THE TRANSMISSION OF SPEECH BY SENSES OTHER THAN THE EAR

by

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Submitted in Partial Fulfillment of Requirements
for the Degrees of Master of Science and Bachelor
of Science.

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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September 1949

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This thesis is an investigation of some original ideas on speech transmission by Prof. Jerome B. Wiesner. I am further indebted to Prof. Wiesner, who as thesis advisor, materially assisted me. I wish, also, to thank Edward E. David for building the first modulator and performing some of the preliminary research. Finally, I want to acknowledge the aid of Walter L. Koltun, Joseph Yamron, Joseph Gottlieb, and Robert Kingston. They served as subjects and provided much needed data on learning via mechanical vibration.

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CHAPTER I

INTRODUCTION

For many years the scientist has applied his skills to the invention of devices to aid the physically handicapped. His achievements have been less publicized than those of his cohorts in other fields of science. Undoubtedly, the rehabilitation of a human being is less dramatic than the invention of radar or the construction of an atom bomb. Nevertheless, the scientist can point to inventions which are today being substituted for lost limbs and senses.

How handicapped is a man who has lost two or even only one of his legs? Even today with all of the modes of transportation at his disposal, man still needs to walk if he would travel unassisted. Once he replaced a lost leg with a wooden stump. Now, the scientist gives him an artificial leg which bends much like a real one and permits him to walk with an almost normal gait. Nor is this the ultimate development. For the near future the scientist holds forth the possibility of a leg that will be able to explore the terrain and relay the information to the nerve system of its wearer.*

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*Because the present artificial leg can in no way indicate the topography over which the wearer walks, the legless man must look at the ground continually. Dr. Norbert Wiener has suggested the design of a leg with electric stimulators attached to the still living stump. Motion of the artificial foot would activate the electrical stimulators. This is similar to the technique used in FEELIES where one part of the nervous system is substituted for another that is destroyed.

Without his arms man is almost completely at the mercy of his environment. Instead of a sleeve filled with a useless piece of wood, the armless man has an artificial arm that can be used for grasping, carrying, and even writing. Not too sightly, but functionally quite capable.

About 80% of the knowledge a man derives about his world he derives through the medium of his sight. A blind man, doomed to spend a life in darkness, is indeed a lost person. Until recently Braille reading and the seeing eye dog were the only aids offered to the blind man. A short time ago two instruments were reported which may do much to improve the blind man's status. The first is a pointing cane, a radar like device, whose auditory signals are used for depth and distance perception. The second is a machine which can scan a page and "read" it aloud.[1]

The hard of hearing are people with deficiencies in the outer or middle ear. Without aid they would live in a very silent world. However, the hearing aid is in such a high degree of development that to get such people to hear has almost ceased to be a problem.

This is the imposing record of success of the scientist, giving aid to the lame, the blind, and hard of hearing. Almost alone among his failures stand the stone deaf (those whose auditory nerve is completely destroyed). Perhaps, this failure is caused by a lack of understanding of the manner in which the ear functions. Maybe, the failure is because our knowledge of speech sounds is inadequate. Whatever the reason the stone deaf have received little succor from science. Without lip reading to guide him, the stone deaf would have exceedingly limited communications with his fellow men.

Although the scientist has not been able to assist the stone deaf materially, he has not ignored this problem. At least three major attempts have been made to minimize the plight of the deaf man. These are in chronological order (1) the work of Robert Gault on tactile stimulators, (2) the studies of the Bell Laboratories on visual speech, and (3) the present research carried on at the Massachusetts Institute of Technology which is described in this thesis.

Robert Gault is a psychologist who was interested primarily in finding a device that could be used to facilitate the teaching of lip reading to the deaf. Any device was necessarily subservient in importance to the teaching of lip reading. Gault started by using a hollow tube which he pressed against the deaf person's palm.[a] He spoke into the other end, and the deaf person felt the changes in sound pressure on his hand. This was the crudest of techniques. Yet the subject was able to distinguish thirty-four different words.

Gault next had the subject grasp the earphone of a telephone receiver in the palm of his hand with about the same results as the hollow tube. Finally, he cooperated with the Bell Laboratories to build a five unit teletactor.[3] The teletactor broke up the speech into five channels (0-250cps, 256-500cps, 500-1000cps, 1000-2000cps, 2000cps to limit of apparatus). The output after suitable amplification went to five mechanical vibrators. These vibrators were easily grasped by the fingers and thumbs when the hand was held in a vertical position. The thumb reveived the lowest frequency band and the little finger received the highest frequency band.

Since Gault was solely concerned with lip reading, he took little data on the effectiveness of the teletactor as a means of communicating speech.[4] But Gault did find that the teletactor fulfilled his limited demands and noticeably sped up the teaching of the lip reading of vowel sounds. Gault used the five unit teletactor a short time. For some unaccountable reason he returned to a single unit teletactor and eventually abandoned his work entirely in 1934.

One can attribute Gault's ultimate failure to one psychological and two physiological reasons. Gault neglected to take into account some tactile phenomena of the fingers. Research by V. O. Knudsen about this time revealed that the fingers respond most readily to frequencies in the 200cps-300cps range and are not sensitive to any frequencies above 1600cps.[5] Thus Gault's teletactor effectively cut out all frequencies much above 1600cps and tended to stress the lower frequencies relative to the higher ones.

Also, Gault neglected the attitude of his deaf subjects. Although the subjects improved their lip reading ability by using a teletactor, they were more interested in augmenting their speaking vocabulary. The deaf have no desire to be passive members of society. They were apathetic to Gault's efforts to teach them lip reading.* Gault quit in 1934, a discouraged man. However, his efforts merit recognition. Gault's major contribution is that he was the first to develop an alternate means of communication for the deaf.

Gault's failure discouraged his fellow workers. For seven years research to assist the deaf remained dormant Then in 1941 spurred on by military needs, the Bell Laboratories launched an extensive spectrograph development project to find the means for a visual translation of sound. Out of this research came the sound spectrograph and the cathode ray direct viewer.[6] Both of these were used for a thorough study of visual speech. In the sound spectrograph the speech of about 2.4 seconds duration is recorded on a magnetic tape.[7] The tape is played back, and it is synchronized with an adjustable filter and a recording paper on a rotating drum. The magnetic tape is played over and over until the speech energy from the lowest to the highest frequency (3500cps) is recorded on the paper. The cathode ray direct viewer

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*This information was obtained in a conversation with R. K. Potter, Director of Transmission Research of the Bell Laboratories. Dr. Potter is acquainted with Dr. Gault and his work.

breaks up the speech into twelve channels.[8] A beam sweeps vertically on a phosphorescent screen, scanning the output of the twelve filters in succession. The sound spectrograph gives a permanent but short record of visual speech. The cathode ray direct viewer presents a continuous presentation of visual speech.

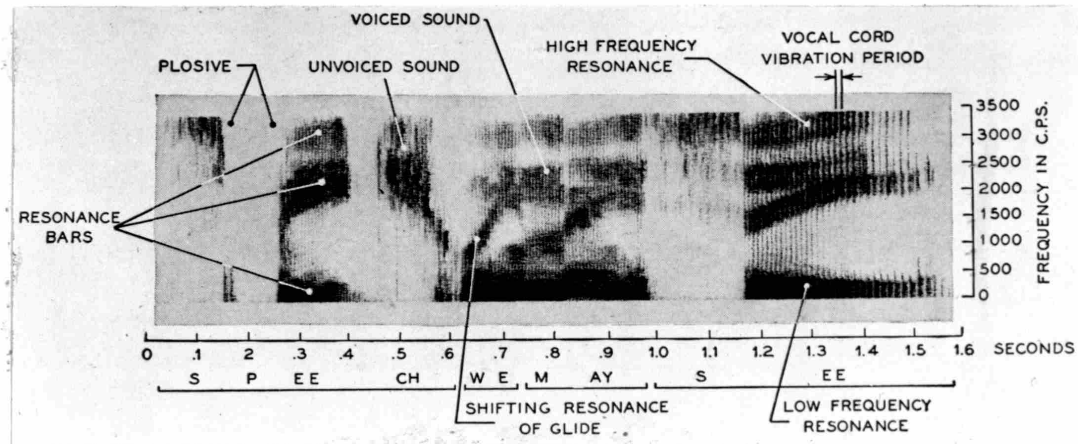


FIGURE I

A Typical Visual Speech Pattern.

The development of the sound spectrograph and the cathode ray enabled scientists to conduct the first dynamic study of speech. Earlier in 1922 Crandall and McKenzie had made a more limited study of the frequency distribution of speech. The two investigators used as a recording device a ballistic galvanometer whose output was proportioned to the square of the current flowing through it. Speaking very slowly, Crandall and McKenzie found that most of the speech energy was found under 500cps.[9] To get what they consider a better visual speech picture, the Bell engineers have had to boost the output in the higher frequencies.

Once the dynamic characteristics of speech could be recorded some obvious last important discoveries about speech ensued. As will be pointed out later these discoveries served as the basis of design of the FEELIES filter unit (See page 11). In Figure I is shown a typical visual speech pattern. In this case the words "speech we may see" are demonstrated. The dark portions indicate where speech energy is present and the light portions show the frequencies where energy is absent.

The primary discovery of the Bell speech study is well shown in Figure I. It is that speech energy occurs in discrete frequency bands. These frequency bands, which are a few hundred cycles in band width, tend to have the total energy in a given band vary at a slow rate, probably less than 20cps. The frequency bands of speech energy are called bars and are numbered consecutively in order of appearance from the lowest to the highest frequency. For example, the "ee" sound of "see" contains four bars. The Bell experimenters found that the second bar, which occurs in the range between 400cps and 2000cps is the one which gives each phonetic sound its unique traits. The subjects that were used in the experiments were trained with emphasis of study on bar #2. After 126 hours of training, the average subject was able to learn more than 1000 words. This is certainly a sufficient vocabulary to provide for normal speech intercourse.

Were it not for two noticeable shortcomings visual speech might provide the means by which the deaf could supplant hearing deficiencies. First, the application of visual speech requires the entire attention of the subject at all times. Furthermore, since the eye must scan the visual pattern and integrate the information, it is possible to have some of the information missed. Thus the subject is prevented from performing any tasks while engaging in visual conversation. The second limitation is that the equipment is bulky and very expensive. This consideration is sufficient to relegate visual speech to institutional work.

Early in 1948 after studying the work of the Bell Laboratories on visual speech, Jerome B. Wiesner, the Associate Director of the Research Laboratory of Electronics, decided that it would be possible to use the peripheral nervous system to perform crudely the function of hearing. The visual speech diagrams appeared to show that the ear mechanism might be more complex than required for speech. At this time Dr. Norbert Wiener was working out a theory of Cybernetics and became interested in Professor Wiesner's conjectures on hearing. After a series of conversations with Dr. Wiener, Professor Wiesner decided that the finger tips of the hand were the best regions to exploit as a substitute ear. Because of their easy accessibility and because they are most used for the transmission of tactile information, the fingers appear to be the logical choice.

The Bell Laboratories have demonstrated that visual speech information can be transmitted when twelve filter bands are used. However, only a portion of the entire 3500cps band width is ever used at any one time. On this basis, Professor Wiesner believed that a five unit system would be adequate. Incidentally, at this time he was unfamiliar with the prior work of Robert Gault. The five filter band widths were selected after a careful study, one finger for the first and third bars and three fingers for the second bar. The first FEELIES unit was built in late 1948 by Edward David, a graduate student at the Massachusetts Institute of Technology. All subsequent work was carried on by the author of this thesis and is described herein.

CHAPTER II

FEELIES Apparatus

The principal units of FEELIES apparatus are an audio amplifier, filters, modulator, and vibrating diaphrams. A block diagram of the relation of these units to one another is shown in Figure 2. The speech is introduced into the system via a crystal microphone. This was one of two

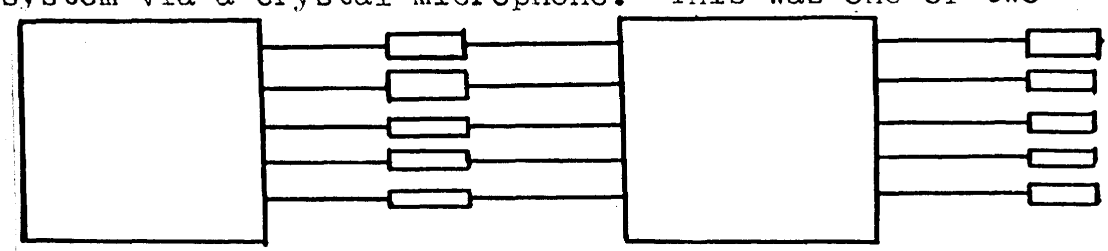


FIGURE 2
A Block Diagram of FEELIES Apparatus.

alternatives given the experimenter in feeding in information. The other choice was a tape recorder. The tape recorder has the advantage of keeping the input constant as messages are repeated. A speaker, employing a microphone input, will vary continually both in the duration of phonetic sounds and the specific sound frequencies emitted. The use of the tape recorder would eliminate the speaker as a variable in the evaluation of the data. However, the tape recorder has one disadvantage and it is a major one. This disadvantage is that the tape recorder offers an inflexible manner of presentation of data. Because there is no feedback from the subject to the tape recorder, it is impossible with a tape recorder to coordinate the input with the rate of learning of the subject

The use of a speaker offers a means of rapid adjustment to the ability of the subject. Furthermore, since the FEELIES apparatus is being designed for general use by all voices, the variability of the voice from day to day cannot reasonably be considered a deterrent factor in the measurement of the ability of the apparatus to transmit information.

From the microphone the speech goes into a Thordarson audio amplifier, Model T-31W10AX. This amplifier passes frequencies up to about 15000cps. After suitable amplification the speech is broken up at the output of the audio amplifier into five bands by sharp cutoff filters. These filters were specifically designed for this project by the Universal Transformer Corporation. These filters are properly matched when terminated in 500 ohms. The filters have the following bandwidths: 0-400cps, 400-700cps, 700-1400cps, 1400-2400cps, and 2400-15000cps. The selection of these filter bandwidths was somewhat arbitrary. As was pointed out in the Introduction the bandwidths were chosen with special emphasis on bar 2. An investigation was made of possible visual speech patterns using the five filters above. This survey revealed that, except for a few vowel similarities, the filter bandwidths produce differentiated patterns for each of the phonetic sounds.

