INFORMATION RATE VIA VIBRO-TACTILE, TWO-DIMENSIONAL "PHANTOM" SENSATION

by

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ABSTRACT

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A triangular pattern of three mechanical stimulators on the abdomen fused into one tactile sensation. The location of this "phantom" sensation depended on the relative amplitude of the stimuli. Emphasized in this study was the possibility of using this display to feed mobility information to the blind. Investigation of the stimulation parameters and information transmission was accomplished by tracking experiments. One of the subjects in these experiments was blind.

Subjects could readily recognize seven positions of this sensation at an average maximum rate of 3.1 bits per second. The experiments demonstrated that the phantom sensation has good potential for use in a simple mobility device intended only to augment the long cane. However, resolution of the display is insufficient to convey the exact location and shape of multiple objects.

Thesis Supervisor: Robert W. Mann
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I thank Mr. Vito Proscia, who, from the standpoint of a blind person, gave me an indication of the desperate need for a good information display for the blind. He also donated many hours as a subject.

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I. INTRODUCTION

A. Aids for Blind Mobility

Blind humans obviously lack the wealth of information that sighted persons use for travel and mobility. In providing some of this information to the blind traveler, the two most successful devices have been the seeing-eye dog and the long cane. The seeing-eye dog is an excellent mobility aid, but the use of dogs has been limited by two factors: The traveler must be strong and agile to control a dog (a large proportion of the blind are older than 65). Only certain people can or will put up with the inconvenience of maintaining a dog. The long cane is a very convenient mobility aid (especially the new folding models). The primary disadvantages of the cane are its short range of detection and its inability to sense overhanging obstructions.

Several electronic devices have been proposed and/or produced which make an attempt to replace, or, in some cases augment the long cane. Kay[23*], has produced a device which outputs an audio-pitch that corresponds to the distance of an object. This hand-held mobility aid is intended to replace the long cane. Rowell[34], has investigated the possibility of using this

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* Superscript numbers indicate the reference number in the bibliography.

Kay system in conjunction with interaural amplitude differences to provide an input of azimuth information. A study by Bach-y Rita[3,4], used an array of 400 tactile stimulators to feed information about the shape of various objects as viewed by a television camera. Bionics Instruments has produced a "laser cane" which provides a tactile poking to the finger for objects directly in front of the traveler, and provides auditory cues of overhanging objects and terrain drops. Recently, there has been research on direct stimulation of the visual cortex. One such research study is being conducted by Brindley[6]. Russell[35,36], has produced a device intended to augment the long cane, which audibly alerts the blind traveler to the presence of an object in one of two regions directly in front of him. This device was primarily intended to reduce the social penalty of striking another person with the cane. Other work on mobility aids for the blind is rather comprehensively referenced (see references 8,9,13 and 31 in the bibliography).

B. Complexity of Blind Mobility Problem

A meaningful question is: Why haven't these devices been enthusiastically accepted and widely utilized by the blind? A partial explanation can be gained by considering the overall complexity of the blind mobility problem. This problem is graphically demonstrated by the block diagram in Figure 1. Note

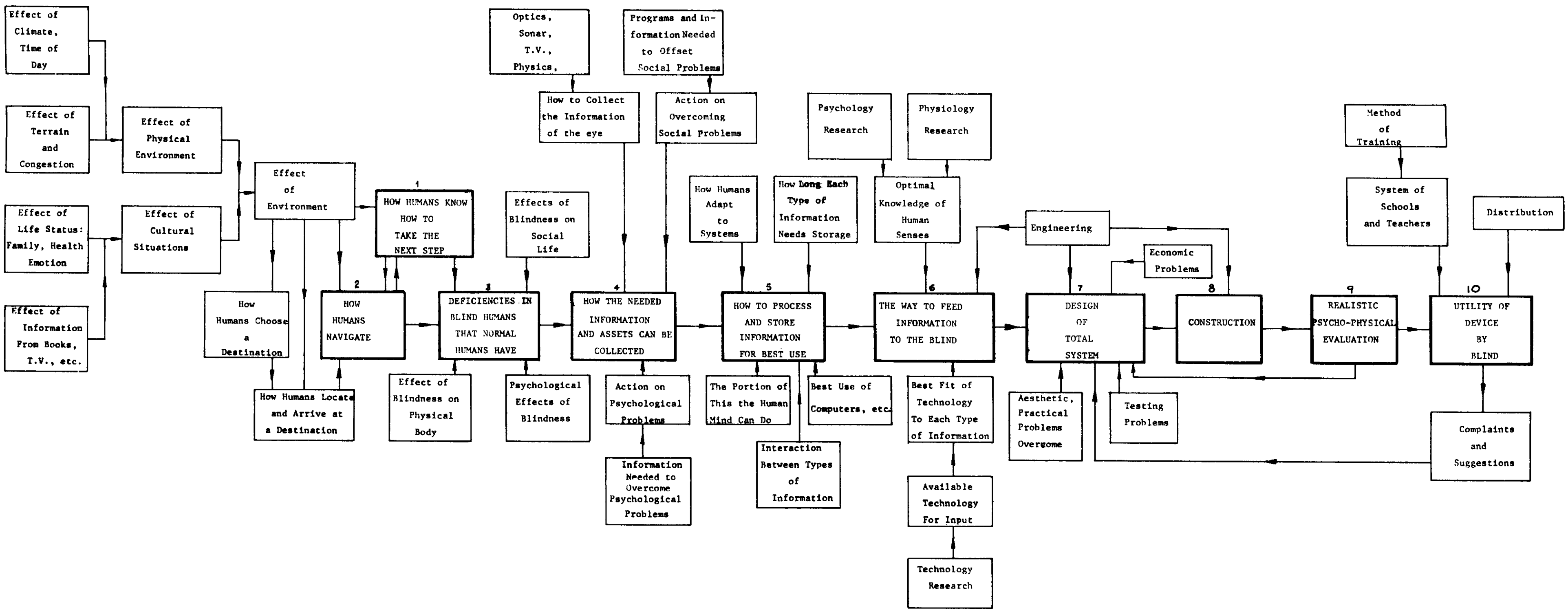

FIGURE 1. GENERAL CLASSIFICATIONS OF KNOWLEDGE THAT ARE NEEDED TO SOLVE THE PROBLEM OF BLIND MOBILITY

that a high percentage of the blocks included in the figure represent broad and intangible problems which will require the coordinated effort of many scientists, psychologists, neurologists, engineers, etc. for solution. Of the research done to date, much concentrated on a search for a substitute sensory modality (which includes blocks 4, 5 and 6 of Figure 1). This, perhaps, has been the correct approach to the problem. There is evidence of plasticity in the human neurosensory system[3]. The modern theory is that part of what humans see is perceptual and learned, and is not totally sensory[5]. In light of these facts, a good "substitute for the eye" might cause the nervous system to adapt itself automatically, giving the blind adequate mobility information without a complete solution of all of the problems listed in Figure 1. This "substitute for the eye" must have the capability of not only sensing that something is there, but also easily identifying what is seen. If the blind person knows what an object is, its location and velocity, then he can ignore the object or adjust his travel to avoid, or comply with it. This theoretical "eye substitute" must also give rapid information about the terrain, relative location of several objects, interrelation between objects, etc. The reception of this information must be done in real time. It isn't like a book, where if the reader misses a line, he can go back. In essence, it is highly unlikely that such an "eye substitute" can be developed in the near future. In my opinion, it is a long way off. Quoting Chardon[7], "Blind persons have lost the major information collection to the brain. Any mobility aid, no matter how elegant, can give to the brain only a very small part of the information collected by the eyes".

The difficulty of getting the information to the human is not the only problem. Even if a good mobility aid were found, there is the possibility that it will be rejected on aesthetic, emotional, and/or other personal grounds. People are unwilling to use sensory aid equipment if it requires daily effort or if it is unattractive and/or unpleasant. For example, there are near-deaf people who do not wear a hearing aid, simply because they can "get along" without it. They don't mind the social penalty for saying huh!, or eh! They would rather not fuss with wires and batteries. Similarly, the benefits of a mobility aid for the blind must far outweigh any inconveniences and unattractive aspects associated with it, or else the blind traveler will also be content to just "get along" using the cane. Blind persons are probably influenced more than sighted persons by the forces of habit. Therefore, in order for a mobility device to succeed, a major task will be the education and training of the blind. Before the blind will use any mobility aid, they must be "sold" on the device.

C. Directives for Research

Where should research begin? Simulation of mobility situations is a likely starting point. It provides the obvious advantage of controlled collection of data*, and also eliminates expensive "gadgeteering" mistakes. "Past experience indicates clearly that to approach sensory aids as a gadgeteering problem is to invite further disappointment. There is a critical need for more fundamental research on the psychology of sensory communication"[27].

Much technological knowledge (electronics, radar, sonar, television, photography, etc.) can be adapted to the area of information collection for mobility devices. The real bottleneck in mobility aids has always been human reception of the information. Due to a limited sensory input capability, too much complex information has confused the blind person. This has been a major objection to some of the present devices. The simple cues received from the long cane has, no doubt, been a factor in its wide acceptance. An information input should not mask the blind person's own remaining sensory abilities. Table 1 shows the

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* A detailed description of the advantages of performing mobility experiments in a simulated environment is given in references 27, 28 and 29.

TABLE 1 -- ATTRIBUTES OF THE HUMAN SENSES

THAT WOULD HINDER INFORMATION INPUT

	HEARING	SMELL	TASTE	TOUCH	HOT, COLD
Will information input disturb normal use?	X	X			
Will the input be discernible by others?	X	X			
Is there insufficient information capacity?		X?	X		
Does the sense fail to follow rapid changes in stimuli?					
Is the sense subject to surroundings that may cause long-term drift?	X	X	X?		X
Will the input possibly be unpleasant or unnatural?		X	X		

X--indicates positive answer

Table adapted from Alles[1].

pertinent limitations of each of the sensory inputs available to the blind. The sense of touch is void of major adverse factors, so it, perhaps, is an ideal mode for the input of mobility information.

Several other factors indicate the potential of the skin as an information input. The skin can withstand rough treatment surprisingly well[43]. Since hearing and skin localization do not mask each other[45], the blind traveler using tactile input will have full use of his natural capabilities. Also, the external environment, such as traffic noises, will not affect the display. A tactile input will not be noisy in normally quiet locations, i.e., a church or a library. The potential information capacity is enormous. Geldard and Sherrick[17], have reported that the human skin constitutes a receptive surface, roughly a thousand times larger than the retina. The skin has numerous qualities of feeling that might possibly be used for input. Some of these are: pressure, contact, prick pain, deep pain, warmth, cold, hot, electric tickle, itch, tickle, vibration and flutter. Since blind persons can read braille, and the deaf-blind can perceive speech through contact with the skin[14], the skin's capacity for information input has been demonstrated. Visual information rates are reported as high as 40 bits per second and it has been estimated that the possible information rate by tactile means is

20 bits per second. To date, no device approaches this value[49]. Humans have a short term memory for tactile stimuli lasting about a second. This factor also could be used to make more information available[27]. All in all, the prospects for receiving information through the sense of touch appears good.

In review, the foregoing discussion has indicated that certain contraints should be considered in defining a research topic on mobility aids for the blind: first, studies should be done by simulation if possible. Second, investigations should be concentrated on the sensory input to humans. Third, in order to be of immediate potential use to the blind traveler, any device should attempt to supply only simple information (perhaps, only to augment the long cane). Fourth, the tactile sense should be the mode for information input.

