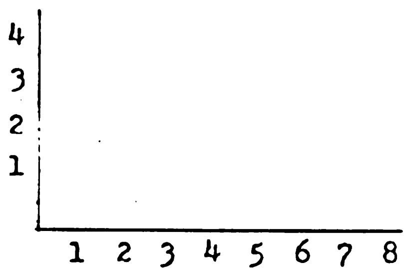
Intensity /u//u/



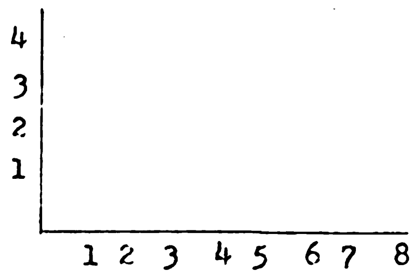
Changing Pattern /n//z/



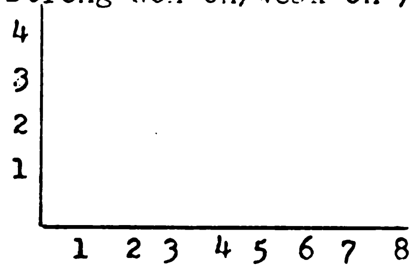
Weak Short/Strong Long/p//ɔ/



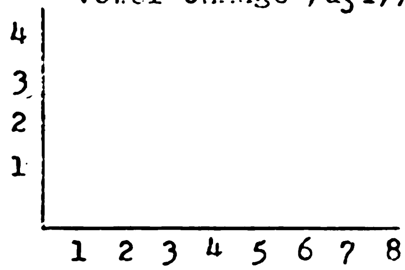
Long Weak/Strong Short/m//I/



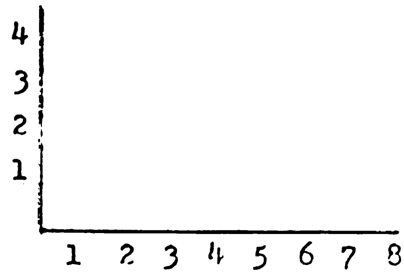
Strong Non-Ch/Weak Ch /u//z/



Vowel Change /dʒI//læ/



Consonant Change /pæ//læ/



Both Change /dʒI//læ/