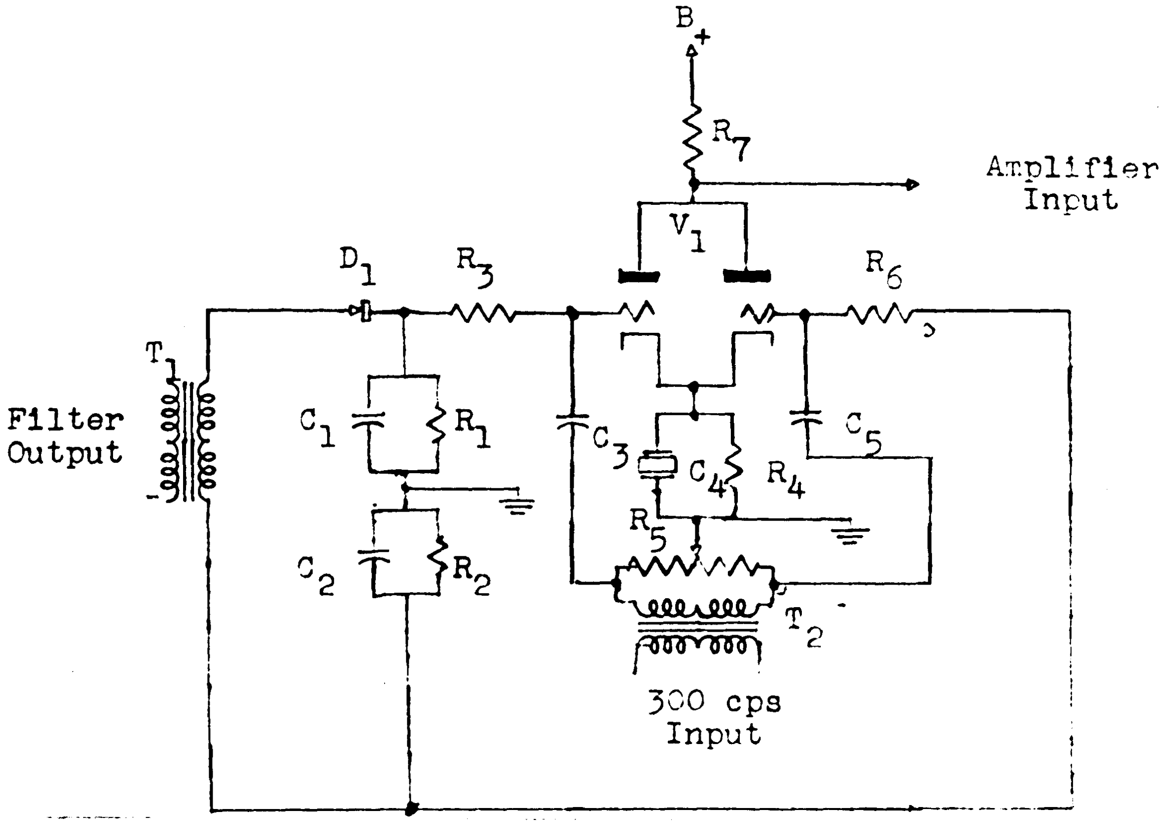


Figure 3. Circuit Diagram of the Modulator

PARTS LIST FOR MODULATOR

Resistors
R1 - 0.1 megohm, 1/2 watt
R2 - 0.1 megohm, 1/2 watt
R3 - 0.2 megohm, 1/2 watt
R4 - 510 ohms, 1 watt
R5 - 5000 ohms potentiometer
R6 - 0.2 megohm, 1/2 watt
R7 - 10,000 ohms, 2 watts

Transformers
T1 - Thordarson T61A93
T2 - Thordarson T61A93

Capacitors
C1 - 0.5 farad
C2 - 0.5 farad
C3 - 400 farad
C4 - 20 farad, 20 volts
C5 - 400 farad

Vacuum Tube
V1 - 6SN7

Diode Rectifier
D1-1N34

The resultant voltage output of each filter feeds into a modulator (see Figure 4), the key unit of FEELIES. It is the modulator which sharply differentiates the present apparatus from that used by Gault some twenty-five years ago. To escape the pitfalls of Gault, the modulator was designed utilizing two important vibratactile physiological considerations. First, the fingers respond most readily to a frequency around 300cps. Secondly, the fingers can measure changes in amplitude that occur at a very low rate. Also, the modulator was built with the realization that the fingers do not feel vibrations over 1600cps.

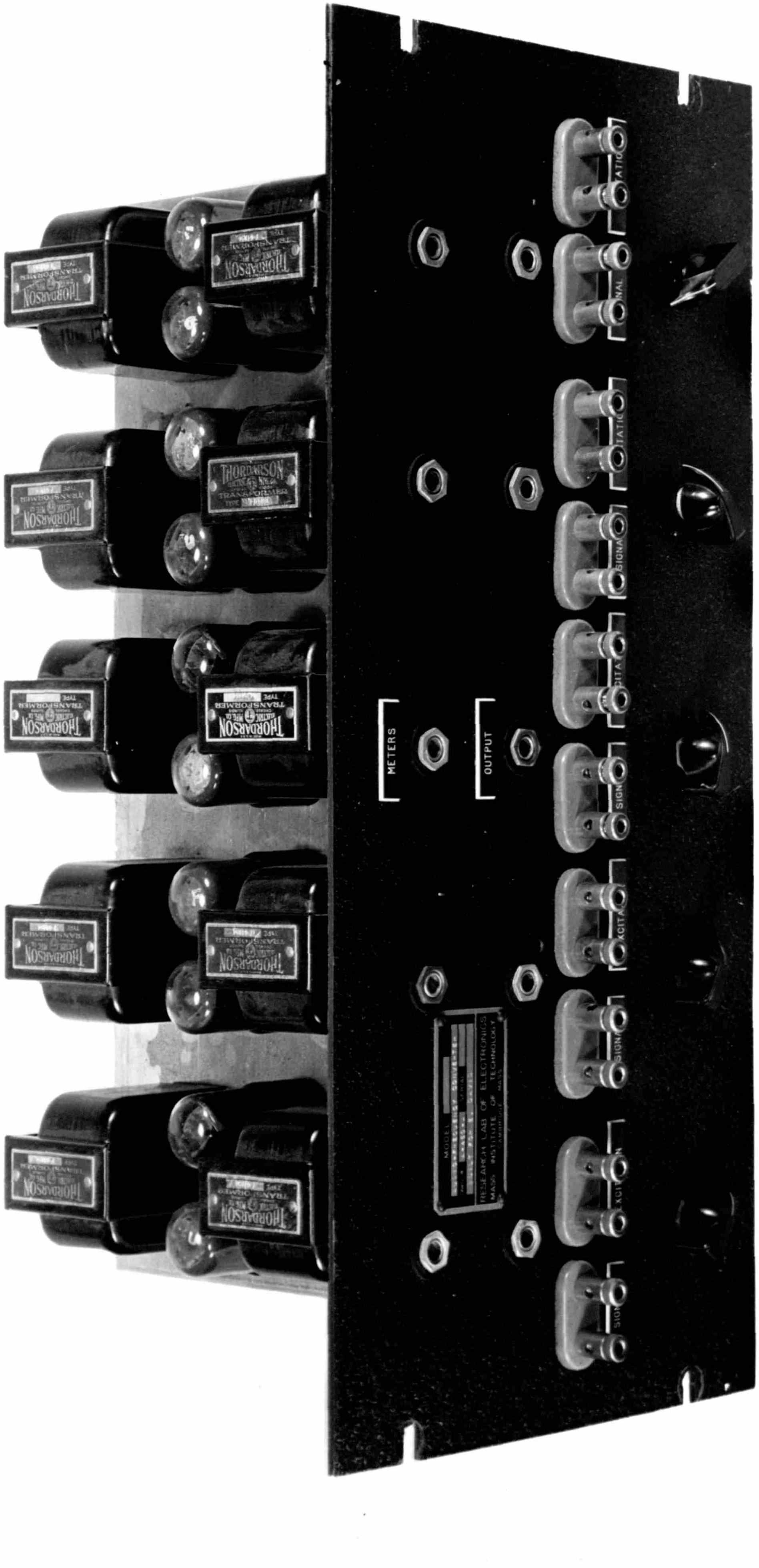
A detailed circuit diagram of the modulator is shown in Figure 3. A constant 300cps sinusoid of 0.8 volts RMS is put into the modulator through transformer T2. The voltage is divided between the grids of the two triodes by means of potentiometer R5. The voltages on the two grids appear 180° out of phase with one another. When the voltage on one grid tends to increase the current flowing through resistor R7, the voltage on the other grid tends to reduce the current. By a proper adjustment of R5 the 300cps voltage can be distributed between the two grids so that there is no 300cps output across R7. This zero output condition prevails and the modulator remains in a balanced condition until there is some speech input at transformer T1.

When there is some filter output applied to T1, it is rectified by D1. From here the speech wave goes into an R-C circuit having a time constant of 0.05 seconds. All of higher

FIGURE 4

THE MODULATOR UNIT, TWO VIEWS

The potentiometers shown are used for balancing the modulator.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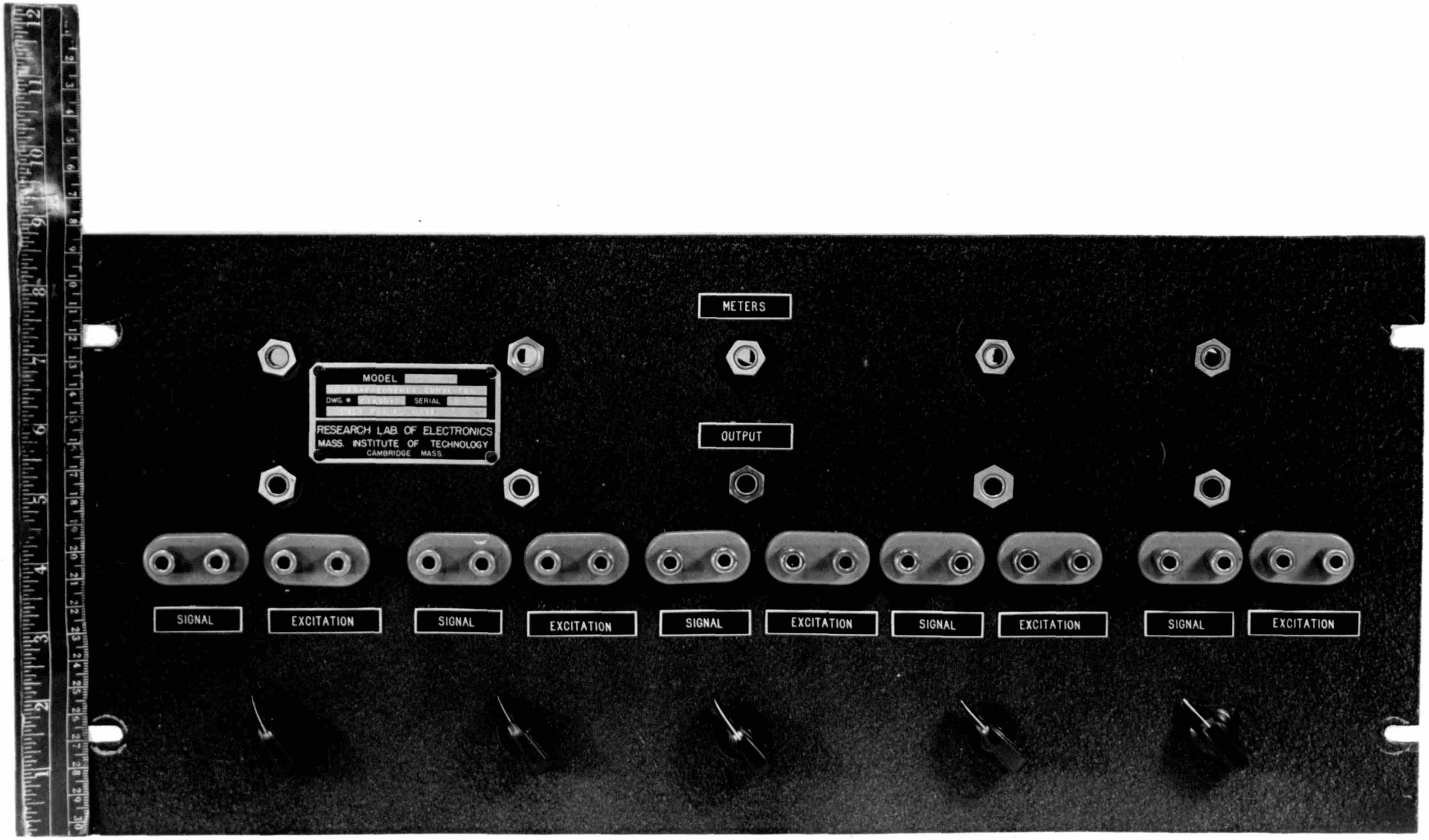
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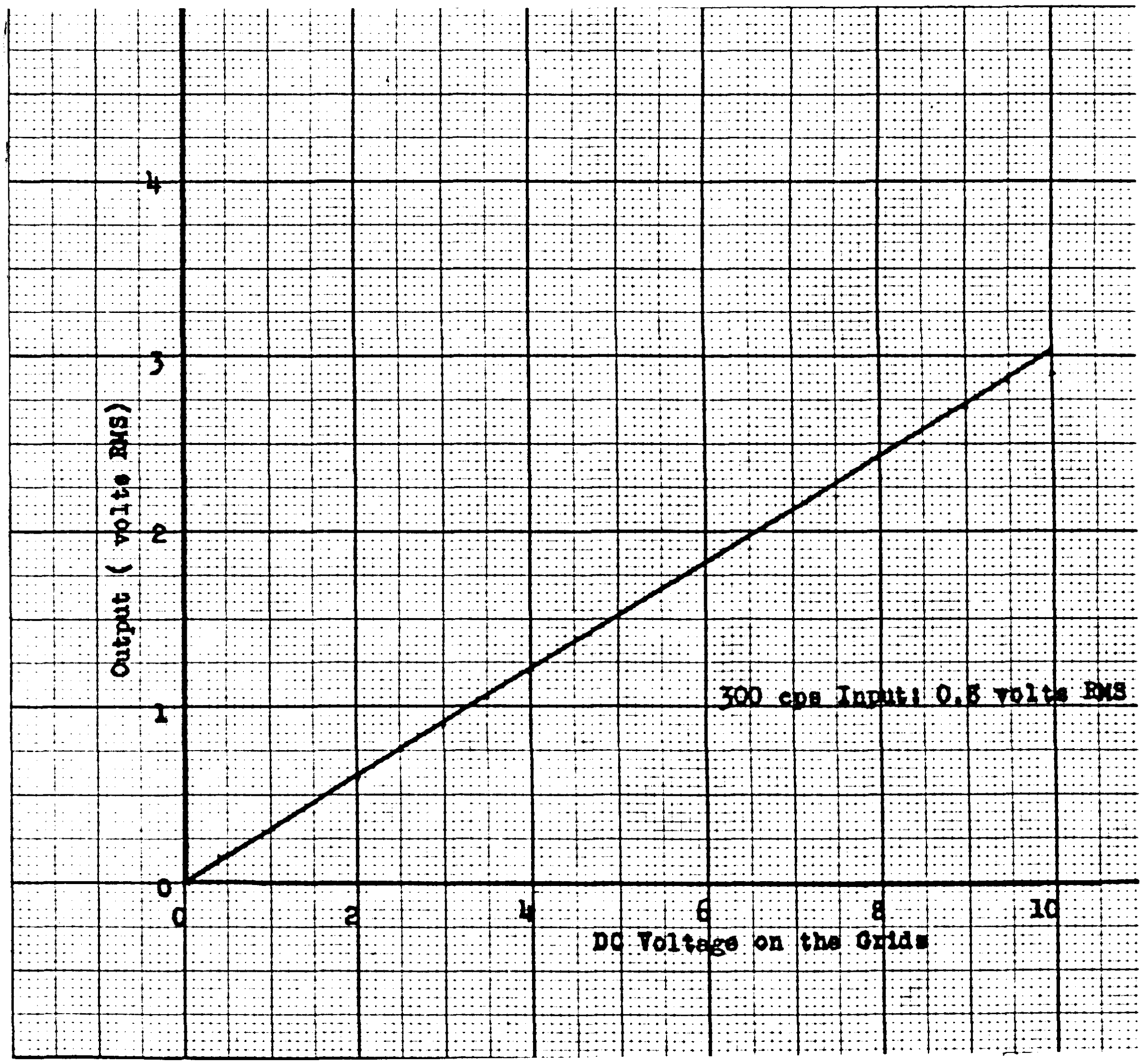


FIGURE 5
Modulator Response

The output of the modulator goes through a stage of amplification and from the amplifier to a vibrator. The five vibrators used come from the minature earphone of an HS-30 headset. The vibrators have a 500 ohm impedance and have a power rating of 0.02 watts. This output proved inadequately frequency components are filtered out by the R-C circuit, and only the envelop remains. The envelop since varies at a rate less than 20cps, something easily detected by R1 and R2 are equal, voltages appear on the grids that the vibrotactile sense in the finger are equal and 180° out of phase. These voltages on the grids change the amplification factors of the triodes. The 300cps note is now amplified a different amount by each tube. The modulator becomes unbalanced and produces a 300cps output.