Using the above constraints, this investigation has been directed toward a particular vibro-tactile input system for humans. It is briefly described in the following section. More detail is given in the body of the thesis.

D. The Phantom Sensation

Von Bekesy[45] reported that under certain conditions, when two mechanical vibrators are set in motion on the skin's surface, only a single sensation located somewhere between the two stimulators is perceived. The position of this "phantom" sensation depends on the relative amplitude and/or temporal order of the two vibrators. Alles[1] used this perception phenomenon to create a continuous one-dimensional information input system on the upper arm. By controlling the relative amplitude of two vibrators, his subjects felt a sensation move continuously between the two stimuli. Reimers[32] demonstrated the capability of this system to feedback elbow-angle information to an amputee wearing a battery powered arm prosthesis (the kinesthetic sense, of course, is missing). The position of the phantom sensation on the amputee's stump indicated the elbow angle and aided the accuracy of reaching tasks using the electro-mechanical arm. Another study[15], examined the possibility of using the phantom sensation as a means of displaying braille.

Alles also mentioned that a similar phantom sensation existed in two dimensions when three vibrators stimulated the skin in a triangular array. In other words, the sensation was localized somewhere in the area of a triangle formed by three vibrators depending on their relative amplitudes. It was suggested that this two-dimensional sensation might be a means of presenting information to blind humans. Alles' experimentation on this topic was brief and subjective in nature.

Depending, of course, upon the acuity and maximum information rates attainable with this two-dimensional sensation, it may have practical application in many areas. The location of the two-dimensional phantom sensation could indicate the location of an object in the space in front of a blind traveler. With some sort of a scanning probe, the display could possibly behave like the moving dot on a radar screen giving stimulation to areas of the skin corresponding to the distance and azimuth of objects. Obviously, such a device would only stimulate when an object was present. If the scanning rate were high enough, not only the distance and azimuth of the nearest objects could be transmitted, but also the relative velocity of the objects. A more detailed description of a possible mobility aid is given in Appendix 4.

Another area of possible application is communicating information to persons whose eyesight or hearing is being taxed. An example of this is the airline pilot, who visually interacts with numerous meters and indicator lights. Perhaps the phantom display could be utilized to present warning signals to the pilot. One such signal might be a warning of the presence and location of another aircraft.

There are situations when the environment makes it impossible or inappropriate to communicate audibily. The workman at a jack hammer cannot hear. The skindiver under water cannot hear. A military operation, where absolute silence is a must, is another possibility. Deaf persons have difficulty controlling the pitch and volume of their speech. The two-dimensional phantom sensation might be used to feed back this information to them. There are more possibilities, but too numerous to mention here.

E. Thesis Goal Defined

This study was an investigation of this two-dimensional phantom sensation with special emphasis directed toward its possible application in a mobility aid for the blind. It was not the intent of this study to create an actual mobility aid, but simply to determine if the resolution and information transmission rates associated with the display were high enough to permit its use in such a device.

II. SKIN LOCALIZATION

A. Comparisons Between Sensory Modalities

Obviously, our senses do not each have the same abilities and aptitudes. For example, the eye can locate in the external world better than the ear, but the ear relates temporal phenomena better than the eye[25]. There are, however, similarities between our several senses.

Much research has shown comparative features between hearing and tactile sensations. Some of these similarities are briefly mentioned here:

When two impulses are presented, one to each ear (depending on relative intensities and/or the time delay), only one sensation will be perceived. This sensation will be displaced to the louder side or the side which is presented first. A simplified example of this is sensed when one hums a tune and closes one ear. Because of bone conduction, which increases the intensity in the closed ear, the tone moves to the closed ear[41]. A similar phenomenon exists on the skin. "Two equally loud stimuli which are presented simultaneously to adjacent locations on the skin are not felt separately, but rather combine to form a sensation midway between the two stimulators. This "phantom" sensation is affected by the separation of the stimuli, their relative amplitudes, and their temporal order"[1]. It has been reported that these hearing and skin localization phenomena can be presented simultaneously and not mask each other out[43]. Since the skin phantom sensation can occur solely on one side of the body, it is probably not a consequence of interconnections between the brain hemispheres as may be the case with hearing[42].

The time interval between two clicks needed to displace the localization of a hearing sensation from the center of the head all the way to one ear is approximately the same time interval needed to displace a skin phantom sensation created by two equally intense air puffs on the forehead from the midway point to one side[41,43]. If the delay is more than about five milliseconds, fusion is lost and two pulses are sensed.

The ear and skin also have similar qualities of sensation. Every type of hearing stimulus produces a sensation with at least eight different qualities: pitch, loudness, volume, roughness, modulation (tremolo), direction, distance, on and off effects, and rhythm. All of these qualities have their counterparts in skin sensation[47].

Phantom localization also has been noted to exist on the tongue when it is stimulated at separate places by spices or electrical stimulation. Again, the time interval necessary to cause the taste localization to shift from the center to one side is approximately the same interval (1-2 msec.) needed for the hearing and tactile sensations[41].

B. Perception of Time Delayed Stimuli

When two equally loud stimuli are presented at adjacent points on the skin, three different sensation phenomena have been reported as a function of time delay between the onset of the two stimuli. For a long delay time, separate sensations are perceived. A shorter time delay (100-200 msec.) will eventually bring a sensation that feels as if it starts at the first stimulator and moves continuously to the other stimulator. This sensation is called apparent movement and is similar to the apparent movement in vision between two sequentially presented spots of light[39]. When the time interval between the two stimuli is further decreased (1-8 msec.), then the phantom sensation takes place. As this shorter time delay is approached, the perceived magnitude of the earlier stimulator begins to increase and the later stimulator begins to decrease until all the sensation is under the earlier probe. As the time delay approaches zero, the sensation moves to the center, its size (area) increases and the intensity decreases[45].

The two distinct and separate sensations associated with long delay time is not of interest for this thesis, and will not be discussed further.

C. Factors that Influence the Apparent Motion Sensation

The apparent motion (sometimes called haptic motion) associated with time delay on the order of 100 milliseconds has been reported to feel "like a vibrator with a smooth contact, like a ball bearing, that is run between the signals"[37]. It has also been described as "a powerful vibratory gouging that moved from one stimulus site to the other"[39]. Bice used this phenomenon to create a "powerful swirling sensation" around the torso with six vibrators[16]. Sherrick and Rogers experimented with several variables in order to define the situations to obtain the "best apparent movement" (defined as the longest uninterrupted feeling of movement between the first and second stimulus site)[37]. The variables they investigated were: perceived sensory magnitude, distance between stimuli, location stimulated, frequency (60-250 hz), direction of motion, interval between stimulus onset, and duration of stimuli. Only the duration of stimuli and interval between stimulus onset had an appreciable effect on the "best apparent movement"[33,37]. A graph describing interval between stimulus onset versus pulse duration to obtain the "best apparent motion" is given in Figure 2.

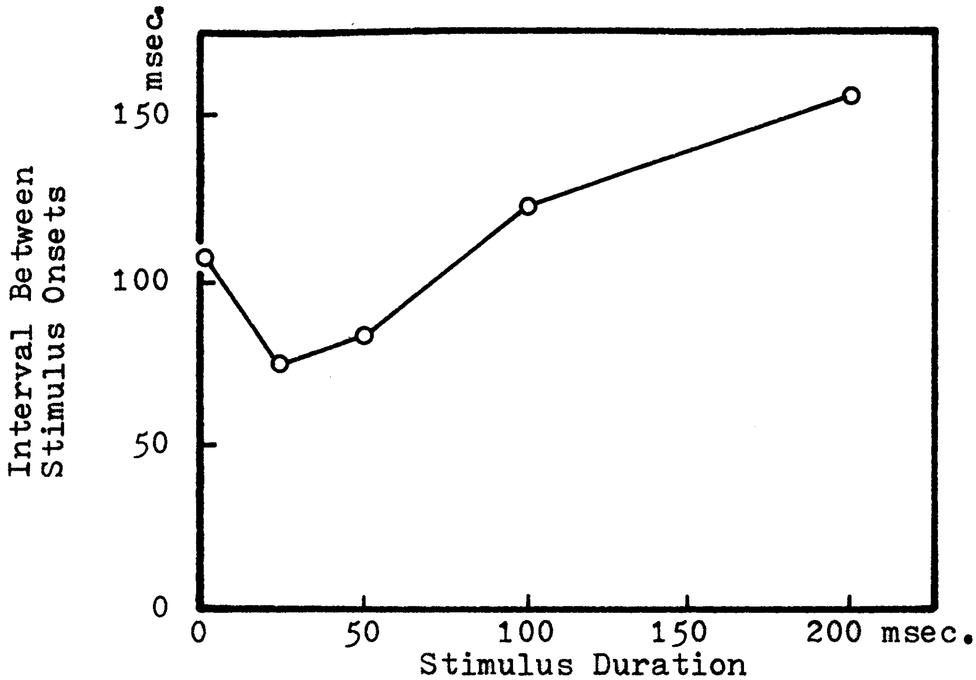


Figure 2-- Plot of stimulus onset interval against stimulus duration for optimal apparent motion on the skin. (From(39))

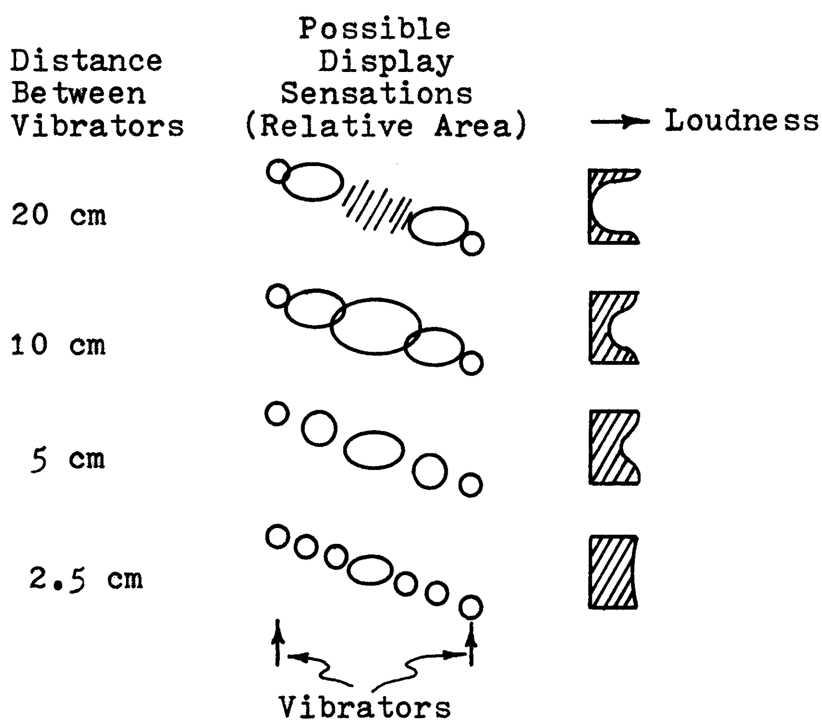


Figure 3-- When the distance between two vibrators is large, the phantom sensation midway between the vibrators is weak. The spread of sensation is large for large separation distances. (From (44))

D. Factors that Influence the Phantom Sensation

The phantom sensation that one experiences when the time delay is short is influenced by several factors. These will be briefly mentioned here. It has been reported that subjects need to "learn" to perceive this sensation. Alles reported that a large amount of learning takes place in the first day of practice with the sensation[1]. At first, as the time delay, or the relative amplitudes of the two stimulators were varied, the sensation jumped from side to side. After some learning, this movement changed to a "creeping sensation". After two or three weeks, a continuous motion was perceptible as the relative intensity or time interval was varied[41].