The relation between the modulator output and the d.c. voltage on the grids is shown in Figure 5. The d.c. voltage indicated in this graph is the voltage super-imposed on the bias of the tube -- which was -9 volts. For example, a d.c. voltage on the graph of 1 volt means that one tube is biased at -8 volts while the other is biased at -10 volts. The graph indicates that the output is a linear function of the d.c. input.

FIGURE 6

THE VIBRATOR BOX

The position of the vibrators is easily adjustable for any size hand and may be used with either the right or left hand.

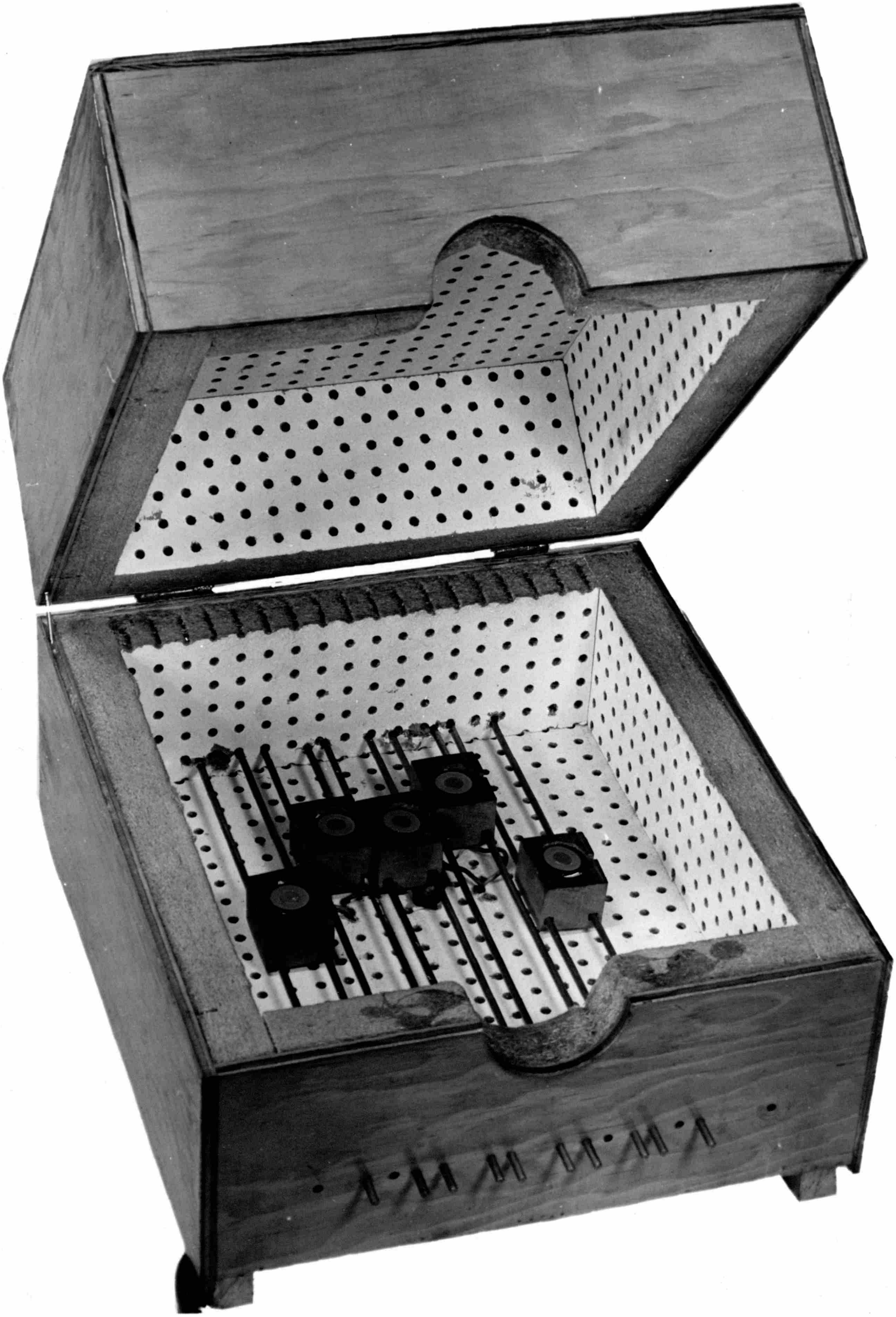


FIGURE 7

A TYPICAL SUBJECT RECEIVING INFORMATION

The earphones produce noise to mask the sounds in the vibrator box.

small for finger sensitivity, and the vibrators were usually overdriven at about .09 watts.

The five vibrators were placed in a plywood box lined with one inch celotex (See Figure 6). The box is hinged and designed to fit tightly around the wrists of the various subjects (See Figure 7). The box was so designed to eliminate as much of the sound of the vibrators as possible. As will be shown in the discussion on Procedure, these precautions were insufficient and other techniques were resorted to. Each vibrator was placed upon a movable block which permitted adjustment of the vibrators to fit the right or left hand of any subject. The cover of the vibrator was removed, exposing the metallic diaphram. The fingers resting lightly on the vibrators, received the information. From the fingers the nervous system transmitted the varying 300cps note to the brain for ultimate evaluation.

CHAPTER III

Procedure for Teaching with FEELIES

Once the apparatus was in working order a decision had to be made on whether to use deaf or normal people as subjects. Although the ultimate user of the equipment will be the deaf person and everything in the design will be tailored to his requirements, he was rejected as a possible subject. Instead, the normal person was selected because he made communication easier and more rapid with his FEELIES teacher. When FEELIES first started, there was no previous work on which to draw for use as a guide in the operation of the apparatus. Virtually everything had to be learned from discussions with the subjects about their particular reactions to the equipment. It was important that the subject be in a position to verbalize his experiences lucidly, and that he be able to thoroughly describe his reactions to the stimuli he received on his fingers.

Furthermore, the deaf man has a psychological factor to work to his disadvantage. A deaf person has too much at stake in trying to learn to use the FEELIES apparatus properly. Mastery of FEELIES could mean a more normal existence for him. With such emotional involvement he might become very disturbed by his failure to learn and by the possible shortcomings of the FEELIES unit. Such an attitude would only serve to retard his rate of learning.

However, insofar as experimenting with mechanical vibrators is concerned, the normal person has one handicap. He can hear. The normal person's ability to hear proved to be a major stumbling block in the teaching of the subjects. When mechanical vibrators are used, the subject can hear as well as feel the impulses. In the initial experiments on FEELIES it was found that the sounds received by the unimpaired aural sense matched the impulses received on the fingers. The subject, despite intense concentration, learned the patterns through his ears instead of his fingers. The ear can distinguish the patterns more clearly and more rapidly than the fingers. Because of this fact, it quickly took over the role of perception from the fingers.

Strenuous efforts were made to isolate the sounds of the vibrators from the subject. The vibrator box was lined with celotex (See Figure 6). Ear plugs and cotton were inserted into the ears of the subject. By these efforts the sound intensity was reduced by about 20 or 30 decibels, but it was not eliminated. The only solution which seemed feasible was to make the subject functionally deaf, i.e., unable to hear during the course of the experiment.

A method for doing this was suggested by Dr. J. C. R. Lichlider of the Harvard Psycho-Acoustic Laboratories. Random noise supplied by two Ballantine voltmeters in cascade is put into the ears via earphones. When the noise level is above the sound intensity of the vibrators, the subject can hear nothing but the noise. Moreover, within ten seconds after the time the noise is first applied, the subject becomes oblivious to it and remains in the condition during the entire course of the experiment. Because his arm is kept in an immobile position, the subject becomes tired after about ten minutes of training. At this time the subject again becomes conscious of the noise in his ear, and the experiment is terminated.

It is possible that the noise may have an adverse effect on a person's ability to learn. Some neural circuits in the brain which might otherwise be used for learning may be excited by the noise. No investigation has been made on the degree of impairment of learning by aural noise. Dr. Lichlider conducted experiments in which aural marking was used and found the effect on learning was negligible. The assumption was made that this would also be the case in FEELIES. Even if the noise should prove to have restricted the learning of the subject, it would serve to present data which would give a conservative evaluation of FEELIES. Incidentally, there is a touch of ironic humor in this problem. All of the effort and concern which went into making a person functionally deaf contributes nothing to improving FEELIES for its ultimate user -- the deaf man.

With the apparatus in working order and the subject rendered functionally deaf a satisfactory teaching procedure had to be evolved. A rapid method for the teaching of the basic English vocabulary was desired. Unfortunately, data on this subject is pitifully inadequate. At the present time, there are at least two schools of thought almost diametrically opposed to one another. One school advocates the teaching of words only in context in sentences. The second method, which is strongly advocated by Professor I. A. Richards of Harvard, has given good results when used in the teaching of English to children and foreigners.[10] Since there was not enough time to use the two teaching methods simultaneously, the word technique was employed almost exclusively. It offered a faster means of teaching and an easier means of calculation of the data.

It is not within the scope of this thesis to examine theories on the learning of language. However, this apparatus does provide an interested philologist with an opportunity to explore language theories with a high degree of control over his subjects. Although FEELIES was built to convey speech information through the fingers, it can as a device be used in research in other fields of interest. The learning of language is one of these fields. There are others which will be mentioned in other sections of this paper.

From a group of ten volunteers, four subjects were chosen. These subjects provided the essential data collected on the mechanical vibrators. The four subjects were Robert Kingston, Walter Koltun, Joseph Yamron and Joseph Gottlieb. All of the subjects were students of the Massachusetts Institute of Technology. Robert Kingston and Walter Koltun were graduate students in the fields of physics and biology, respectively. Joseph Yamron and Joseph Gottlieb were upperclassmen in the general science course. The subjects, who were all personally interested in the success of the project, always exhibited a desire to learn to use FEELIES better. The attitude of the subject is an important factor. On several occasions it was demonstrated that a spiritless subject was able to receive a very small amount of information via FEELIES.

Just prior to his first lesson, each of the four subjects was given a brief indoctrination talk on FEELIES. This talk outlined briefly the technical considerations in the design of the equipment, the desired objectives of the project, and the expected pitfalls in learning. Every effort was made to have each subject feel he was an important cog in the project. The advice of the subjects was freely solicited, and on occasion the subjects responded with some very helpful suggestions.

The vocabulary list from which words used for the teaching of the subjects were selected consists of twenty words. The vocabulary list came from a group of words that were used to make up six simple sentences. These sentences are:

1. Pick up the glass.
2. Open wide your mouth.
3. Touch the right ear.
4. Lift your arm high.
5. Comb back the hair.
6. Point straight at me.

The word list was derived in this manner so that the subject could ultimately be tested on his ability to receive sentence ideas instead of words. The vocabulary list was chosen arbitrarily, but these twenty words contain thirty-five of the recognized forty-five phonetic sounds. The words were printed on a piece of drawing paper, which was mounted on a cardboard and placed within easy reaching distance of the subject.

When the teaching session began, the speaker and the subject were seated some fifteen feet apart. (See Figure 7 for a typical seating pose of the subject). The subject was allowed about thirty seconds to become accustomed to the noise in his ear. During the first lesson three or four words were given to the subject. A word was introduced by the speaker who pointed to it as he spoke into the microphone. The word was repeated several times. Precautions were taken by the speaker to make certain that his mouth was not visible to the subject. This care was especially warranted because one of the subjects, Joseph Gottlieb, is an accomplished lip reader.

When the subject indicated orally that he recognized the tactile pattern, the speaker presented another word in the same manner. After the subject had been given the three or four words, the speaker prepared to take data. In subsequent lessons much the same procedure outlined above was followed. The subject was given a brief review of the old words. He was given a new word if the record justified it. On the average a subject received a new word every two lessons.

For data taking the speaker spoke into the microphone without pointing to the word on the chart. The word he chose was randomly selected based upon a random set of numbers.[11] This was done to make each word equally probable, something which simplified the calculation of the data. The word was given at least twice (except when Kingston was a subject -- he almost invariably responded the first time). The subject answered orally. If the subject was correct, he was given recognition by a nod or some other gesture, and the speaker presented another word. If the subject was wrong, the speaker pointed to the correct word. Then the speaker repeated the correct and incorrect word a few times until the subject believed that he knew the difference between the two words. The data taking continued until the subject became tired.

During his entire period of learning the subject was encouraged to take any notes that he considered would help him in remembering the word and in distinguishing it from other words. All of the subjects except Kingston took copious notes. These notes varied from pictorial representations to written descriptions of the phenomena. As the subject learned his words more thoroughly, his descriptions became more detailed. A chronological study of these notes served as a helpful guide in determining the learning pattern of the subject.

From his initial feeling of eagerness to learn, the subject almost instantly derived a feeling of frustration. His first tries to learn on FEELIES made him feel that his task of learning would be a difficult and, perhaps, impossible one. After a few of the earliest experiments, it became obvious that certain types of word pattern structures were more easily differentiable.

During the earlies stages of learning, the subject has to find out many things like the proper way to rest his fingers on the vibrators that do not relate directly to learning. Provided the words offer no problem, the subject can develop his skill with FEELIES at his leisure. It was found that the teaching was greatly accelerated if the subject began with words that could be almost immediately differentiated from one another. These words are straight, high, and pick. Thereafter, as the subject became more perceptive in his use of the equipment, words more similiar to one another were introduced. These words in the order of their appearance are open, glass, the hand, lift, up, high, mouth and point.

CHAPTER IV

INTERPRETATION OF THE DATA

The capacity of FEELIES to aid the deaf is measured by its ability to transmit information. Until recently information was an ambiguous, ill-defined term to communication engineers. However, as a result of pioneering work by Shannon, Wiener, and others a rigorous proof exists which shows that information may be expressed in the form of a mathematical equation. This now permits one to compare systems of transmission of information, even when the systems employ entirely different means of transmission.

According to Shannon,[12] the total amount of information available in a message of one unit length and of order word selection is

$$H_N = -\sum p(k) \log_2 p(k) \qquad (1)$$

the probabilty of occurence of a given word. This equation represents the minimum number of linary selections which have to be made to uniquely identify a message. It should be noted that H also is the mathematical statement of entropy. On occasion it is referred to as the entropy of information. As was pointed out previously in this thesis the words presented to the subjects were selected at random. This rendered the selection of each word used equally probable and independent. Under this condition, the information equation reduces to the following simplified form:

$$H_N = \log_2 \frac{1}{p(k)} \qquad (2)$$

Apart from the fact that it simplified the information equation there is another reason for having each selection equally probable. This is the condition for the maximum amount of information that is available in a message of N order selection.[13]

Where the selections are not independent, a different equation for information results. This equation may be used to calculate the amount of information which is still available in a message which the subject has received on FEELIES. Or to express it in another way the equation represents the amount of information which is lost to the subject in the transmission of the message.

$$H_L = -\sum p(y)\, p(y,x) \log_2 p(y,x) \qquad (3)$$

where $p(y)$ = the probability of receiving a given word out of possible word selections

$p(y,x)$ = the probabilty that when a given selection (y) was received by the subject, the selection (x) was sent by the speaker.

Note that when $p(y,x) = 1$ for any word this part of the summation reduces to zero. When $p(y,x) = 1$ for all words, the $H_L = 0$ and there is no information lost in transit. This is the prerequisite for the maximum amount of information received by the subject for a given amount of information sent. This is obvious since it means that when $H_L = 0$, the subject has been able to identify correctly every word that he has received. The total amount of information received is represented by the difference between the information sent and the information lost.

$$H_R = -\sum p(k) \log_2 p(k) + \quad p(y)\, p(y,x) \log_2 p(y,x) \qquad (4)$$

Or when the words sent are equally probable

$$H_R = \log_2 \frac{1}{p(K)} + \sum p(y)\, p(y,x) \log_2 p(y,x) \qquad (5)$$

To illustrate more clearly how the probabilities involved in information arise, a sample table of data collected is shown in Table 1.

		Word Received			
		straight	high	your	
Word Sent	straight	8		1	
	high	2	6		
	your	1	3	5	
	Totals	11	9	6	= 26

Table 1, Sample Data

Using the word "straight" as a specific example, the probabilities are as follows"

p(h) straight = 1/3

p(y) straight = 11/26

p(y,x) = p(straight, straight) = 8/11

p(y,x) = p(straight, high) = 2/11

p(y,x) = p(straight, your) = 1/11

Equation (5) defines the absolute amount of information received. Because the subject increases his vocabulary periodically, the total amount of information available increases with each new word as shown by Equation (1). As a general rule H_R in equation (5) will also increase. To measure a subject's progress in learning, calculations were made on the basis of the amount of the total information received divided by the amount that was available. The normalized information shown in equation (6) permitted a continuous comparison of the subject's work on FEELIES.

$$H = \frac{-\log_2 p(k) + \sum p(y)\, p(y,x) \log_2 p(y,x)}{-\log_2 p(k)} \qquad (6)$$

The analysis of the data collected is shown in the graphs (Figure 8 to Figure 11 inclusive), which measure the Normalized Information Received per Lesson of Learning for each of the four subjects. The numbers on each curve indicate the number of words that were used in the lesson following.

The learning curves of the four subjects show a remarkable degree of similarity to one another. All of the subjects began the first lesson at a very low level of information reception, varying from 0.33 for Joseph Gottlieb to 0.69 for Robert Kingston. This may be explained by the fact that the subject used his first lesson primarily to become familiar with the apparatus. After this initial session the information received rose to a high level, oscillating between 0.80 and 1.00. With but five exceptions the value of normalized information decreased

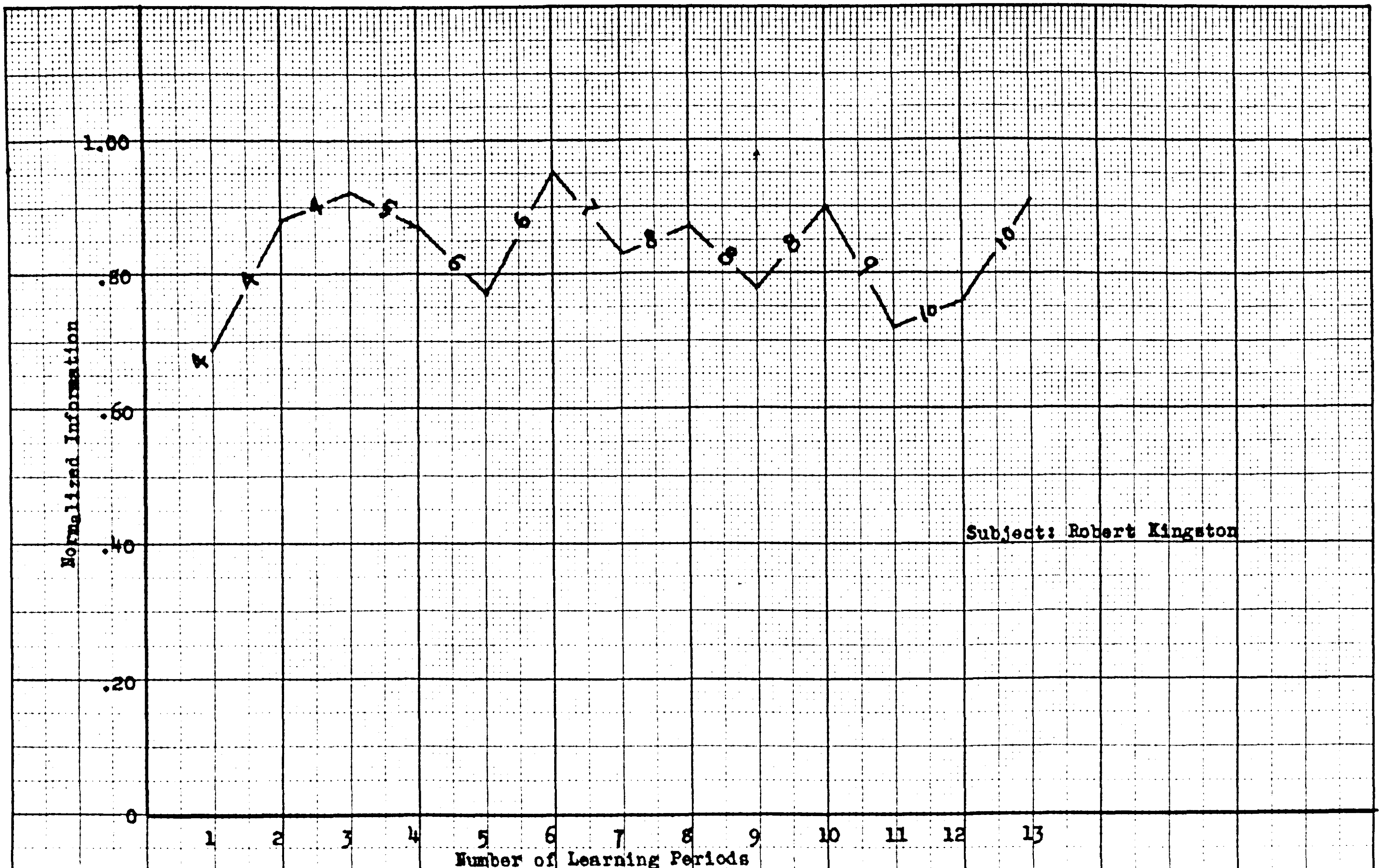


Figure 8, Measurement of the Amount of Information Received versus the Learning Period. The numbers on the graph indicate the amount of words that were used. Mr. Kingston used no notes to assist him in the learning of the words.

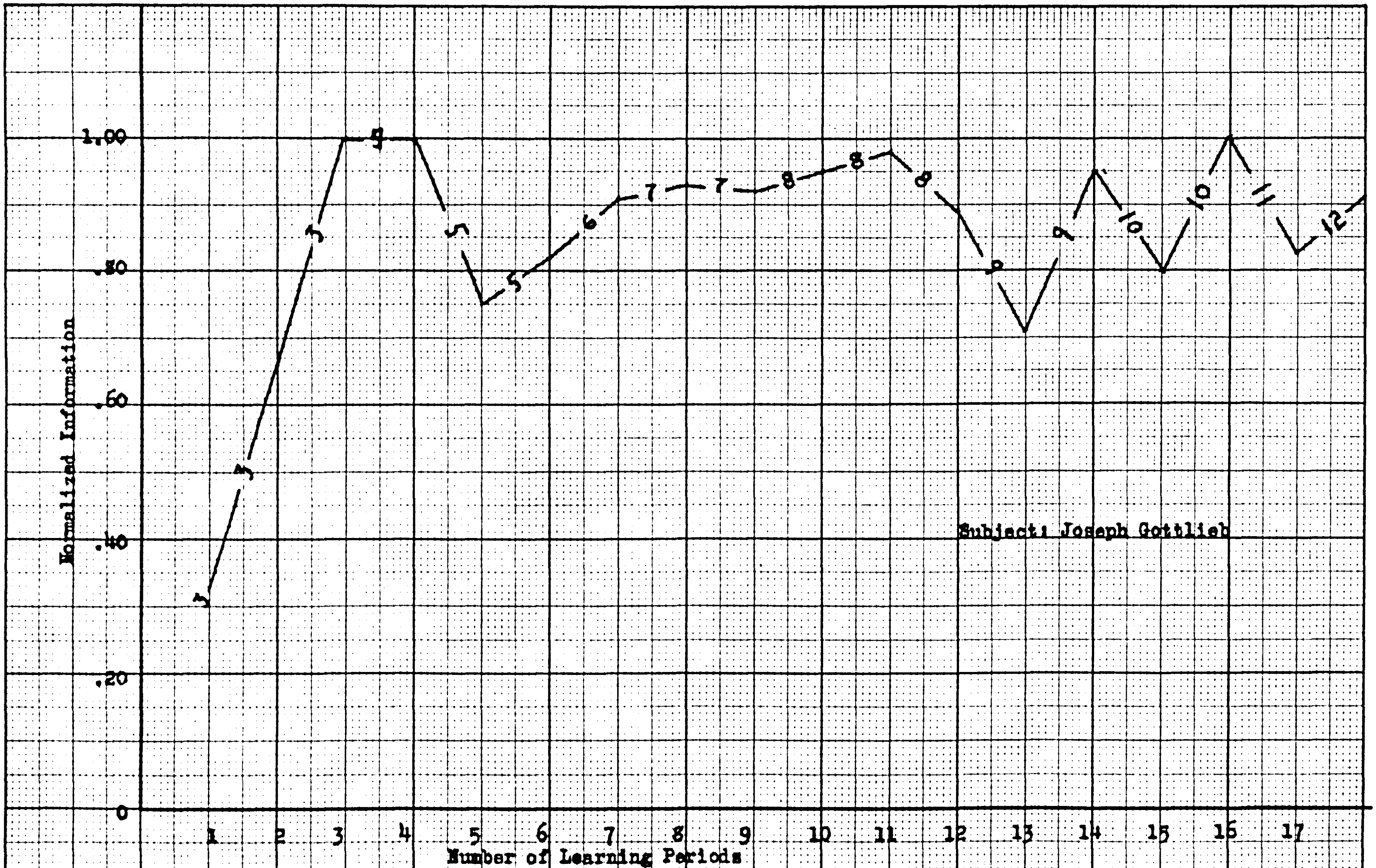


Figure 9. Measurement of the Amount of Information Received versus the Learning Period. The numbers on on the graph indicate the amount of words that were used.

Figure 10, Measurement of the Amount of Information Received versus the Learning Period. The numbers on the graph indicate the amount of words that were used.

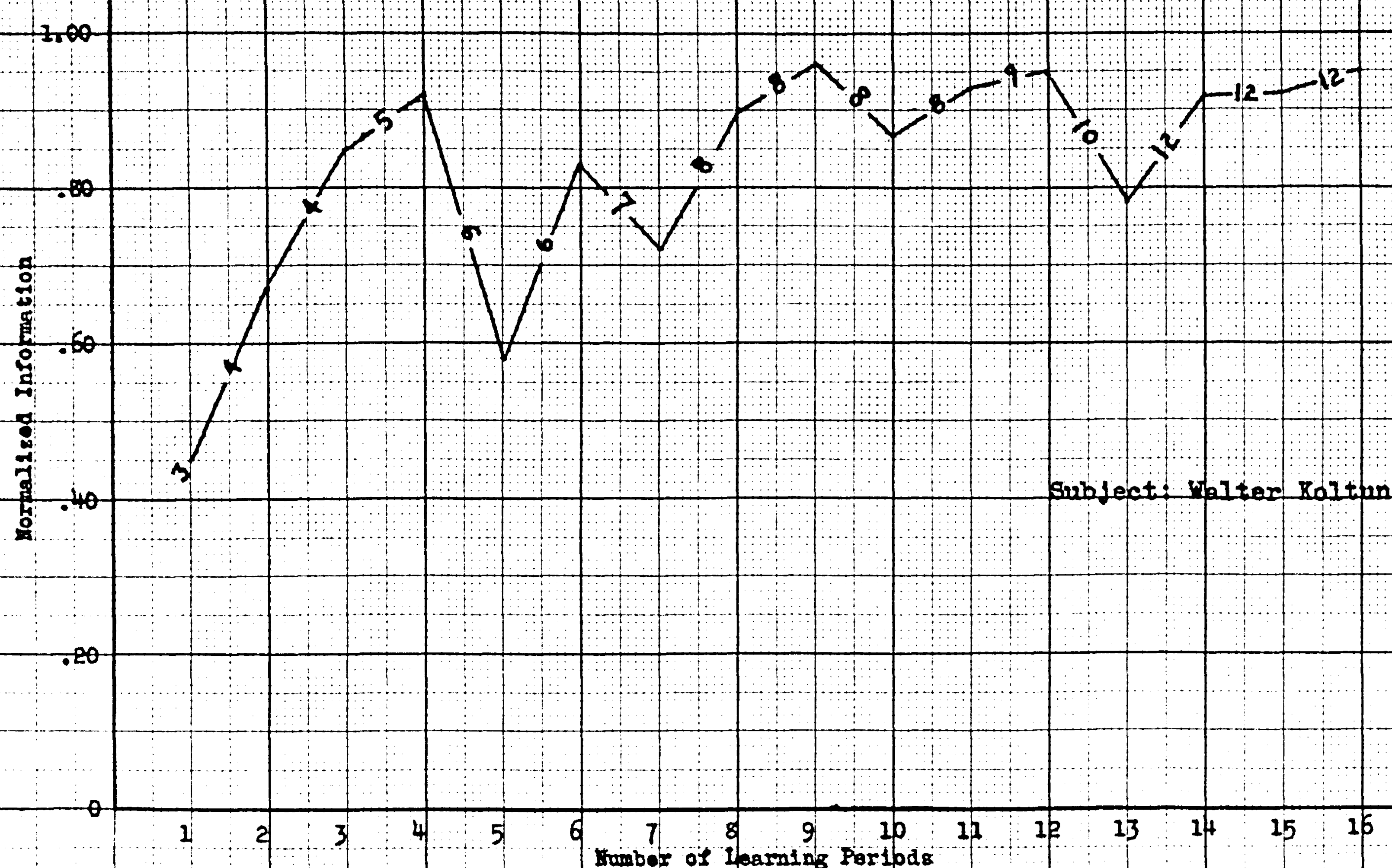


Figure 11. Measurement of the Amount of Information Received versus the Learning Period. The numbers on the graph indicate the amount of words that were used.

every time the subject was given a new word. Each new word compelled the subject to remember a new vibrotactile pattern.

In some cases the introduction of a new word produced further complications. Sometimes the new word was confused with a word the subject already knew. On other occasions the presence of the new word caused confusion between two old words which the subject differentiated adequately prior to the introduction of the new word. Of course, each subject reacted to a word in modifying degrees of recognition. While some words tended to be uniformly more difficult than others, there was no way of predicting in advance that a given word would present difficulty to a subject. This knowledge was obtained empirically, by having the subject himself state the degree of difficulty he encountered from a given word.