In past studies, the type of vibrational stimulation was an important parameter. Subjects seemed to prefer a sine vibration of at least 100 hz[1]. This frequency is below the frequency for the lowest threshold (250 hz). In the Alles study, 100 hz was chosen as a trade off between adaption to vibration, which increases with frequency and the sensitivity to vibration which also increases with frequency up to 250 hz. A click type onset of stimulus enhanced the phantom sensation and a short (5 msec.) pulse duration helped prevent adaption[1]. It was easier to make observations of localization with a series of clicks than a single set of clicks[41]. A repetition rate of 20 - 30 pulses per second was preferred by some subjects[1]. The phantom sensation could be localized precisely even when noise is present in the presentation[41]. Reimers[32] found that pulsed stimulation (50 msec. of 100 hz vibration, then no stimulation for 450 msec.) prevented adaption. The sharp onset of the pulse aided the subject's localization of the phantom.

For precise observation of the phantom sensation produced by time delay, the magnitude of the sensations must be equal for both stimuli when presented alone[41]. When there is an imbalance in magnitude, the phantom sensation is displaced toward the louder stimulus and an increase in the time delay of the louder stimulus is necessary to center the phantom sensation[18].

As was mentioned, amplitude can be used to create the phantom sensation when no time delay is present. Ratios of intensity of 1:2 to 1:8 have been needed to localize the sensation under one stimulator[38]. Alles reported that the sensation works well with amplitude variation alone.

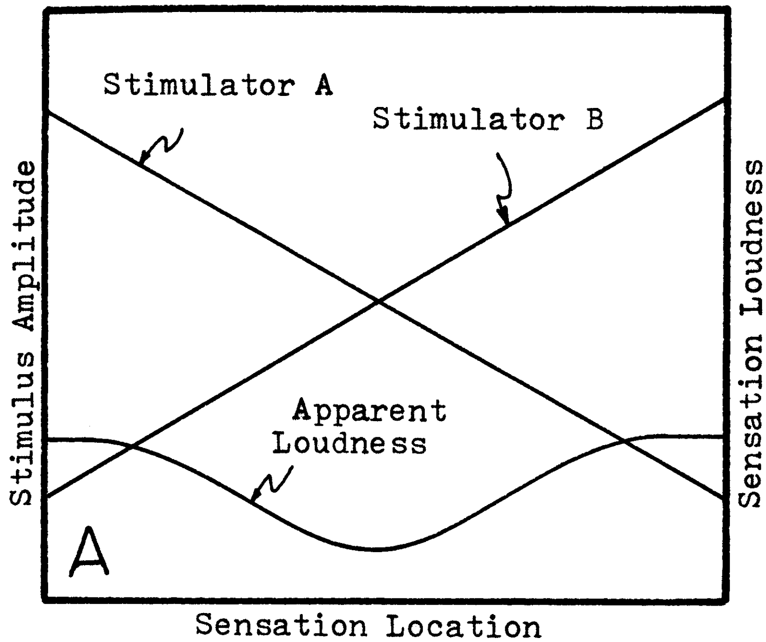
The distance between the two stimulators effects the phantom sensation. When the sensation is located midway between the stimuli, it is widely spread; near the stimulators it is more sharply defined. Figure 3 presents Von Bekesy's representation of relative loudness between the stimuli as a function of distance. Placing the vibrators too close lessens subject's ability to discriminate where, in between the stimulators, the sensation is. If the vibrators are too far apart, the center drops out of the perception and two stimuli are felt. Alles found that a stimulator distance of 4 to 5 inches was best for the upper arm.

Alles varied the relative amplitudes of the stimulators logarithmically (see Figure 4-B) instead of lineraly, as was done by Von Bekesy (see Figure 4-A), to keep the intensity of the phantom more constant as it traversed from one stimulator to the other. The maximum amplitudes used in the Alles experiments were about 30 db above the vibro-tactile threshold.

Certain areas of the skin are more sensitive than others. This difference in sensitivity can have an effect on the position of the phantom sensation. Naturally, the sensation will be moved toward the area of greater sensitivity when dissimilar areas are stimulated. It is interesting to note that the position of the phantom sensation can be altered by warming or cooling the skin under one stimulator[41]. Also, the phantom sensation will be more sharply produced if the stimulators are as far from the bones as possible[1].

E. <u>Electrical Stimulation of Phantom Sensation</u>

This phantom localization can be produced by electrical stimulation also. Under certain circumstances, the electrical stimulation can be indistinguishable from mechanical vibration[1]. Electrical



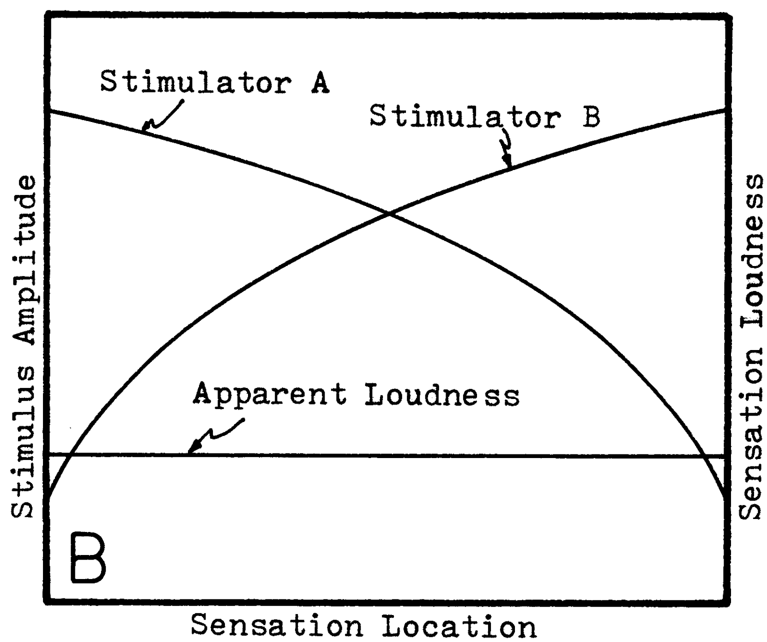


Figure 4-- (A) Linear variation of the relative amplitudes produces a lower intensity in the middle. (B) Logarithmic variation provides a uniform loudness. (From (1))

stimulation has been reported to be more difficult to fuse than vibrational stimulation[42]. Electrical stimulation will also produce the apparent motion sensation[39].

F. <u>Phantom Sensation Sensed External to the Body</u>

We seem to localize sensations that are on the retina and/or in the cochlea as somehow being outside the body. The more we are trained to project external sounds outside the body, the easier it is to inhibit internal body sounds. An example, given by Von Bekesy, of this is that we don't hear the tremendous pressure of blood flowing through the cochlea as the heart beats[41].

An example of free space perception is the blind traveler using the long cane. The cane becomes an extension of the body and the location of its end is somehow sensed without touching it. After practice, clicks on the skin of some observers produced a sensation of the stimulus as being somehow outside the body[41]. In experiments intended to duplicate the directional hearing of the ear using two "models of the cochlea" placed on the skin, subjects reported to "feel" the sound source that triggered the vibrating models as being outside the body[43]. When the phantom sensation was attempted using two vibrators placed one on each knee of a subject, after a time of training, the subject was convinced he felt the sensation in mid air between his knees[41].

G. Funneling Theory of the Phantom Sensation

Von Bekesy has proposed a theory explaining this phantom sensation[41]. His theory, which is based on the processes of inhibition, summation, and funneling in the human sensory system, will be given briefly here.

Inhibition, a sensory process that lessens the perception of stimuli due to stimulation at another location, has the basic role of limiting the amount of information that is transmitted to the higher centers. (When an observer is given too much information he may become confused.) There are several ways of reducing the amount of information flow. The simplest is to reduce the sensitivity of the receptors. Adaption is such a means of reducing inflow of information. Compensation, a system which only relates information when it is not at the normal (equilibrium) point, is also a suitable method of limiting information. Summation, a system that increases the signal of one stimulus because of the presence of another, also has a role in presenting more pertinent information. Funneling, which channels and condenses information, is also important in information reduction. The human body exhibits all of these phenomena to reduce and compress the vast information that is in the external world.

Von Bekesy claims that this inhibition occurs through the operation of well defined neural pathways[41]. In a cross section of the skin we find nerve fibers that go directly to the ganglion cell and also fibers that run parallel to the surface connecting two or more end organs with each other. By means of these neural paths, the end organs can be inhibited in four ways as shown in Figure 5; laterally, forward, backward, and from the central nervous system[41]. This inhibition can act on vibrational stimuli.

A good example of lateral inhibition is when a vibrating pin sets up a traveling wave on the skin. There is significant vibration of the skin around the pin, but only the vibration under the pin is felt[41,43,47]. Lateral inhibition is witnessed in vision in the suppressing of reflected light and also in the phenomenon of Mach bands. The Mach band overshoot and undershoot sensation is observed on the skin for both pressure and vibration. This effect is shown in Figure 6. Often, the undershoot sensation gives the impression that there is no existence of the skin in that area at all[41].

When sensations add or reinforce each other, the process is called summation. A direct example of summation is more difficult to isolate than the previous inhibition example. Perhaps the following will suffice. When several stimuli are simultaneously vibrated on the body at different locations, each with the same magnitude of stimulation, subjects have perceived an increase in the magnitude of stimulation as compared to the magnitude of a single vibrator[11]. (See Figure 7). The loudness

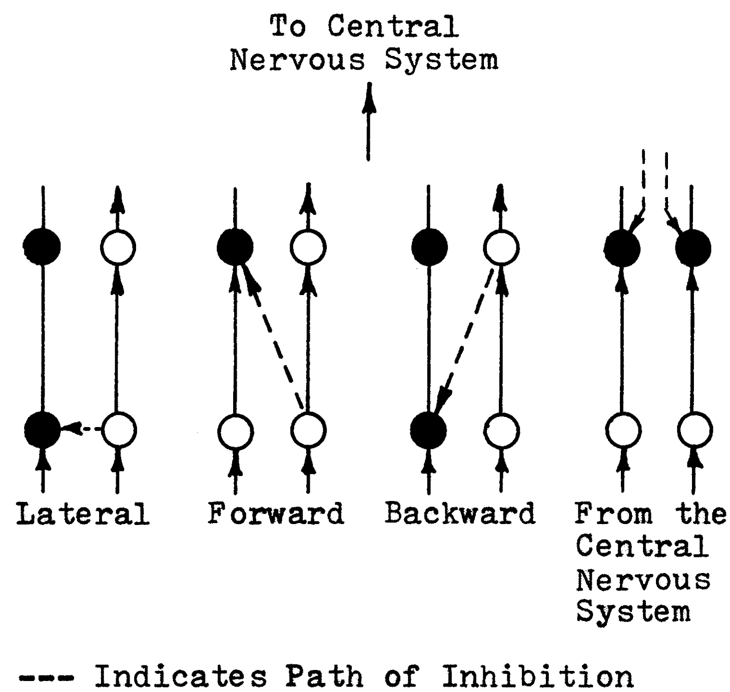


Figure 5-- There are four types of inhibition: lateral, forward, backward, and from the central nervous system. (From (41))

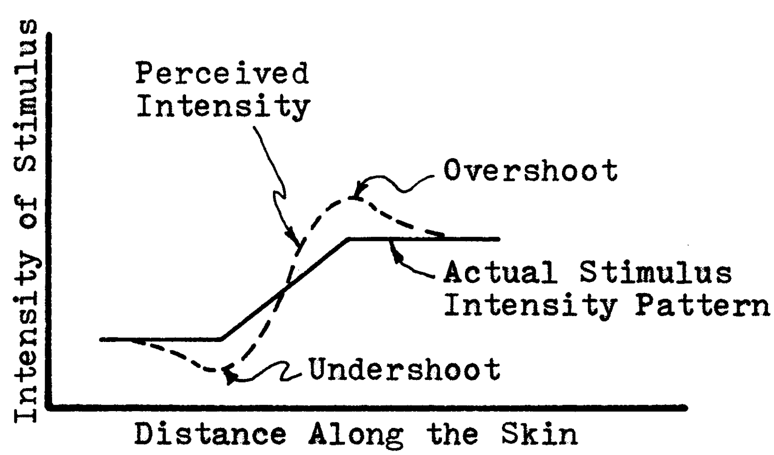


Figure 6-- Mach band type overshoot and undershoot of sensation is experienced on the skin. (From (44))

of this multi-stimulus display was ascertained by having the subject match it with a separate auditory stimulus. For loudness summation, the type of vibration, the distance between the vibrators, or loci on the body made little effect[11].