Although each new word reduced the normalized information received, it usually took the subject only one lesson to integrate the word into his vocabulary. Two things must be borne in mind about these graphs. First, no lesson was more than ten minutes in duration. Secondly, there was at least a day's interval between lessons. However, the short period of the lesson and the relatively long time between lessons appear to have had little effect on the subject's ability to learn. This suggests that the subject has a high degree of retentivity of tactile patterns received on FEELIES. This point is more dramatically underscored when it is realized that there was a twenty-one day interval between the last two lessons for Walter Koltun and a fifteen day interval between the last two lessons for Robert Kingston. Both subjects received information on the last lesson without showing any lapse of memory because of the long delay.

On only three occasions, all of them by Gottlieb, was a subject able to achieve a perfect normalized information score of 1.00. However, the subjects constantly varied around a 0.90 value.

An average normalized information of 0.90 is represented by forty correct and six incorrect responses by the subject. In ordinary conversation with the repetition that exists in the English language, this degree of correctness is sufficient to convey ideas accurately. After a subject learned the words he was able to understand simple sentences composed of these words.

Twelve words and eighteen lessons comprising about three hours of training is too small a gathering of data to form any lasting conclusions about FEELIES. Nonetheless, the limited conclusions which can be drawn are encouraging. An intelligent subject can learn rapidly and remember a large percentage of what he has learned over a long period of time. Only a very brief interval of time is required by the subject to adapt himself to the equipment. At this primary level of learning

FEELIES does work. An overall study of FEELIES would involve a very long time. At the present time, Professor Jerome B. Wiesner and the author of this thesis believe that the five unit vibrator system is inadequate. Some tests taken reveal that the apparatus in its present form is deficient at least where electrical stimulation is involved.

Certain factors contribute to make the exact interpretation of the data a difficult one. The voice of the speaker and the response of the subject change continually. That the voice of the speaker changes in tone and manner of delivery can not be regarded as too objectionable. This closely approximates conditions under which the apparatus will normally be required to function. The variability of the subject is more serious matter. The physical condition, the mental attitude, the position and the pressure of the fingers on the vibrators all modify the ability of the subject to receive information. The physical condition and the mental attitude of the subject are very difficult to ascertain. Their effect upon the accuracy of the data cannot be gauged except in a general way.

The variability of the subject poses a problem which presents itself early in the experiments. From time to time, the subject encountered difficulty with individual word patterns. Every time the subject had trouble learning a word the experimenter was assailed by the same doubts. Could the subject's failure to learn be attributed to inadequate training or, instead, to shortcomings of the instrument? Fortunately in all cases the subject resolved all of his difficulties with further training. However, the data thus far obtained is too insufficient for passing judgment on the apparatus.

To resolve some of the doubt about the limitations of FEELIES, test equipment was constructed to record its word patterns. The test unit consisted of six neon bulbs and a moving picture camera. Each neon bulb was attached to the output of one stage of the equipment. They were adjusted to light whenever there was any output. The sixth neon bulb was connected to a variac and served as a 60cps marker. The neon light patterns were photographed on Super XX film by a moving picture camera which had no shutter. These pictures are shown in Appendix I.

The pictures of the vibrotactive response are similar in content to those of visual speech. In both cases the energy output for a given bandwidth is recorded in the picture of speech. However, the picture representation of FEELIES is cruder than that of visual speech. FEELIES has five bandwidths of unequal width whereas visual speech has twelve equal bandwidths over a range of 3600cps. In the FEELIES pictures the bottom line is a marker serving as a timing pulse. Each pip represents 1/120 second. The next five lines represent the response of the lowest frequency bandwidth on the bottom line to the response of the highest frequency bandwidth on the top line.

The subject cannot detect the patterns indicated in the pictures. There is a minimum time interval less than which impulses received on two fingers will appear to arrive at the same time. The minimum time intervals are shown in Table 2.

Fingers	Time Interval (in seconds)
Thumb - First Finger	.070
Thumb - Second Finger	.092
Thumb - Third Finger	.091
Thumb - Fourth Finger	.092
First Finger - Second Finger	.076
First Finger - Third Finger	.067
First Finger - Fourth Finger	.077
Second Finger - Third Finger	.081
Second Finger - Fourth Finger	.075
Third Finger - Fourth Finger	.086

TABLE #2, Minimum Time Interval For Impulse Differentiation

Using Table 2 as a guide, it can be shown that the phonemes have too much similarity in pattern, particularly among the vowels. However, this cannot be used to deduce that FEELIES apparatus is incapable of differentiating between the different phonemes. The pictures have one defect. When the mechanical vibrators are used, the fingers can distinguish relative differences in intensity of vibrations received. The photographs show only a yes-no response, i.e., whether or not there is energy present in a given frequency band. Thus these pictures are an inconclusive guide concerning the capacities of mechanical stimulations. But as will be shown in the next chapter they are very important in regard to electrical stimulation.

One thing not clearly understood is the manner in which a primary task is learned. A close scruting of this problem has been evolved. The learning procedure may be subdivided into five stages:

1. Impulse Counting
2. Impulse Duration
3. Temporal Recognition
4. Spatial Recognition
5. Temporo-Spatial Recognition

Impulse Counting - In the earliest work on the apparatus, the subject feels that it will be impossible to learn anything. After he overcomes this initial barrier, the subject seeks to identify words by the number of distinct pulses they have. He also learns to identify the fingers mainly involved in the individual pulses. Thus he differentiates between "high", "open" and "straight" because "high" has one impulse, "open" has two impulses, and "straight" has three.

Impulse Duration - After the subject has fully mastered the first stage of learning, he becomes conscious of the time duration of each pulse. He now learns that some pulses are of a longer time duration than others. "Pick" and "up" are two words that give the subject a great degree of difficulty in his first stage of learning. Now he has no trouble distinguishing between these two words. "Pick" consists of a short vibration followed by a long one, whereas "up" has a long vibration followed by a short one.

Temporal Recognition - After the subject is able to detect the relative lengths of impulses, he becomes pattern conscious. He now is aware not only of the number of impulses and their relative duration but also the general direction of movement of the pulses over the fingers. Now he may say typically that a given word starts on the little finger, moves over to the thumb, and then back to the middle finger where it terminates. When the subject reaches this point (usually after about fifteen minutes of training), he begins taking copious notes in an attempt to verbalize his experiences. This helps the subject remember details he might otherwise forget.

Spatial Recognition - The next step in the subject's learning process comes after a rather long period of training. After a while the subject, almost unaware that he is doing so, can in isolated instances tell not only the strongly stimulated fingers but also the fingers that are activated to a lesser degree. Thus he may describe the hypothetical word mentioned in Temporal Recognition by saying that the word starts on the thumb with the index and middle fingers involved to a lesser degree. This is the farthest stage of learning to which any one of the four subjects progressed.

Spatio-Temporal Recognition - It is believed on the basis of present experience that the ultimate stage of learning will occur when the subject is able to identify all of the fingers involved to a primary and secondary degree throughout the entire course of the word. When the subject reaches this point, he will be able to describe completely the information received by the fingers. Only when a subject has reached this stage of learning will it be possible to give an accurate appraisal of FEELIES.

CHAPTER V

ELECTRICAL STIMULATION

Most of this thesis is devoted to the study of the transmission of speech information via mechanical excitation of the fingers. However, electrical stimulation exists as an alternate means of excitation of the peripheral nervous system. In the long run, this mode of transmission of energy may prove to be even better than the vibrotactile stimulation which has been used almost exclusively to date. The FEELIES apparatus in its present form with mechanical output is large and offers little possibility for substantial reduction in size. Although less expensive than its visual speech counterpart, mechanical FEELIES would cost several hundred dollars if it were marketed with components like those employed in the experimental model. Like visual speech, mechanical FEELIES appears to be relegated to use by the deaf only in institutions.

If FEELIES is to be used by the deaf as portable device like a hearing aid, a stimulation other than mechanical will have to be employed. For many reasons electrical stimulation is a likely choice when considered as a replacement for mechanical stimulation. Less energy is required to activate the sensory receptors in the skin by electrical means. About six milliwatts per stimulator is needed as compared to some 90 milliwatts per stimulator for mechanical vibrators. Moreover, because of their smaller size (a diameter of 6/32 inches versus a diameter of 3/4 inches for the mechanical vibrator) the electrical stimulators present the possibility of putting more than five stimulators on the hand. This might be a very important consideration if the five unit system should ultimately prove to be inadequate. The palm of the hand is readily accessible if more than five stimulators are necessary. Indeed, information may be transmitted via another part of the body, like the forearm. Such a design would grant the deaf person complete use of his hand for other tasks. Even if this technique does not work, the deaf person will be able to wear the vibrators attached to a glove without impairing the usefulness of his hand.

However, electrical stimulation has one strong disadvantage. It has a very restricted range of excitation. It is commonplace knowledge that excessive electrical stimulation is very painful. Under adverse conditions it can be injurious to health and can even be fatal. The threshold of pain, above which the body cannot endure electrical stimulation, is the upper limit of excitation. The threshold of feeling, below which the subject cannot feel anything, is the lower limit of excitation. Between these two limits information can be transmitted. Actually the range of transmission of information is somewhat less, since the ability to receive information must drop off rapidly as either threshold is approached.

The graphs of Figure 13 to Figure 17 inclusive show the thresholds of feeling and pain for each finger. An investigation

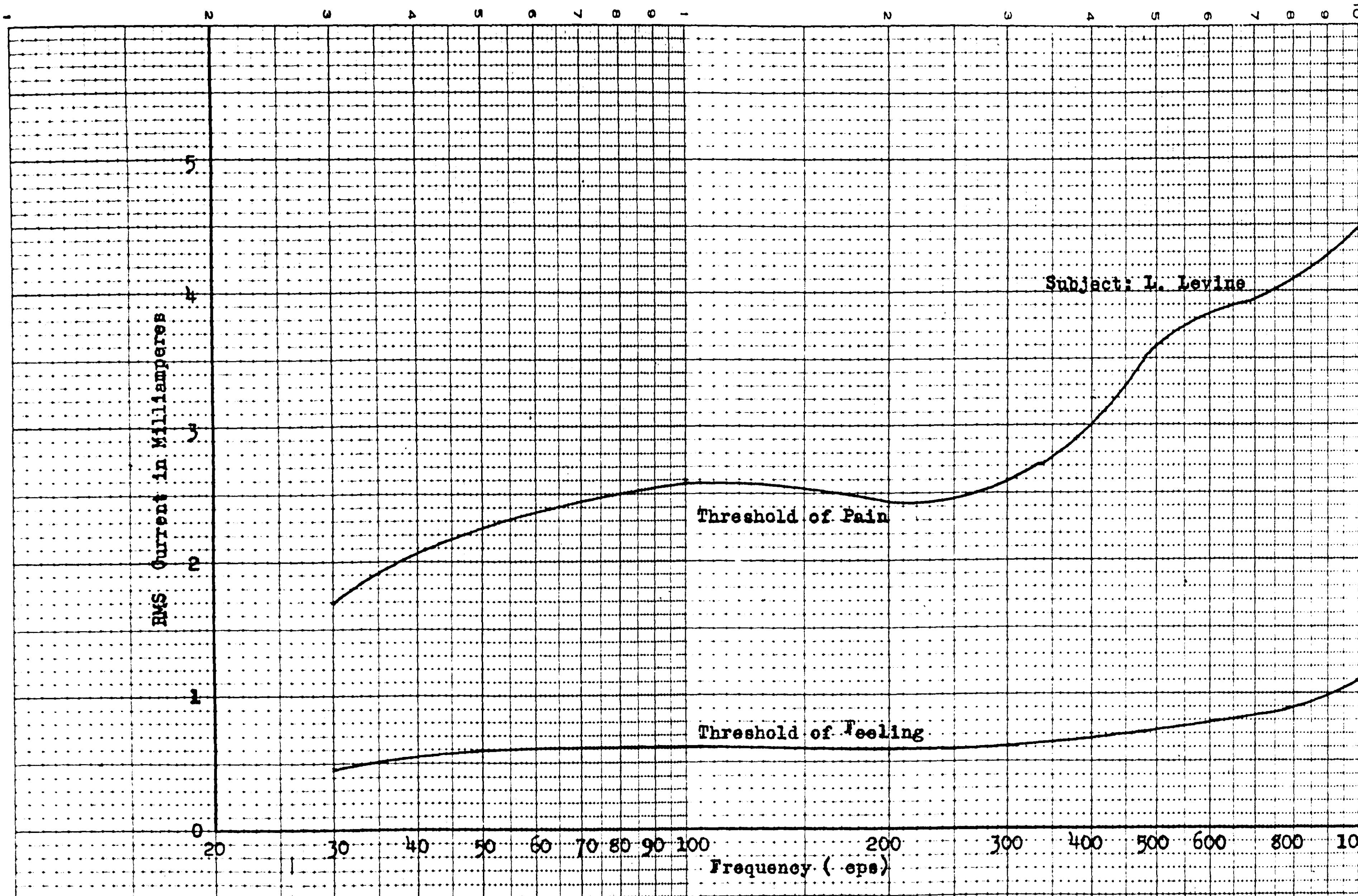


Figure 13. Measurement of the Thresholds of Pain and Feeling for the Thumb of the Left Hand. Sinusoidal Stimulation was used.

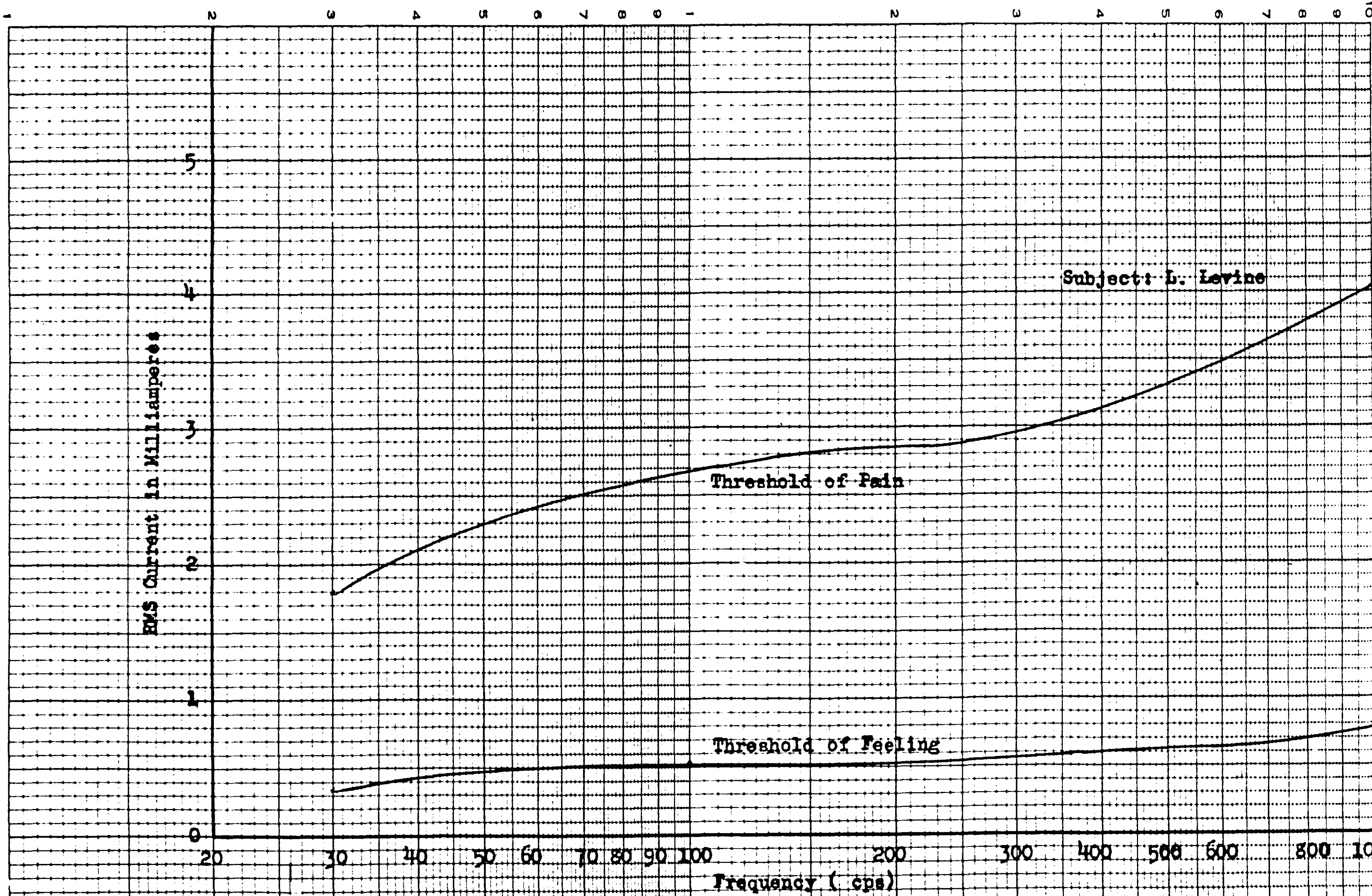


Figure 14, Measurement of the Thresholds of Pain and Feeling for the First Finger of the Left Hand. Sinusoidal stimulation was used.

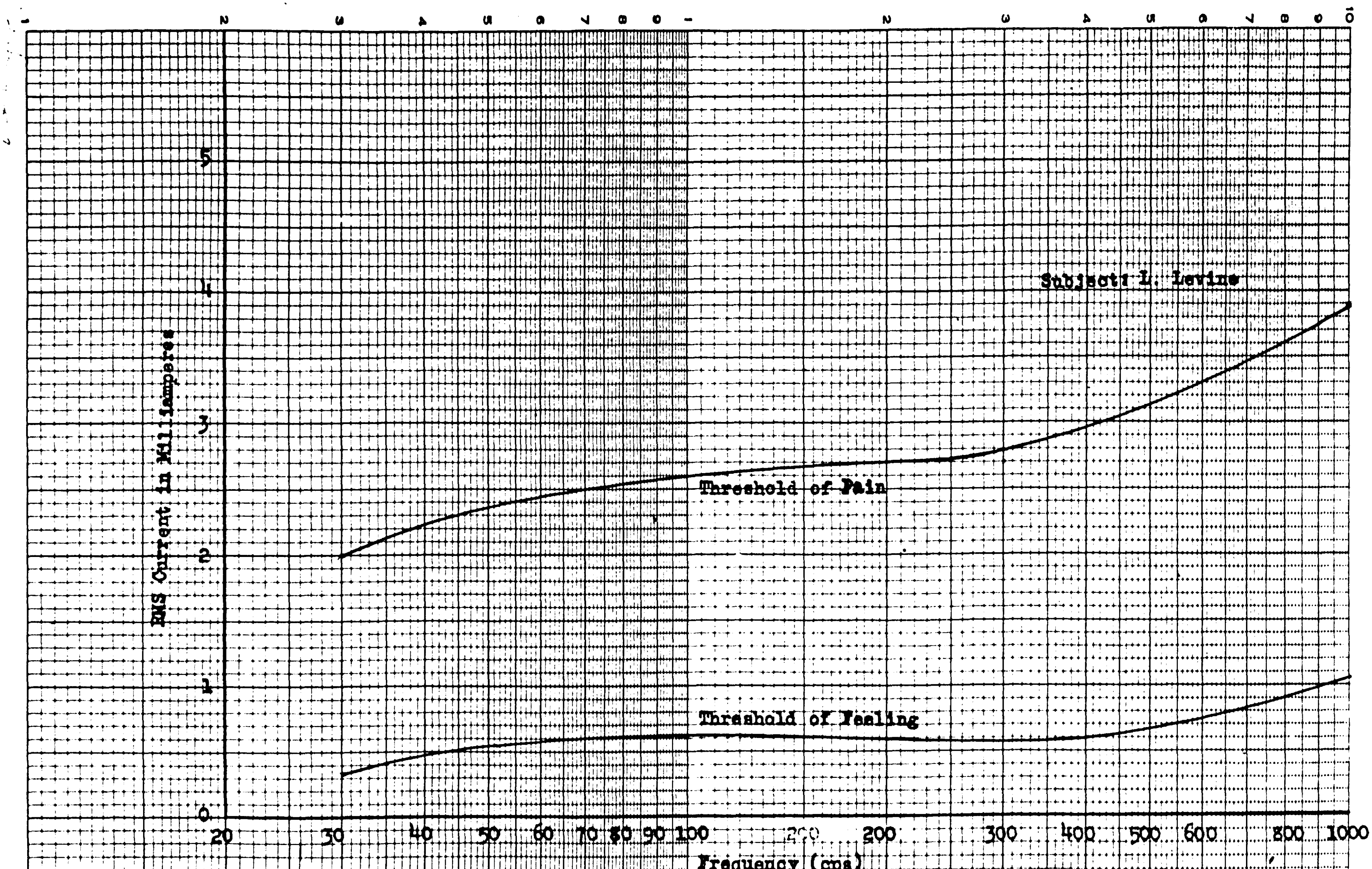


Figure 15. Measurement of the Thresholds of Pain and Feeling for the Second Finger of the Left Hand. Sinusoidal stimulation was used.

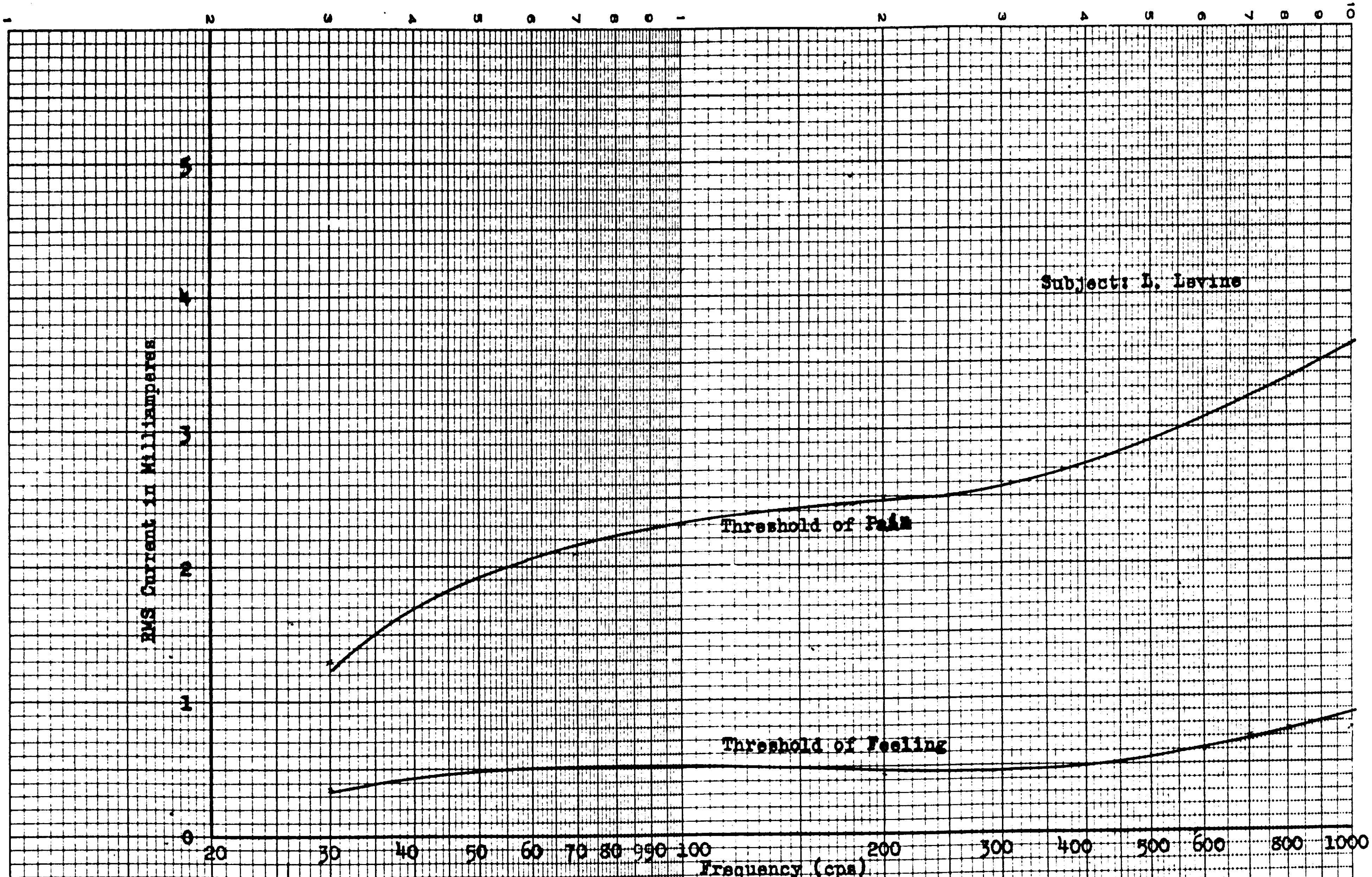


Figure 16, Measurement of the Thresholds of Pain and Feeling for the Third Finger of the Left Hand. Sinusoidal stimulation was used.

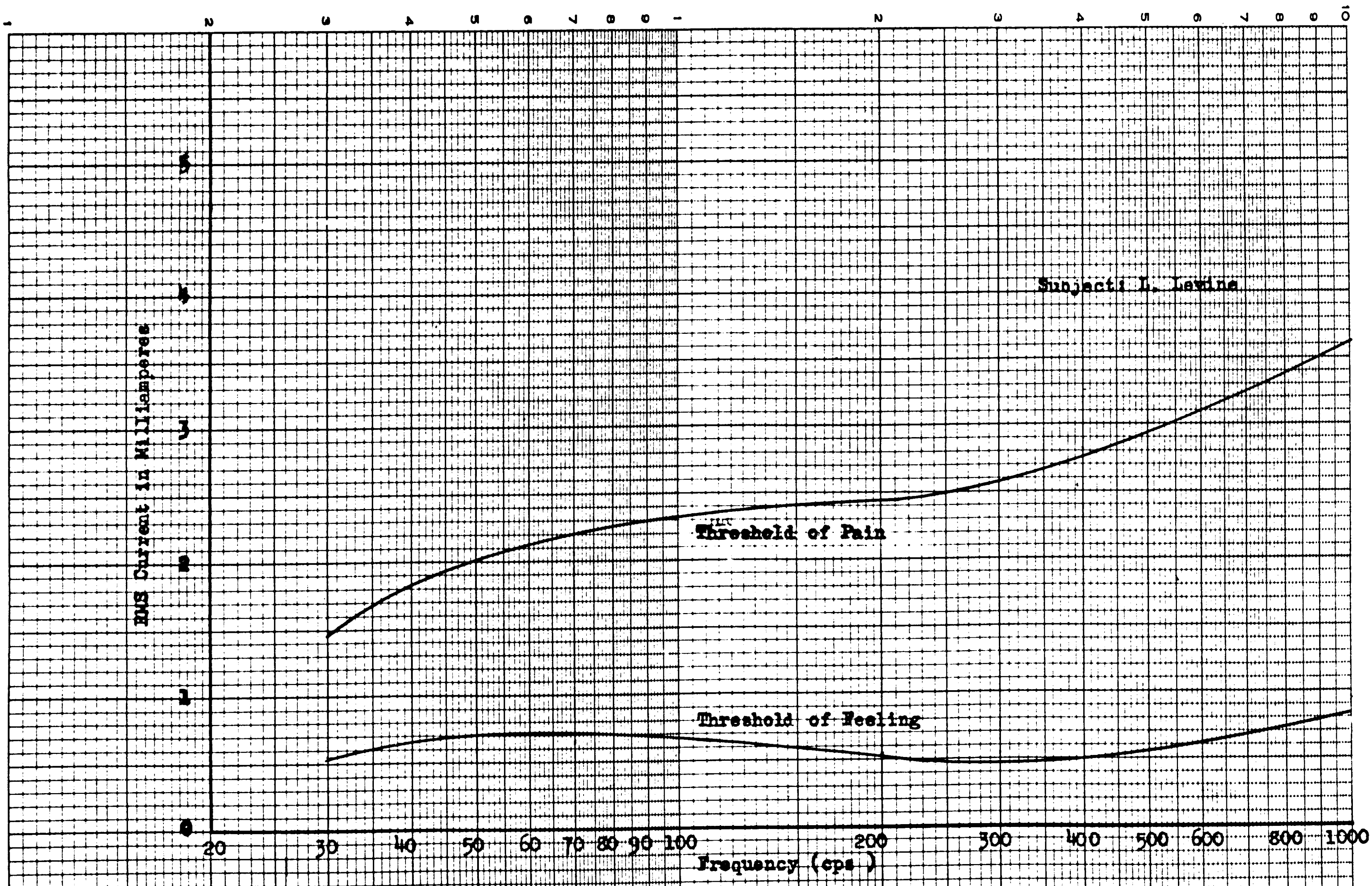


Figure 17. Measurement of the Thresholds of Pain and Feeling for the Fourth Finger of the Left Hand. Sinusoidal stimulation was used.