When both summation and inhibition operate to sharpen the input of a stimulus, the process is called funneling. Funneling inhibits the smaller stimulus effects and collects the stronger effects into a single neural pathway[41]. A similar phenomenon occurs with two stimuli presented one after the other by a certain time delay. Von Bekesy claims that this funneling action is the basic mechanism by which the phantom sensation operates.

A simple conception of funneling can be gained by examining Figure 8, which gives a simplified representation of the interaction of two stimuli. Part A of Figure 8 shows the stimuli presented to the skin. Part B represents the excitation and inhibition caused by these stimuli. In part C the two stimuli are close together and are summating. As the distance between the stimulators increases, the inhibition increases as depicted in part D. The two sensations finally begin to become separate as shown in part E. The above pattern can be sensed using two stationary pressure points[41,45]. The critical distance at which inhibition takes over in such a display becomes wider if sharp clicks to the skin are used[45]. Von Bekesy demonstrated this funneling

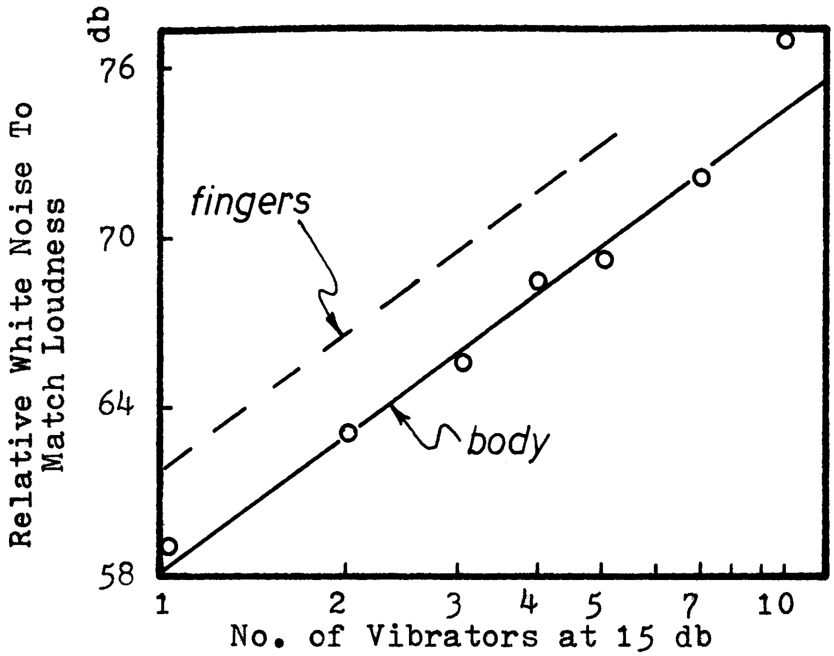


Figure 7-- White noise level needed to match the loudness of multiple vibrators on the body. (From (11))

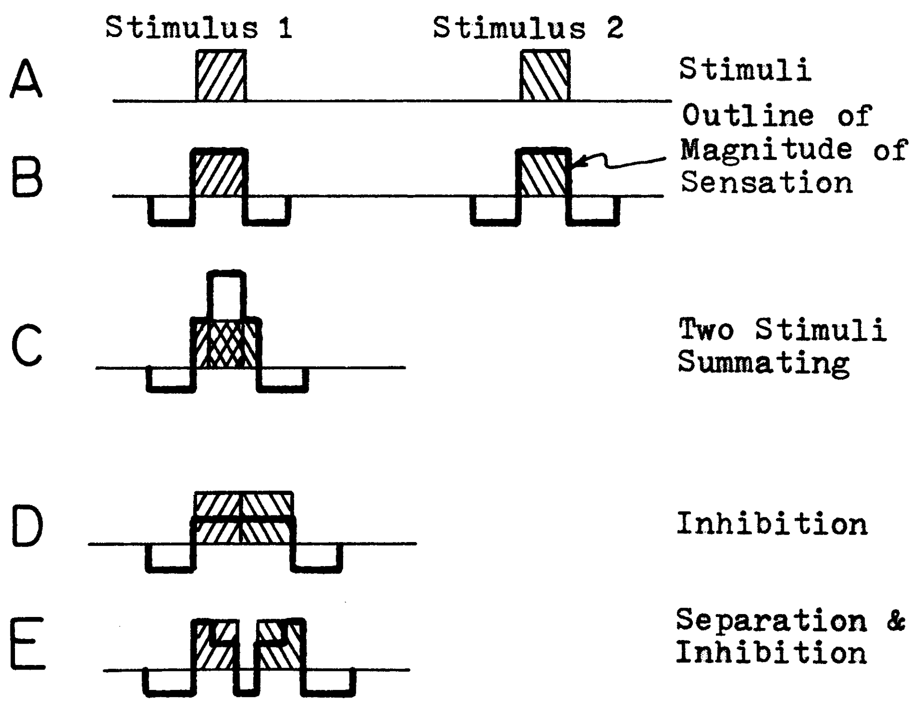


Figure 8-- Effects of combining two neural stimuli on the skin. (Adapted from (41))

by stimulating the arm with five vibrators, each at a different frequency. After ten seconds, only the middle vibrator could be sensed considerably louder than when presented alone and at the same frequency as when alone. The other vibrators added magnitude to the center stimulus but their own pitch was supressed[41,46].

As was mentioned, it is felt that the phantom sensation is a product of this funneling action. When the phantom is localized directly under one of the stimulators, shutting off the suppressed stimulator decreases the sensation[41]. Even when one stimulator is not felt because of adaption, it will interact with another stimuli[1].

There have been studies that seem to contradict this funneling explanation of the phantom sensation. One work suggests that localization of the phantom had little to do with delay of stimulators[19]. Sherrick and Rogers argue that because the eye and the ear require the same interstimulus onset interval for optimum apparent motion, the apparent movement is perceived in the cortex and not at the receptor level[39]. Held[22] suggested the sensation could not be totally neural due to the fact that learning is involved in receiving a continuous phantom sensation.

H. Predicted Parameters of the Two-dimensional Phantom Display

Extending the results obtained from experiments with the one-dimensional sensation, several logical predictions were made concerning the two-dimensional system parameters. It was assumed that perception would be sharply defined at the actual points of stimulation and more spread along the edges and the middle of the triangle. To create a more uniform magnitude of perception throughout the area, it seemed that the relative amplitudes of the vibrators should be varied by some power function. Alles showed that time delay was not an especially effective means of creating the phantom display. This fact, coupled with the fact that the electronics involved in amplitude control is much simpler than time delay control, suggested that the experiments should be conducted using only amplitude variation. Other predictions were: (1) The frequency of stimulation should be about 100 hz. (2) The maximum amplitude should be about 30 db above the threshold. (3) The amplitudes should be adjusted to have equal sensation when presented individually. (4) The stimulation should be pulsed, "on" for a short time (50 msec.), then "off" for approximately 200 msec. (5) The stimulators should be placed somewhere between three and six inches apart.

III. PRELIMINARY DESIGN, EQUIPMENT AND EXPERIMENTS

A. Electric Stimulation on the Skin

Electrical stimulation and vibrational stimulation often arouse similar touch sensations and often exhibit similar interaction between stimuli[1,20]. For mobility display purposes, direct electrical stimulation of the skin has several appealing factors. It is not impeded by its own mass as is the case with vibrational stimulators. Power requirements for an electrical stimuli are less than one percent required for mechanical stimuli[20]. And lastly, electrodes are relatively easy to attach to the body.

The primary problem with electric stimulation is pain. There are two thresholds: a threshold of feeling, and a threshold of pain. Once the electrical pain threshold has been exceeded, it sensitizes the receptors so that the pain threshold is lower than the feeling threshold for several hours[1]. This is probably caused by dielectric breakdown of the skin. Painless stimulation has been reported by using very brief d.c. pulses[10,20]. It appears that temporal properties of the signal determine whether touch or pain is arroused. Collins and Saunders[10] measured the electrical resistivity of the skin to be 15-40K ohms, and found comfortable stimulation in 4-20 microsecond pulses spaced every 2 milliseconds and presented at a rate of 25 hz. The stimulation was comfortable at about 6 ma, but pinch or pin-prick pain was observed if current exceeded 20 ma. Von Bekesy[42] reported that the phantom sensation is more difficult to fuse by electrical stimulation. Because of sweat, electro-dermal conditions vary widely. The above facts, coupled with the fact that pain is a real factor to be contended with, made vibrational stimulation of the skin more appealing for this study. Also, electrical stimulation would limit the type of input to brief d.c. pulses.

B. <u>Vibrational Stimulation of the Skin</u>

Vibrational stimulation, of course, is not without problems. Vibrators are bulky and inconvenient to couple to the body in a manner which successfully avoids intensity variation with body movement[20]. Waves, set up by vibration, are complex due to the varied resilience in layers of the skin. Bones and joints also cause problems because bones transmit pressure waves well and joints have sensors that tend to disrupt vibrational sensation of the skin[41]. While these problems exist, they do not present the danger of pain to subjects. Proper design of the stimulators and proper choice of location for stimulation can overcome these problems. Traveling waves can be minimized by surrounding the point of stimulation by a fixed plate[1].

Of course, the primary advantage of vibro-tactile stimulation is the fact that it requires no special precautions with regard to pain. As one author[43] reported, the skin can withstand relatively rough treatment.

Although vibration was chosen as the mode of stimulation for this study, the "portability" of electrical stimulation would suggest that some future study should investigate its applicability to mobility aids.

C. Symmetry Restriction for Input Area

The field in front of a blind person is symmetrical; objects in his path are either straight ahead, to the left or the right. (See Appendix 4 for a description of a hypothetical scanning device as it would be coupled to the two-dimensional phantom sensation.) It is reasonable that any tactile location chosen for input of information about objects in the path of travel of a blind person should be symmetrical on the body. This would not only minimize concentration during travel, but also would make the training task easier since a stimulation to the right of the midline would indicate an object to the right, etc. This symmetrical restriction limited the possible locations for input to the torso or the forehead.