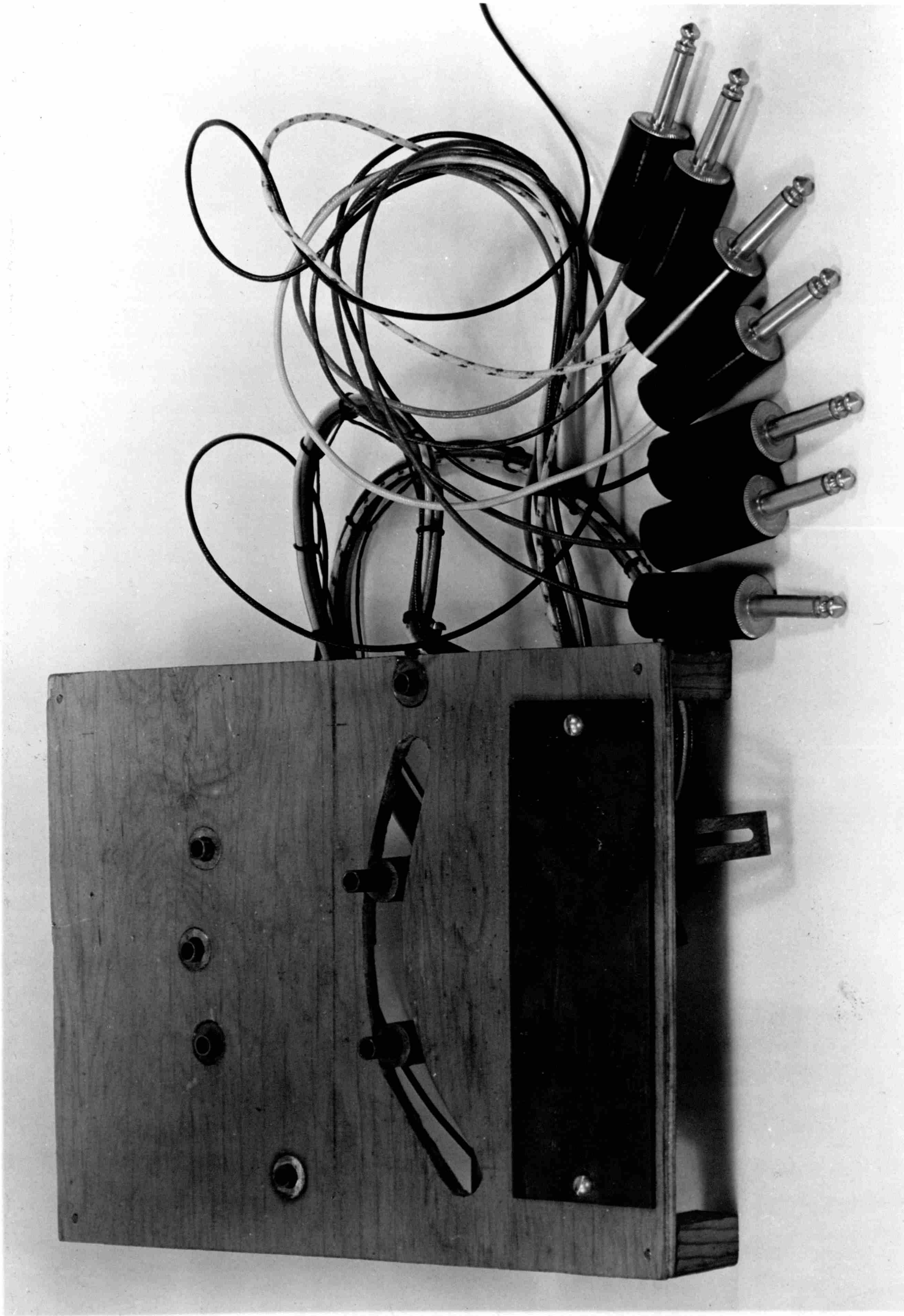
of these thresholds was made with four different electrodes (6/32 inch and 8/32 inch hollow copper tubing and 6/32 inch and 8/32 inch solid copper tubing). All of the electrodes produced substantially the same results. The graphs demonstrate that the thresholds tend to remain the same for all of the fingers. Repeated usage of electrical stimulation does not alter a person's thresholds. There is approximately a twenty decibel difference between the threshold of feeling and the threshold of pain over the entire frequency range. This limited range could be a serious detriment to the design of an electrical FEELIES were it not for one consideration. Tests conducted on five subjects show that the thresholds, measured as a function of the current, varied plus or minus 10% of the values shown on the graphs. The thresholds, measured as a function of the voltage, are more erratic. Therefore, a constant current source, i.e., a pentode, will provide nearly the same stimulations for all users. The only other modification which need be made to FEELIES besides the installation of a pentode output is the addition of a limiter to insure that the threshold of pain is not exceeded.

Is the present FEELIES adequate for transmitting speech with electrical stimulation if a limiter and pentode output are added? Although no actual experiments have been conducted with subjects, this question can be answered with an unequivical <u>no</u>. Because

FIGURE 18

AN EXPERIMENTAL SEVEN UNIT ELECTRICAL STIMULATOR

The copper plate serves as the common ground for all of the electrodes.



of the very limited range between the thresholds of pain and feeling, information in each channel will be transmitted on a yes-no (or on-off) basis. The optimum of learning an electrical Feelies is represented by Stage 3 instead of Stage 5 in the case of mechanical FEELIES (see page). As was pointed out in Chapter IV the five channel picutes in Appendix II also pictures the presence or absence of energy in each channel. These pictures, then, more closely approximate conditions with electrical stimulation than mechanical stimulation. To analyze these five channel pictures, it is essential to know the minimum time difference at which pulses arriving at two fingers can be perceived to arrive at different times. The minimum impulse differentiation times for the ten combinations of two fingers are shown in Table 3. The average minimum time is about 0.084 seconds, similar to the differentiation times of the mechanical vibrators shown in Table 2.

Fingers	Time Interval (in seconds)
Thumb - First Finger	.105
Thumb - Second Finger	.092
Thumb - Third Finger	.086
Thumb - Fourth Finger	.083
First Finger - Second Finger	.064
First Finger - Third Finger	.076
First Finger - Fourth Finger	.090
Second Finger - Third Finger	.063
Second Finger - Fourth Finger	.079
Third Finger - Fourth Finger	.106

TABLE 3, Minimum Time Interval for Electrical Impulse Differentiation

A study made of the pictures using the mechanical differentiation times indicates that there is insufficient contrast of patterns, particularly in the case of the vowel sounds. The same conclusions are applicable to electrical stimulation. This rules out the use of a five unit electrical stimulator at least with the present bandwidths.

Once it is know that a five channel FEELIES will be inadequate, the problem is only how many stimulators are needed to make it successful. Without further study we would still know that the number lies between five and twelve. The lower limit is fixed by the study of five channel pictures. The upper limit is set by the Bell Laboratories work on visual speech. In this work, the Bell Laboratories showed that twelve channels would produce adequate discrimination between all of the phonemes.

Supplementary study has reduced the uncertainty concerning the number of stimulators required. In Appendix II a seven unit FEELIES pattern is shown for each word below its five unit counterpart. The seven unit system is broken up into the following bandwidths: 0-200cps, 200-400cps, 400-800cps, 800-1100cps, 1100-1400cps, 1400-2400cps, 2400-15000cps. The seven channel system differs from the five channel system in that the first and third of the five channels have been subdivided into two channels each.

A study of the seven unit system which allows for the phenomenon of Table 3 is shown in Appendix III. There is enough discrimination between the phonemes shown there to permit unique recognition of each with sufficient learning. A seven unit FEELIES should be successful. The patterns in Appendix III reveal that there is almost no difference between the first two channels. A combination of these two channels would not materially affect the pattern received by the fingers. If the remaining phonemes should have patterns consistent with the ones already studied, six channels will be the maximum number required.

CHAPTER VI

SUMMARY

Although research has been conducted continuously since December 1948, the work on FEELIES is still in its early stages. The development of electronic equipment to transmit speech information to the body encompasses the fields of phonetics and psychology as well as electrical engineering. Because the task is such a large one only limited objectives have thus far been achieved. The present evaluation of FEELIES can only be tentative and subject to modification by further research.

However, results already obtained are encouraging. Mechanical FEELIES is definitely successful in primary stages of learning. Four subjects have demonstrated that word patterns are learned rapidly. Once learned, these vibrotactile patterns are retained by the subject with a high degree of accuracy. The apparatus itself is easy to use. Within a few minutes after his introduction to FEELIES, the subject becomes acquainted with all of the ramifications of its use and encounters almost no trouble with the apparatus thereafter.

The emphasis in this thesis has been on the transmission of speech to the deaf. FEELIES may perform another task equally important, the teaching of the deaf to speak. To teach a child to speak who has been deaf from infancy is a long and tedious job. When the child is also blind, the task assumes enormous proportions. With endless repetition of effort the child eventually learns to speak. Even with this effort, his speech may be low and gutteral, lacking in the higher overtones that give a voice its quality, and he may speak in an almost indistinguishable monitone.

FEELIES is in a position to revolutionize this phase of a deaf person's life. In May 1949, Leo Sablosky, a twenty-three year old man who was deaf almost from birth and blind since the age of twelve, was tried out on FEELIES. In a short span of two hours, he was taught to make phonetic sounds which he had never been able to utter before. The learning technique was simple. A person spoke into the microphone after which Leo spoke and tried to repeat the pattern he received on his fingers. For the first time in his life, Leo was able to monitor his own voice. A feedback circuit, like that described by Dr. Norbert Wiener in his Cybernetics, permitted Leo Sablosky to compare the pattern he received on his fingers with the correct pattern. Each time he spoke he tended to come closer to the correct sound. To people like Leo Sablosky, FEELIES offers a chance to develop a speaking vocabulary almost as rapidly as a normal person can.

Nor is this all that FEELIES offers to the deaf. Using electrical stimulation FEELIES may soon be designed as a portable, inexpensive unit. A seven unit system will work and there is a strong possibility that a six unit system will also be sufficient. When portable FEELIES are perfected, the stone deaf man will be able to vie with his more fortunate handicapped friends who can use hearing aids.

All enthusiasm about FEELIES should be tempered by the realization that much work remains to be done before the equipment is perfected. It would be inconsistent with good scientific procedure to extrapolate results to a desired conclusion. However, when the work on FEELIES is finished, the deaf man will be able to walk amongst his fellow men unhampered by the curse of eternal silence.

Appendix I

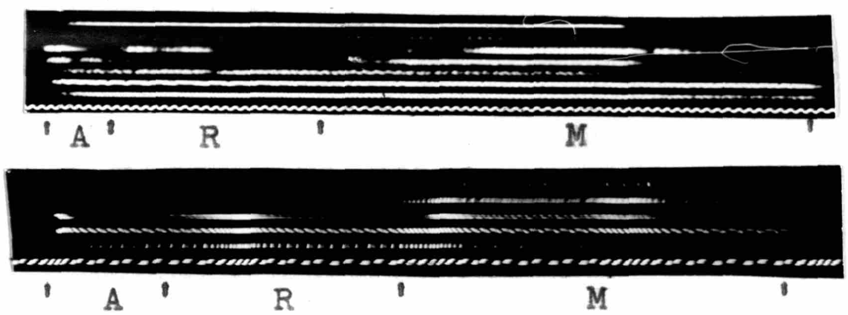
Reference Listing of Phonetic Symbols, Key Words, and Webster's Diacritical Markings

Phonetic Symbols	Key Words	Webster's Diacritical Markings	Phonetic Symbols	Key Words	Webster's Diacritical Markings
i	eve	ē	t	to	t
ɪ	it	ĭ	d	day	d
e	hate	ā, ā̇	k	key	k
ɛ	met	ĕ	g	go	g
æ	at	ă	h	he	h
a	ask	ȧ	ɦ	ahead	—
ɑ	father	ä, ŏ	f	for	f
ɒ	not	ŏ, ô̆	v	vote	v
ɔ	all	ô	θ	thin	th
o	obey	ō̇	ð	then	t͟h
ʊ	foot	o͝o	s	see	s
u	boot	o͞o	z	zoo	z
ɝ	word, bird	û, ẽ	ʃ	she	sh
ɜ	word, bird	—	ʒ	azure	zh
ʌ	up	ŭ	tʃ	church	ch
ə	about	*ă, ĕ, ŏ, ŭ, ȧ*	dʒ	judge	j
eɪ	say	ā	m	me	m
aɪ	I	ī	n	no	n
ɔɪ	boy	oi	ŋ	sing	ŋ, ng
ɑʊ	out	ou	w	we	w
oʊ	go	ō	j	you	y
ɪu	new	ū	r	read	r
p	pay	p	l	let	l
b	be	b	hw	when	hw

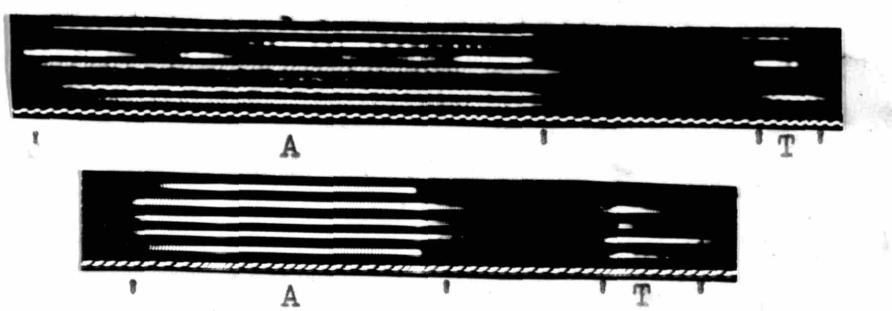
APPENDIX II

A Comparison of the Word Patterns of the Five and Seven Unit FEELIES. The bandwidths of the five unit FEELIES are (1) 0-400 cps, (2) 400-670 cps, (3) 670-1400 cps, (4) 1400-2400 cps, (5) 2400-15000 cps. The bandwidths of the seven unit FEELIES are (1) 0-200 cps, (2) 200-400 cps, (3) 400-670 cps, (4) 670-1000 cps, (5) 1000-1400cps, (6) 1400-2400 cps, (7) 2400-15000 cps. The lowest frequency band in both cases is nearest the marker on the bottom.