Although the skin of the forehead is sensitive, there is relatively little fatty tissue. As discussed by Alles[1], the phantom operates best when the points of stimulation are as far as possible from bone. The forehead is also a poor location for cosmetic reasons.

D. Threshold Experiments on the Torso

With the forehead eliminated, the possible input locations were the lower and upper back, the breast, and the abdomen. To obtain an indication of the vibrational sensitivity of these locations, simplified vibrational threshold experiments were conducted at various locations. The equipment used in thesis tests is described in Appendix 1-A. One of Alles' vibrators driven by a signal generator at 100 hz was used for stimulation. A Decker system (902-1,2), which was coupled to a variable capacitor mounted on the vibrator, gave an output voltage proportional to the vibrational amplitude. Before the tests were conducted, the system was visually calibrated using stroboscopic light and a calibrated hairline microscope. The threshold, for these simplified experiments, was defined as the point when the subject first felt the stimulation. Threshold experiments conducted in this manner, usually give results slightly lower than the two-choice, forced-choice (TCFC) method. Figure 9 compares the threshold findings on the arm to those values listed by Alles who used the TCFC method. As predicted, his data was slightly higher.

Figure 10 presents the results of the experiments conducted on the torso. The thresholds on the back were about twice those on the front. The threshold on the upper back and chest are relatively uniform, while the threshold increases slightly on the lower torso. The

Table 2-- Weinstein's[48] Tactile Thresholds on the Body.

	Sex	Belly R	Belly L	Back R	Back L	Arm R	Arm L	Palm R	Palm L	Units
Pressure	M	2.7	2.8	2.9	2.9	3.1	3.0	3.2	3.1	log (.1mg)
	F	1.8	1.9	1.9	1.9	2.0	1.9	2.6	2.4	"
Two-point	M	36	36	41	39	44	46	11	11	mm
	F	32	33	42	40	42	41	12	12	mm
Point Localization	M	8.7	8.0	12.4	11.1	10.4	11.0	5.5	5.5	mm
	F	9.0	8.5	10.0	10.6	10.2	10.2	8.8	8.0	mm

R=Right L=Left

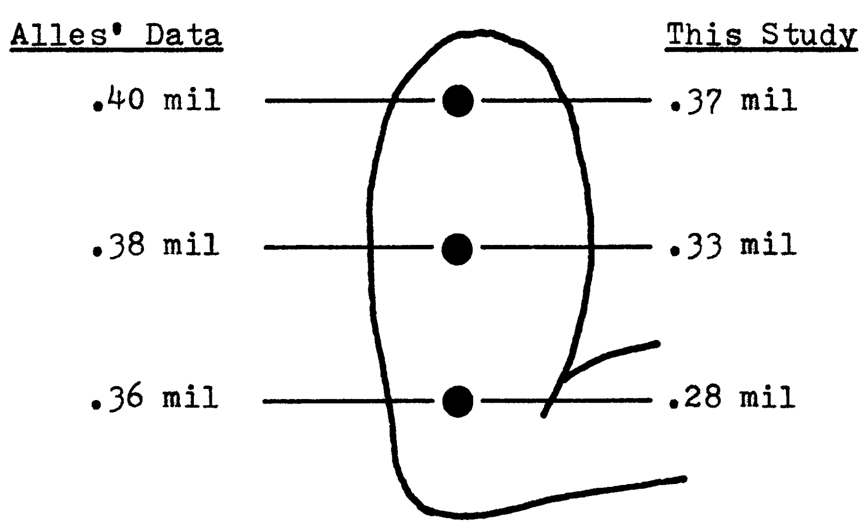
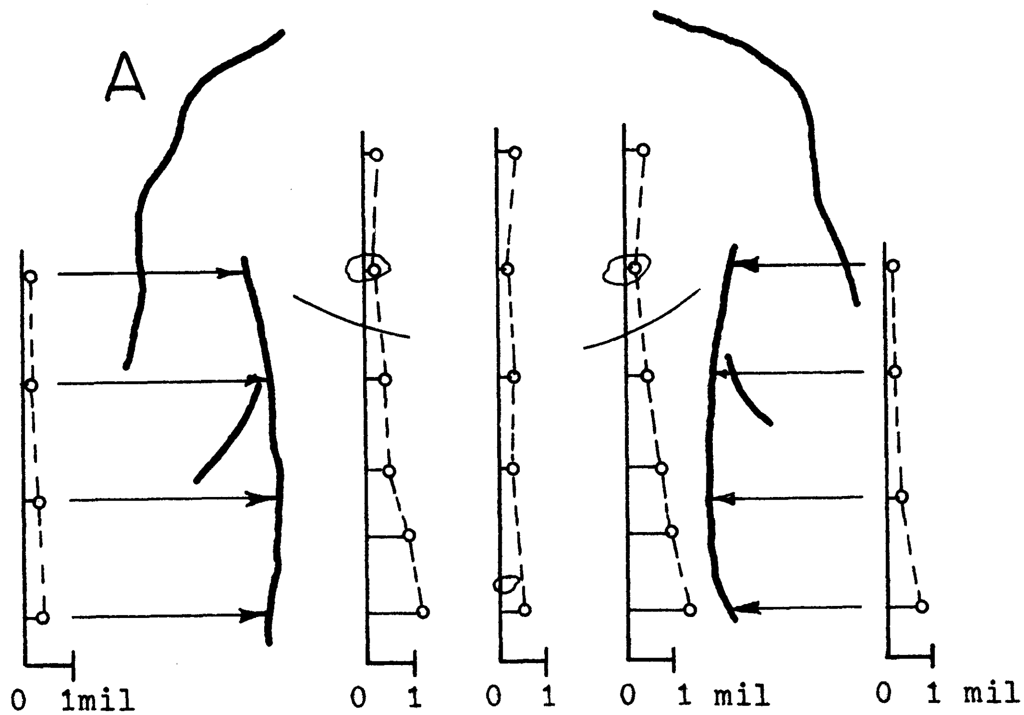


Figure 9-- Comparison of Threshold experiments on the Arm.



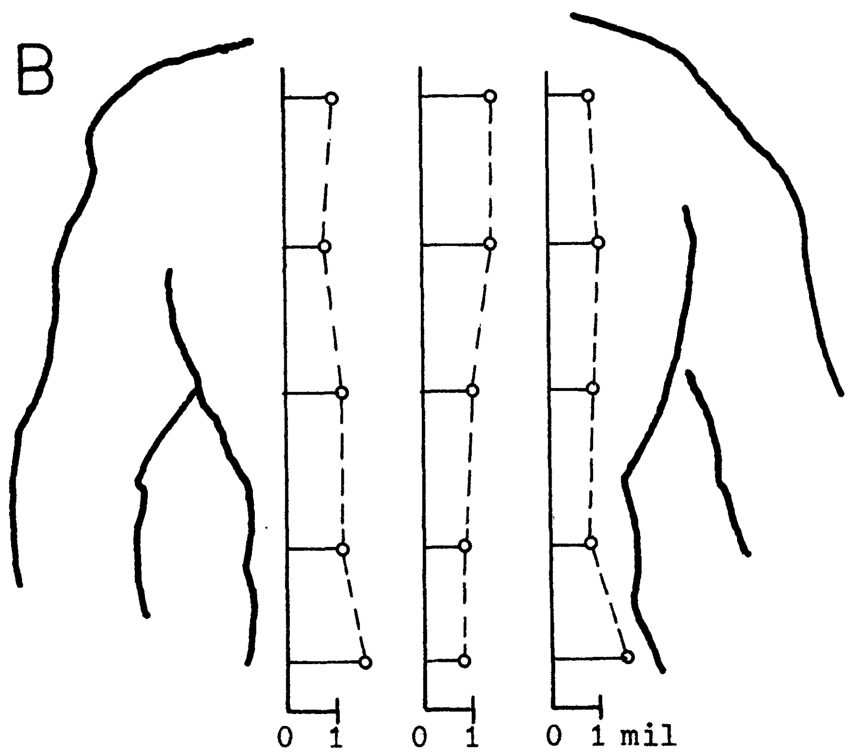


Figure 10-- Threshold of 100 hz stimulation on the torso. (A) Front. (B) Back.

sides of the torso seem to have about the same sensitivity as the arm, while the abdomen is slightly higher. The data suggested that the abdomen or chest are better locations for vibrational input.

Weinstein[48] presents a comprehensive listing of three different thresholds for various body locations. The thresholds are: (1) two point threshold (defined as the minimum distance required between two contactors in order for them to be perceived as two), (2) pressure sensitivity threshold, and (3) point localization threshold (defined as the minimum distance at which a subject can distinguish the location of a single contactor from the location of a previously presented contactor). In all but one of the cases, the abdomen thresholds were slightly lower than for the back. Table 2 presents Weinsteins results. Again, this data indicated that the front is more sensitive than the back.

E. One-Dimensional Phantom Sensation of the Torso

Using Alles' stimulators (shown in Appendis 1-A) and the equipment described in section I of this chapter, a one-dimensional phantom sensation was investigated at various locations on the torso. The intention of these experiments was only to demonstrate the existence of the one-dimensional sensation at these locations. The vibrational parameters were adjusted to comply with the specifications listed at the last of Chapter II. The maximum amplitude used was .030" peak to peak which is