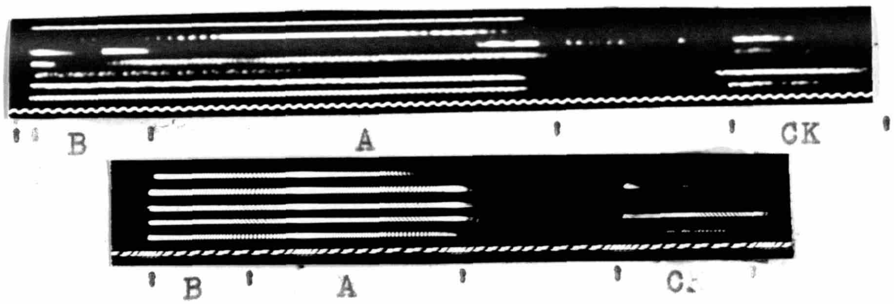
Arm



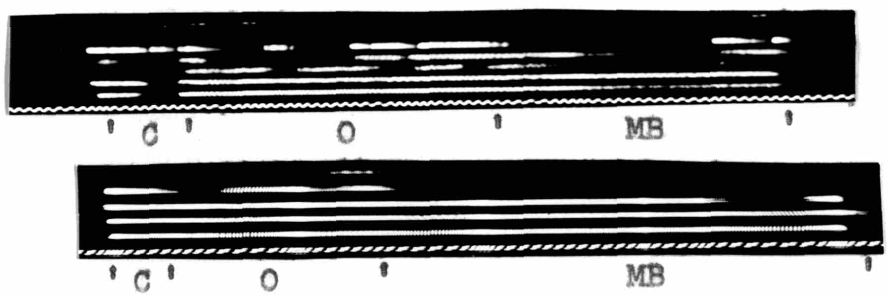
At



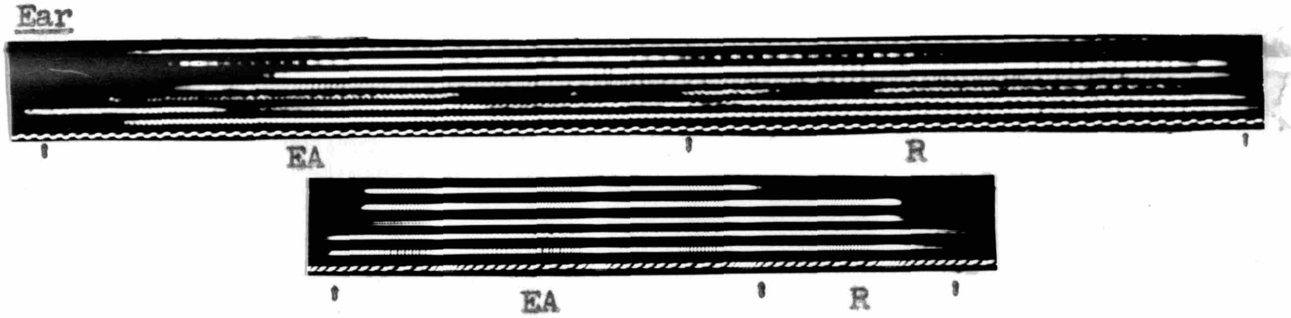
Back



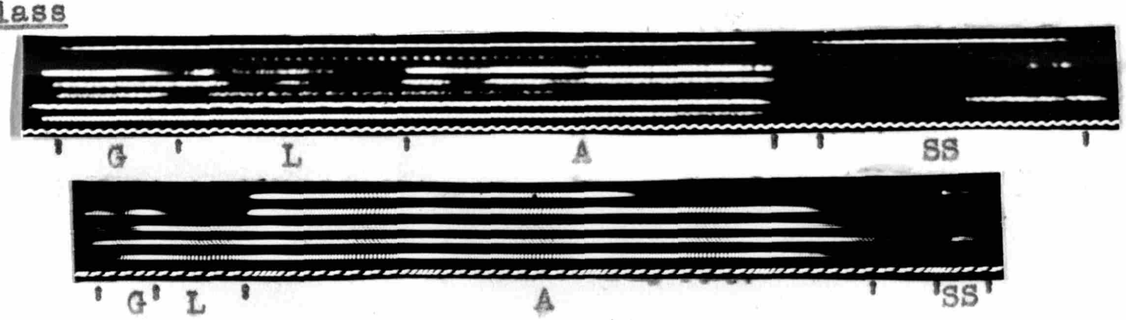
Comb



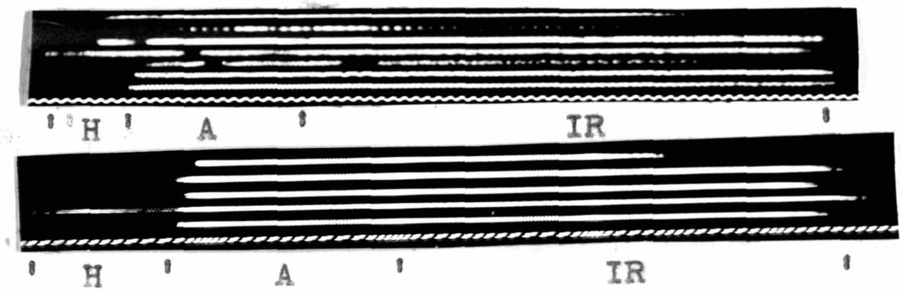
Ear



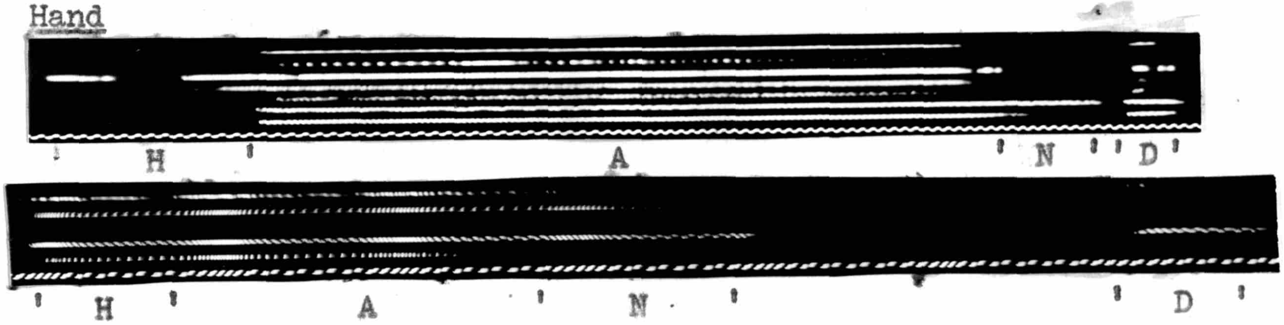
Glass



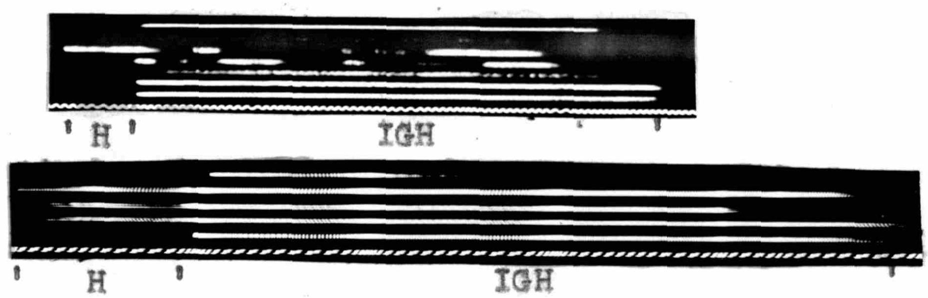
Hair



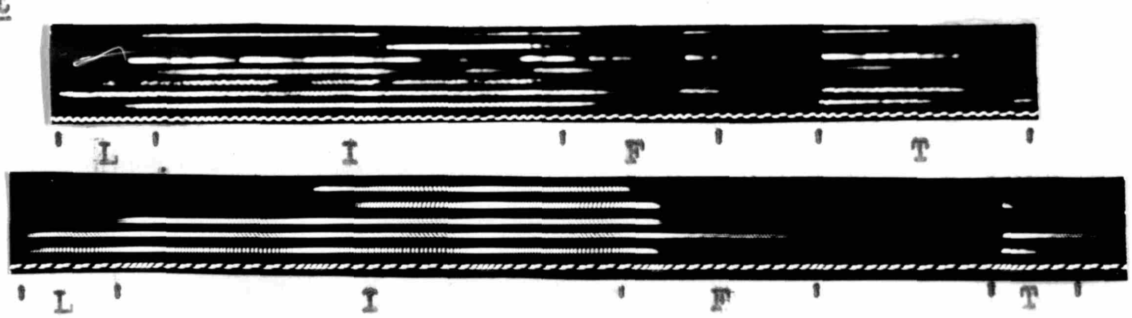
Hand



High

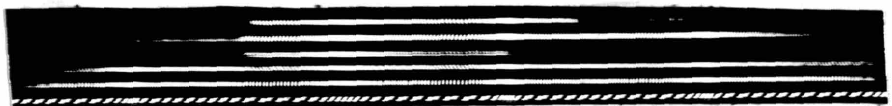


Lift



Me

M E



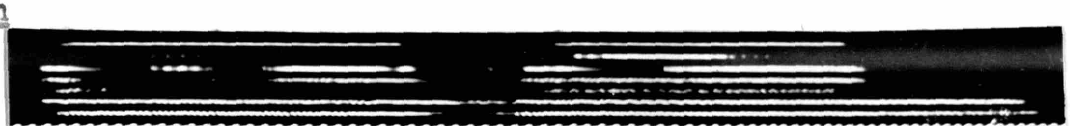
M E

Mouth

M OU TH

M OU TH

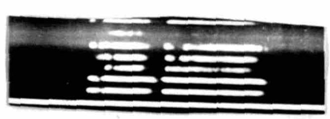
Open



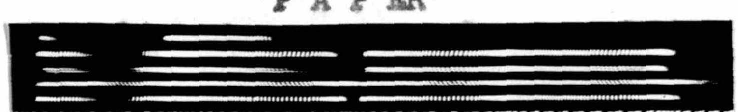
O P E N

O P E N

Paper



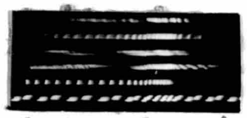
'P'A'P'ER'



P A P ER

Pick

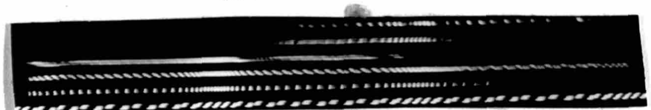
' P ' I ' ' CK '



'P' I 'CK '

Point

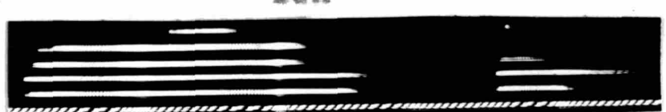
' P ' OI ' N ' ' T '



' P ' OI ' N ' T '

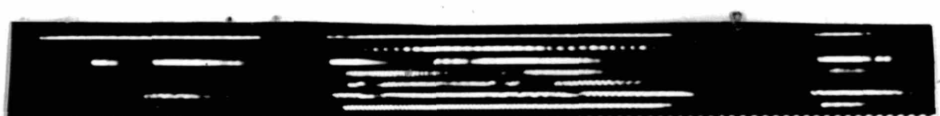
Right

' R ' IGH ' ' T '



' R ' IGH ' ' T '

Straight

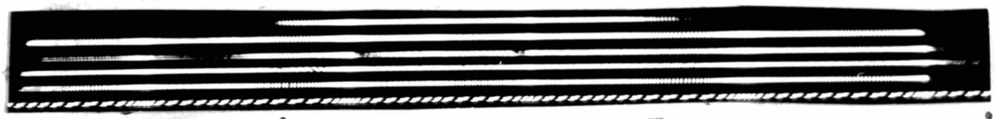


' S ' 'T ' R ' AIGH ' ' T '

'S 'T' R ' AIGH 'T '

The

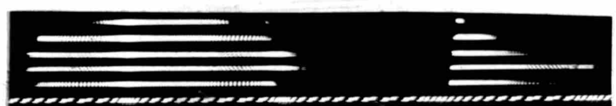
TH E



TH E

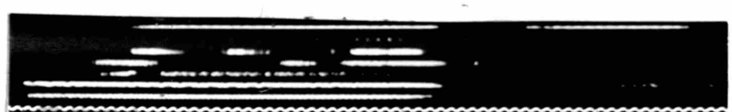
Up

U P



U P

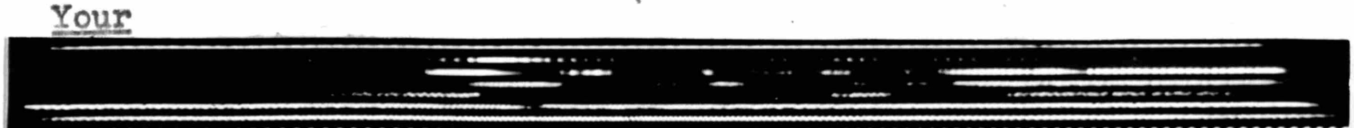
Watch



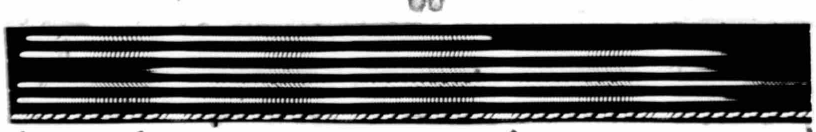
W A TCH

W A TCH

Your



Y OU R



Y OU R

APPENDIX III

Phonetic Patterns of the Seven Unit FEELIES Apparatus

These patterns, taken from the pictures in Appendix II allow for the impulse differentiation times between fingers. The bandwidths for each channel are (1) 0-200 cps, (2) 200-400 cps, (3) 400-670 cps, (4) 670-1000 cps, (5) 1000-1400 cps (6) 1400-2400 cps, (7) 2400-15000 cps. Each ½ inch equals 0.2 secs.

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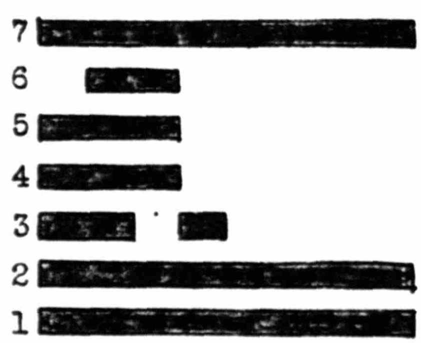

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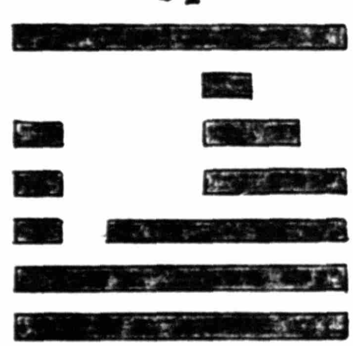


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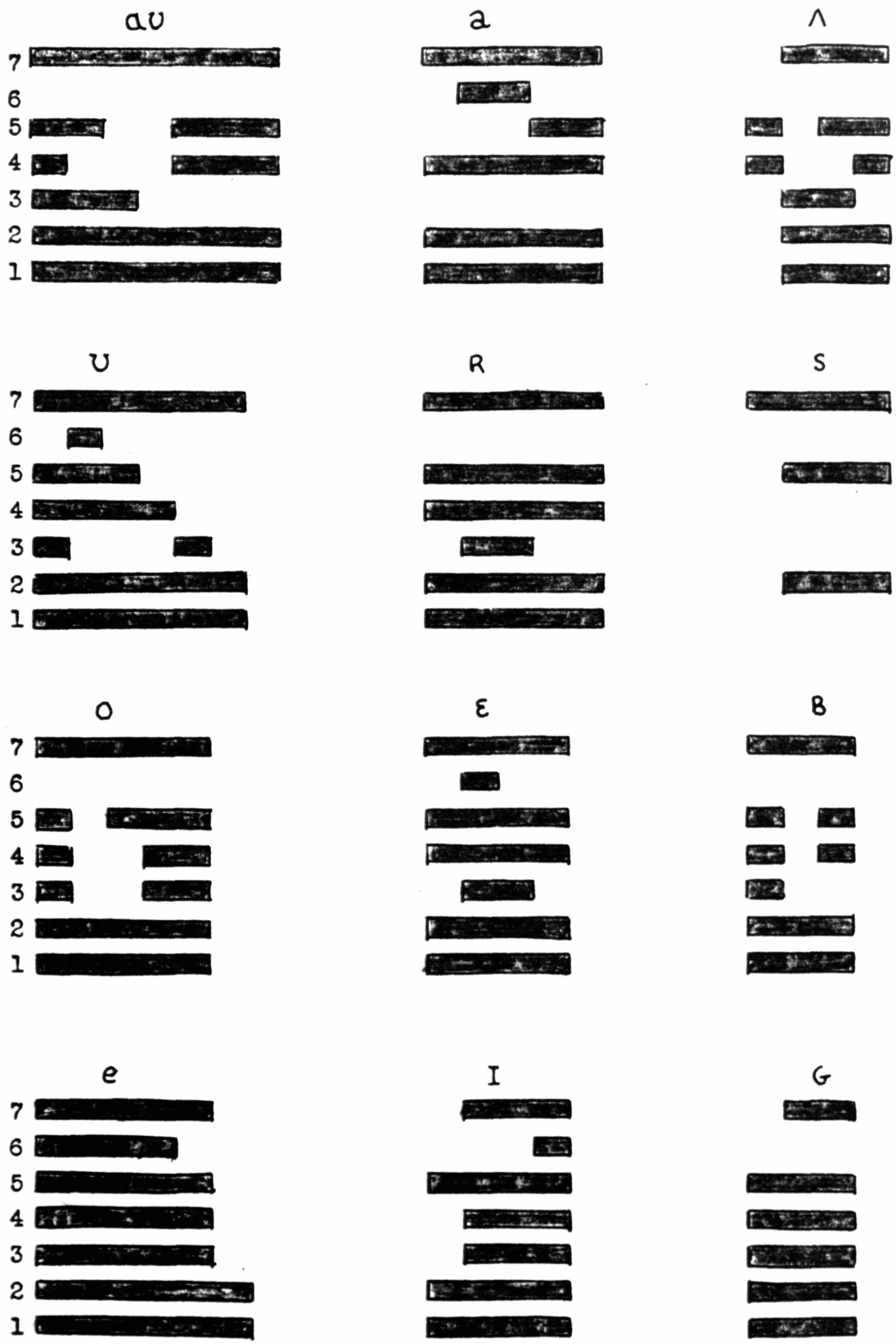
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Credits

Figure 1 and Appendix I were both taken from "Visual Speech". See Reference 6.