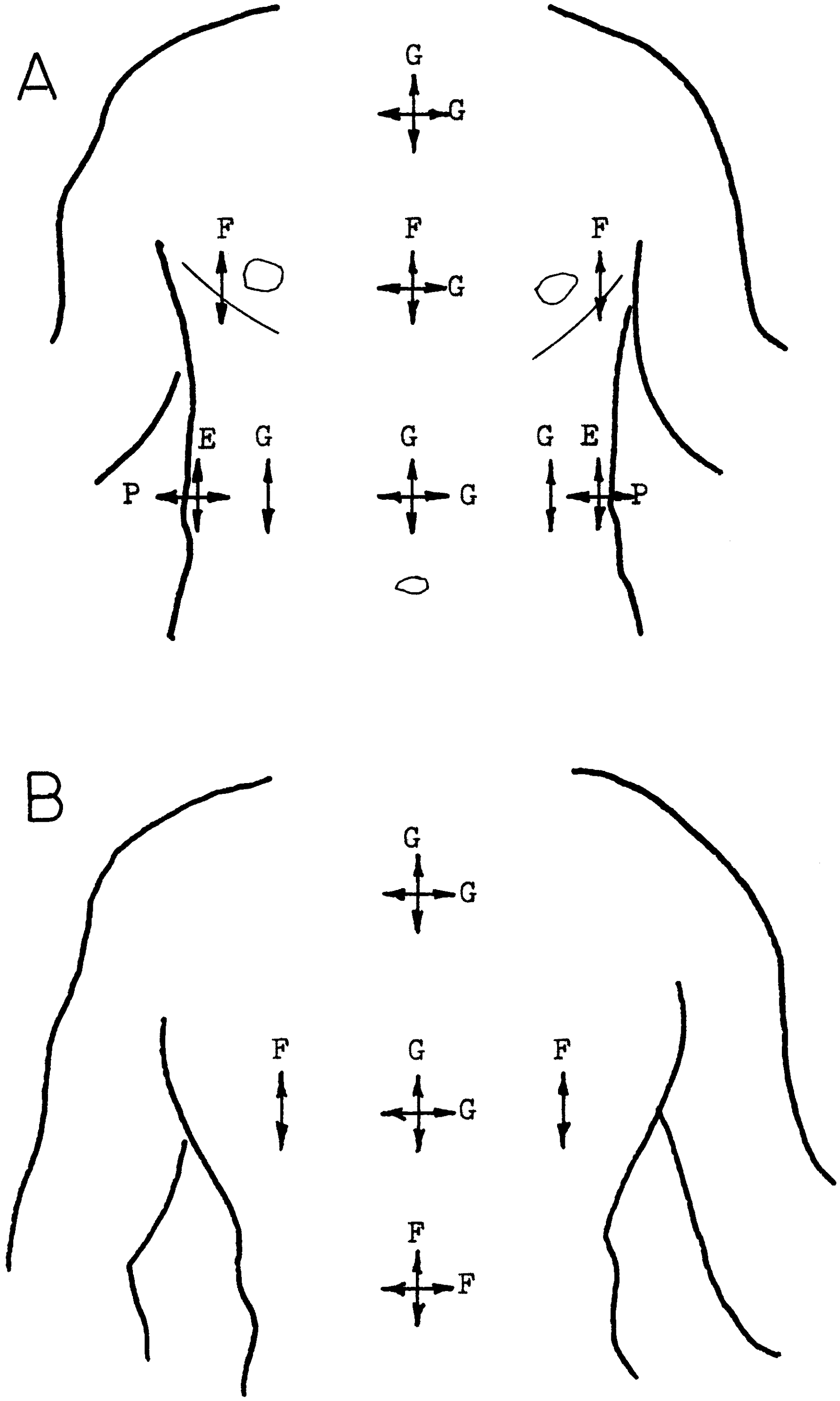


Figure 11-- Perception of the one-dimensional phantom on the torso. (A) Front. (B) Back. Code: E=Excellent, G=Good, F=Fair, and P=Poor.

about 35 db above threshold on the stomach and sides and 30 db above threshold on the back. The quality of fusion and motion of the phantom were classified into four categories: excellent, good, fair and poor. The results of this experiment (shown in Figure 11) indicated that the sides, the upper back and the abdomen are good locations for input.

Obviously, the only location on the torso away from bones and joints is the abdomen.

F. Choice of Location on the Body for Input

Based on the results from the previous section, the abdomen was chosen for input during this study. Figure 12 shows the approximate locations.

G. Vibration Parameters for Phantom Stimulation

Alles conducted a detailed investigation on vibrational stimulation of the skin. Some of the design criteria he suggested are:

1. Motion of the stimulator should be parallel to the skin but not slide relative to the skin.

2. The maximum amplitude required to produce the phantom should be on the order of 20 db to 30 db above threshold.

3. A frequency of 100 hz pulsed for short intervals produces the phantom without excessive adaption.

4. The skin around the point of vibration should be covered with a stabilizer baseplate to prevent the transmission of surface waves.

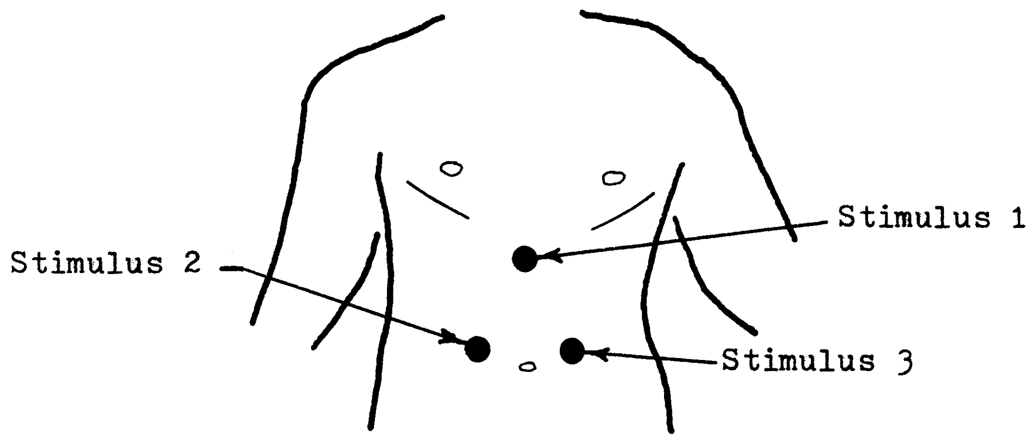


Figure 12-- Approximate choice of location for two-dimensional phantom sensation.

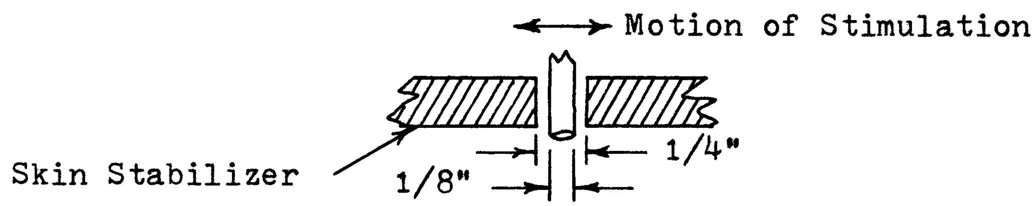


Figure 13-- Vibrator tip passes through 1/4 inch hole in stabilizer plate.

5. The skin impedence is spring dominated in the frequency range of interest. Measured spring constant was .44 Lbf. per inch.

6. The vibrational contactor tip should be pressed against the skin with a pressure less than .54 psi to prevent reddening of the skin under a static load. There also should be no relative motion between this tip and the skin.

7. The baseplate hole through which the tip passes should be small enough to prevent a "window edema".

8. The stimulator should have a spring dominated mechanical impedence higher than that of the skin to prevent excessive changes in the stimulus due to small changes in skin impedence and also to prevent resonance of the total system.

H. Design of Stimulators

In search of a stimulator, a short investigation into piezoelectric bimorph reeds was conducted. Though reeds are extremely lightweight and require relatively little power, they were deemed unusable for this study primarily due to their fragility. Also, the reeds were easily overloaded by the skin, resulting in inadequate stimulation. The reeds, which were designed by Ellison et al.[14], supposedly matched the impedence of the skin and met the vibrational characteristics suggested by Alles. A photograph of the bimorph used is in Appendix 1-B.

Before designing and constructing an electromagnetic stimulator, the devices readily available on the commercial market were investigated. From among several solenoids and buzzers, a Potter-Brumfield (type BU, 24 volt) buzzer was found to have characteristics suitable for this experimentation. Assuming that the impedence characteristics of the skin on the abdomen is not radically different than on the arm (the tests using Alles' stimulators exhibited no marked differences on the stomach), the design criteria listed above were used to adapt the buzzers for use as stimulators. A plastic contactor tip one eighth inch in diameter was constructed. (If the area is too small, it can be painful; if it is too large, the localization of the stimulation is poor). A spring was designed to exert a force of approximately 2 to 3 grams between the tip and the skin. The stimulators were mounted on plexiglass in a triangular pattern. A $\frac{1}{4}$ inch hole through the plexiglass allowed contact with the skin. (See Figure 13). A pattern of these holes allowed variation in the distance between stimulators. (See Figure 14; further detail is given in Appendix 1-B).

I. Electronic Equipment

A detailed description of the electronic equipment used to drive the three vibrators is presented in Appendix 1-C. Basically, it consisted of a pulsed, square-wave generator and three power amplifiers controlled by a three-way logarithmic "joy stick". The purpose of the

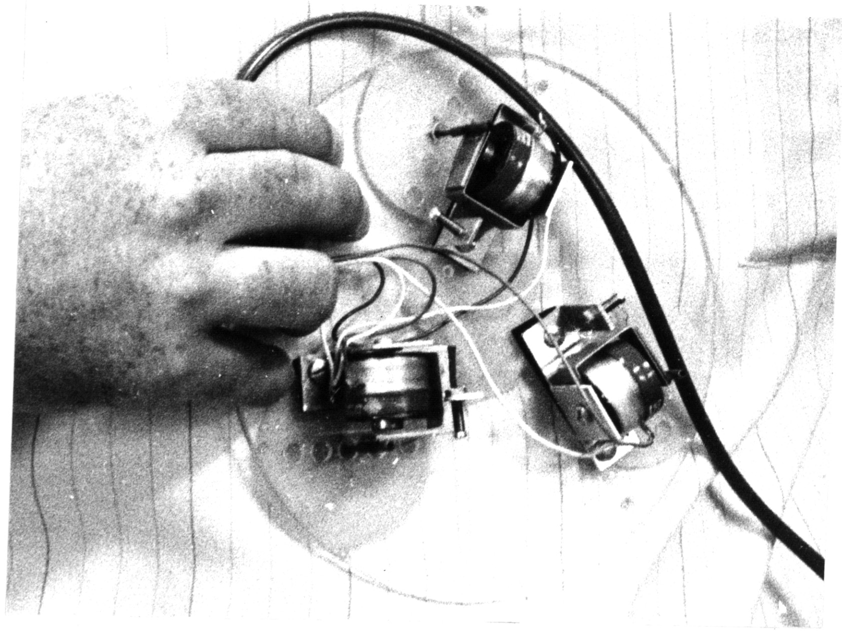


Figure 14-- Vibrators mounted on stabilizer baseplate.

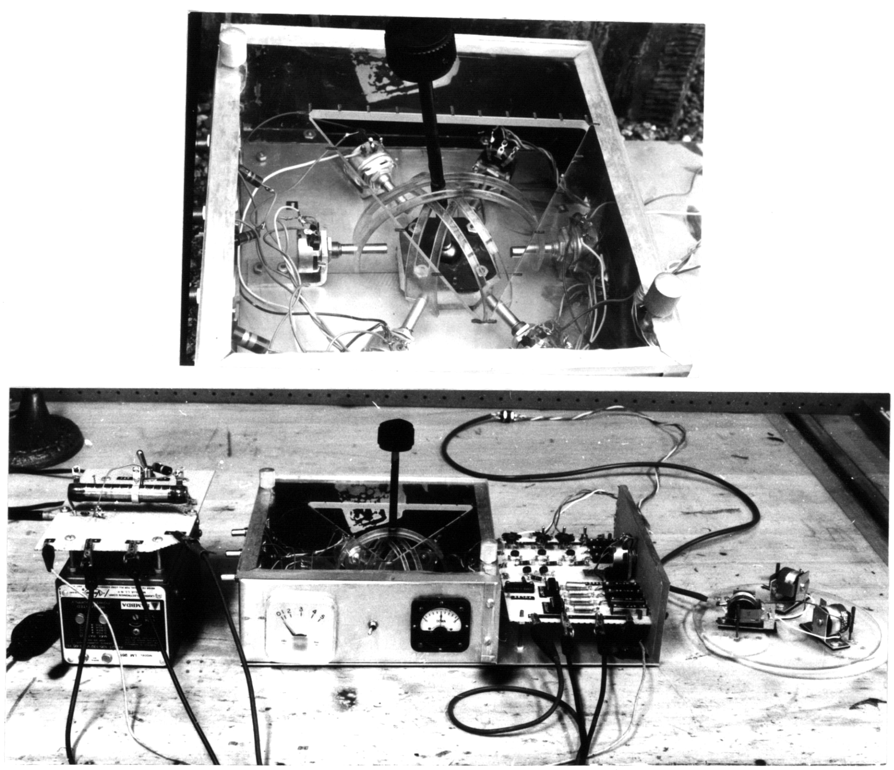


Figure 15-- Three-way logarithmic control ("joy stick").

joy stick was to allow simultaneous logarithmic variation of the amplitudes of the vibrators. The joy stick control is shown in Figure 15. The perpendicular distance from an edge of the triangle toward the opposite apex was the coordinate system used. With the controls located at one corner of the triangle, the corresponding vibrator was at maximum amplitude.

J. Preliminary Experiment with Two-Dimension Phantom

With the basic equipment constructed and adjusted to the appropriate stimulation parameters, a simple experiment was conducted on myself to determine the existence of the two-dimensional phantom sensation. With one hand, the vibrators were held so the three stimulators were in contact with the abdomen. The vibrators were adjusted to be equally loud when presented individually at their maximum amplitude (about 30 db above threshold). With all three stimulators operating, there was a definite phantom sensation as the joy stick control was moved along the edges of the triangle; the sensation was well defined at the apexes and of lower intensity and spread over a wider area between the apexes. The sensation in the center of the triangle was highly dispersed. It felt as if the entire baseplate was in vibration but somehow localized in the center.

K. Problems with Initial Equipment

Four problems became apparent from the above experiment. One was the poor sensation in the center of the display. It was felt this, perhaps, was caused by other equipment problems. There was transmission of vibration through the baseplate. This was especially evident when only one of the vibrators was receiving power. Another problem was non-linearity of the joy-stick control. The plastic restraining plate, a plane, was inappropriate to control the joy stick which operated in spherical coordinates. A fourth problem was the clear fact that the experimentation was not at all objective.

However, in spite of these problems, it was possible to create a sense of phantom motion in two-dimensions on the abdomen, which encouraged further experimentation.

IV. OBJECTIVE EXPERIMENTATION

A. Information Theory

The experiments in Chapter III on the two-dimensional phantom display were highly subjective. A review of information theory aided the planning of objective tracking experiments to determine the possible information transmission rates and the acuity of the display. A more detailed discussion of information theory is given in Appendix 2. Only a brief discussion is presented here.

When information is being transmitted via some communication channel, several processes take place. As depicted in Figure 16, there is information being supplied to the channel [H(in)], information being lost from the channel [H_{out}(in)], spurious noise being added to the signal [H_{in}(out)], and information coming out of the channel [H(out)]. With the aid of a Venn diagram, Figure 17, this process can be better visualized. From the diagram, it can be seen that the information transmitted is:

$$T(in,out) = H(in) + H(out) - H(in,out) \qquad (1)$$

For quantized information, only one discrete element out of a possible number of inputs (N) is transmitted at a time. The information transmission is easily calculated by forming a matrix of inputs and outputs for a particular series of in-out events. This "contingency table" is shown

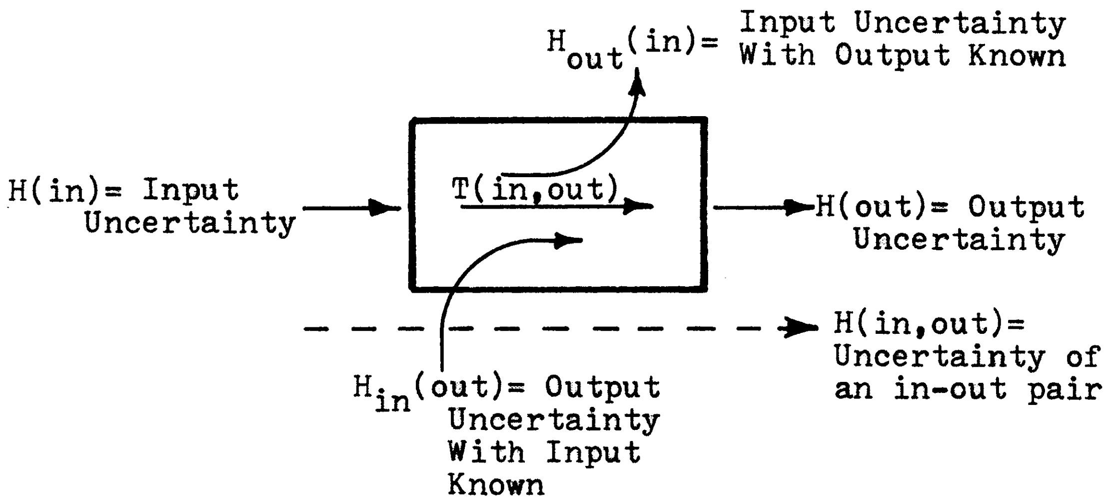


Figure 16-- Diagram of an information channel.

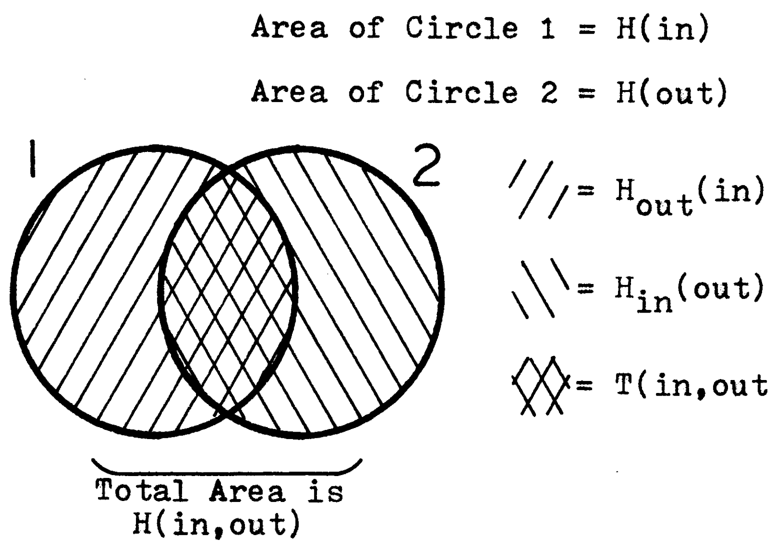


Figure 17-- Venn diagram of information channel.

in Figure 18. Each distinct input and its associated output are accumulated in the appropriate square of the matrix. Hence, for perfect transmission, all the accumulated numbers lie in the matrix diagonal. Since numbers in each square indicate the relative frequency of occurrence of a particular input-output event, the probabilities can be estimated. With these estimated probabilities, the parameters H(in), H(out), and H(in,out) can be computed, hence, the information transmission can be calculated. A simplified formula for the transmission is:

$$T(in,out)=\log_2 M-\frac{1}{M}\left[\sum^{i} n_i \log_2 n_i+\sum^{j} m_j \log_2 m_j-\sum\sum^{ij} n_{ij} \log_2 n_{ij}\right] \quad (2)$$

This equation is easy to use with an adding machine and tables of $\log_2 n$ and $n\log_2 n$ (See Appendix 2).

The information transmission rate is the product of the number of input-output events per second ($\dot{n}$) and the information transmitted:

$$\dot{T} = \dot{n}T(in,out) \quad (3)$$

The reliability of transmission is defined as:

$$R = H(in)/T(in,out) \quad 100\% \quad (4)$$

This fraction simply indicates how much of the original information was transmitted.

Input Locations

Output Response Locations	1	2	•••	i	•••	i=N	Sums of Rows
1	$n_{1,1}$	$n_{2,1}$	•••	$n_{i,1}$	•••	$n_{N,1}$	m_1
2	$n_{1,2}$	$n_{2,2}$	•••	$n_{i,2}$	•••	$n_{N,2}$	m_2
⋮	⋮	⋮		⋮		⋮	⋮
j	$n_{1,j}$	$n_{2,j}$	•••	$n_{i,j}$	•••	$n_{N,j}$	m_j
⋮	⋮	⋮		⋮		⋮	⋮
j=N	$n_{1,N}$	$n_{2,N}$	•••	$n_{i,N}$	•••	$n_{N,N}$	m_N
Sums of Columns	n_1	n_2	•••	n_i	•••	n_N	Total M=in-out Targets

Figure 18-- Contingency table for processing an in-out information experiment.

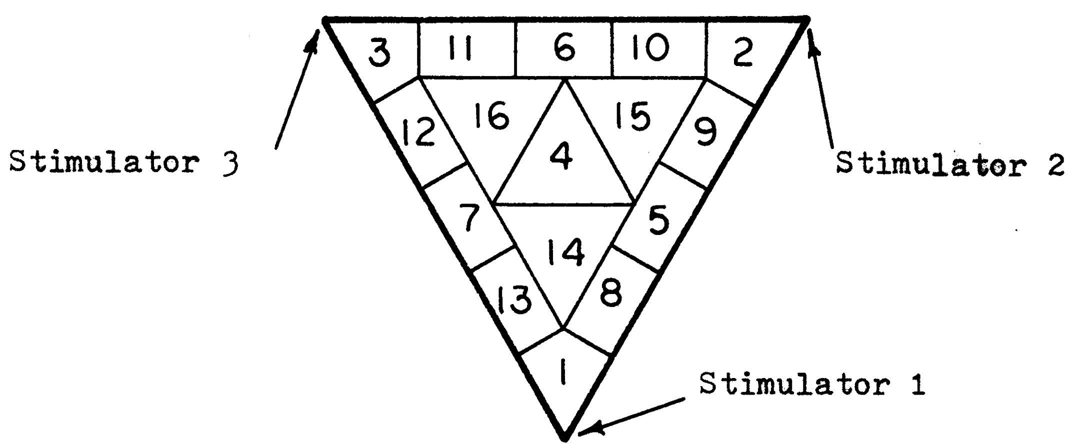


Figure 19-- Division of input triangle into quantized areas.

B. Division of Triangle into Areas

To permit a quantized tracking experiment, the area of the triangular display was subdivided. Based on previous experiments, it was felt that five positions along any edge of the display would be discernible. The dispersed sensation of the phantom in the center of the triangle indicated that the central areas should be larger. The final pattern chosen is shown in Figure 19.

C. Planning of Tracking Experiment

Using the quantized areas as a basis, a tracking experiment was planned. As shown in Figure 20, the experiment consisted of a random x-y input representing the quantized positions, electronics to control the relative amplitudes of the vibrators, a mechanism by which the subject can respond to the input, and a F.M. tape recorder. (An F.M. recorder can record d.c. voltages.)

This experiment is basically a step input to the subject. Sheridan and Ferrell[40] report that a typical human response to such a step is as depicted in Figure 21. The delay time is due to two factors: reaction time and neuro-muscular lag. A typical reaction time for visual inputs is about .15 seconds. A typical lag time constant is .1 to .2 seconds.

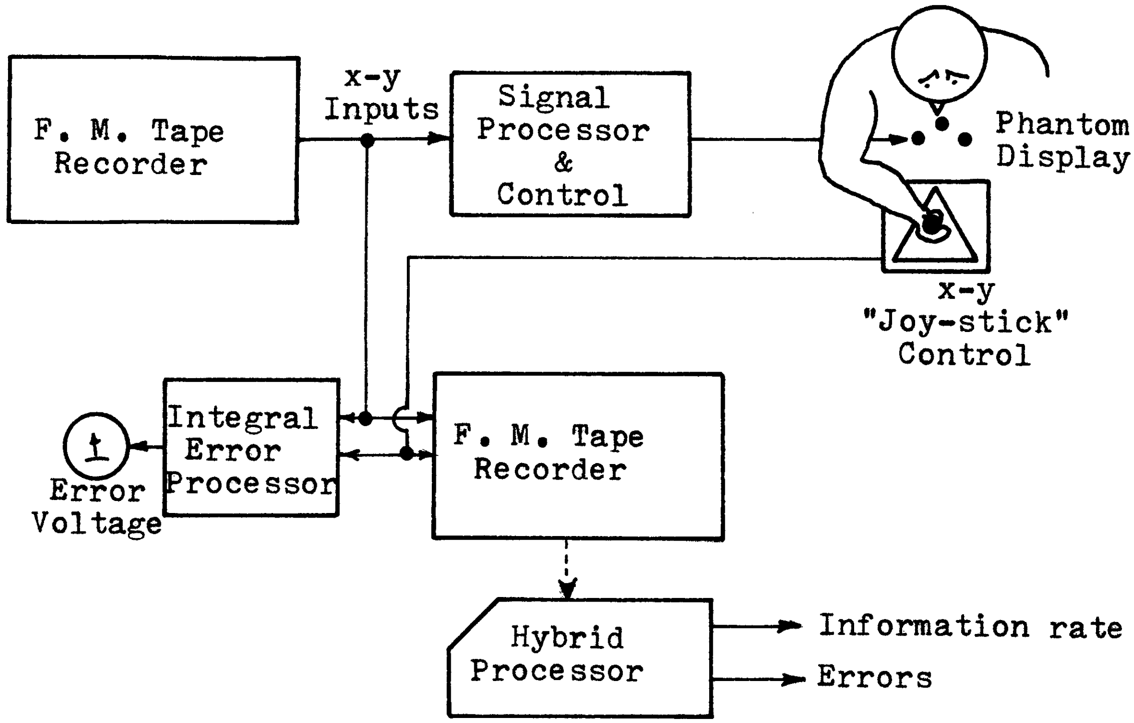


Figure 20-- Planned tracking experiment.

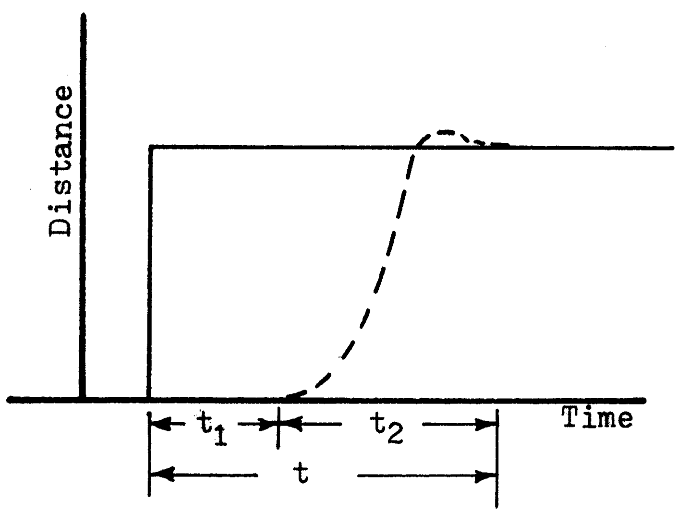


Figure 21-- A typical human response to a step input. t_1=reaction time, t_2=neuro-muscular lag time, and t=total response time.

D. Planning of Experimental Processing

Using hybrid computational methods, the experimental in-out signals can be fed to a digital computer. The system can be programmed to read the input and output signals at different times as controlled by a timing pulse from a separate track of the tape. By properly delaying the reading of the output signal, the input and output signals can be compared independent of the response time. The calculation of the information is straight forward once the in-out records are accumulated into memory.

Since the response time to such a tracking experiment is almost constant, another measure of the subject's ability to track the phantom is possible. If the input signal was delayed somehow, bringing the input and output signals into close correlation, the integral-absolute error between the signals should provide an indication of the ability to receive information.

V. EQUIPMENT IMPROVEMENTS

This chapter briefly discusses improved equipment and also computer programs used in tracking experiments on the two-dimensional phantom sensation.

A. Elimination of Vibrational Transmission

As was mentioned in Chapter III, transmission of vibration through the baseplate was a problem. Figure 22 gives a simple one-dimensional undamped model of the interconnection between the vibrators mounted on the baseplate. One vibrator is assumed to be in motion [y(t)]. This is a simple second order system with the equation:

$$\ddot{x} + \frac{k}{m}x = \frac{k}{m}(a + y_o \sin wt) \qquad (5)$$

The solution is (assuming $x(0)=0, \dot{x}(0)=0$, and $w_n = \sqrt{\frac{k}{m}}$):

$$x = y_o\left[\frac{\sin w_n t}{\left(\frac{w}{w_n} - \frac{w_n}{w}\right)} + \frac{\sin wt}{\left[1 - \left(\frac{w}{w_n}\right)^2\right]}\right] + a \qquad (6)$$

In this form, it can easily be seen that in order to isolate the vibrators, the natural frequency between stimulators due to the baseplate must be much lower than the frequency of vibration; a result identical to that listed in Den Hartog[12].

$$w_n \ll w \qquad (7)$$

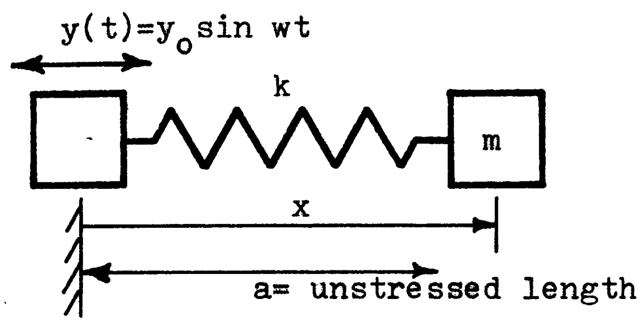


Figure 22-- One-dimensional model of interconnection between vibrators.

Because the masses (primarily the vibrator coils) had to remain constant, this result suggested that the only way to isolate the vibrators was to mount them on soft springs. This was a knotty task since it was also required to maintain a pressure on the baseplate normal to the skin and still be able to adjust the location of the vibrators.

The solution to this problem was a baseplate with extremely soft springs in the direction parallel to the vibration (parallel to the skin), but relatively stiff compliance perpendicular to the skin. Figure 23 is a photograph of the vibrator mount. Plans were made to mount the stimulators in a clothlike mount, perhaps a tee shirt, once the appropriate stimulator distance was determined.

The isolation frame effectively eliminated transmission. It also improved the phantom display as was

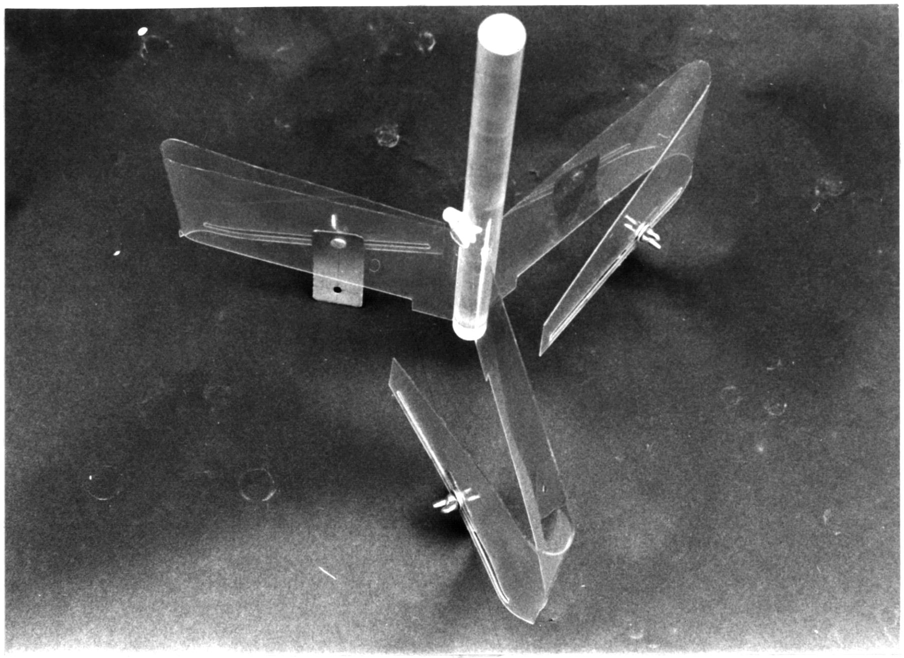


Figure 23-- Adjustable mount for vibrators. It is stiff in vertical direction; very compliant in horizontal direction.

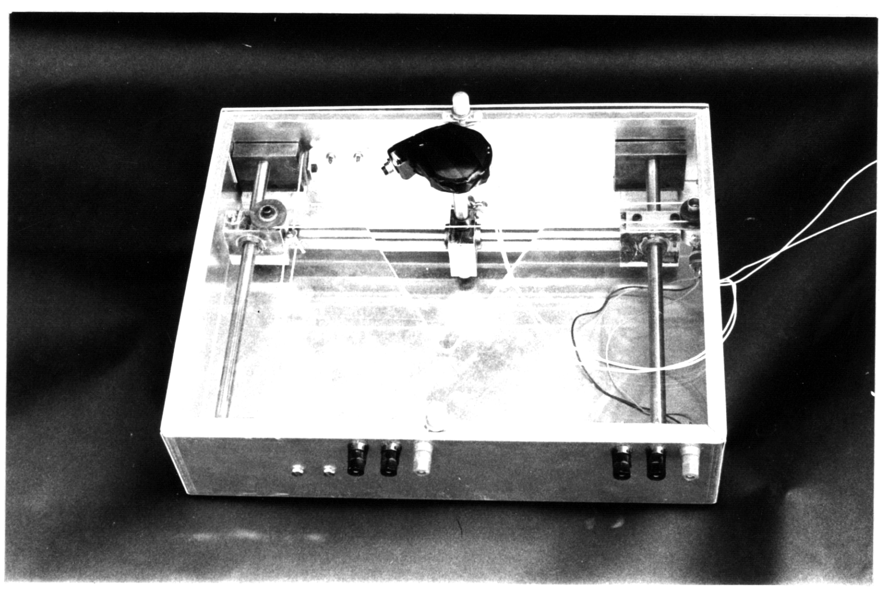


Figure 24-- x-y voltage control ("joy stick").

demonstrated by a simple tracking experiment. Out of the view of the subject, the input joy stick was varied and the subject responded to the stimulus by pointing to the perceived location. Along the edges of the triangular display the subject tracked the input well. The central area was tracked with moderate correlation.

B. Linear x-y Control

To eliminate any electric non-linearities in the response of the subjects, a better "joy stick" was constructed. The joy stick handle was supported by two sets of bearings: one set free to move in the x direction, and one free to move in the y direction. Cables attached to the handle operated precision ten-turn potentiometers for electric output of the x-y position. Figure 24 is a photograph of the mechanism.

C. External Control of Vibrator Amplitude

As mentioned previously, it was desired to be able to control the stimulators from an F.M. tape recorder. The electronics used to do this are briefly mentioned here.

As mentioned in Chapter III, the amplitude of each vibrator was controlled as a function of the perpendicular distance of the input position from an edge of the triangle. This somewhat confusing coordinate system is shown in Figure 25. The coordinate R (right) indicated how far from the 1-3 edge the input position is toward apex 2. Coordinates L and T were similar. Since only two

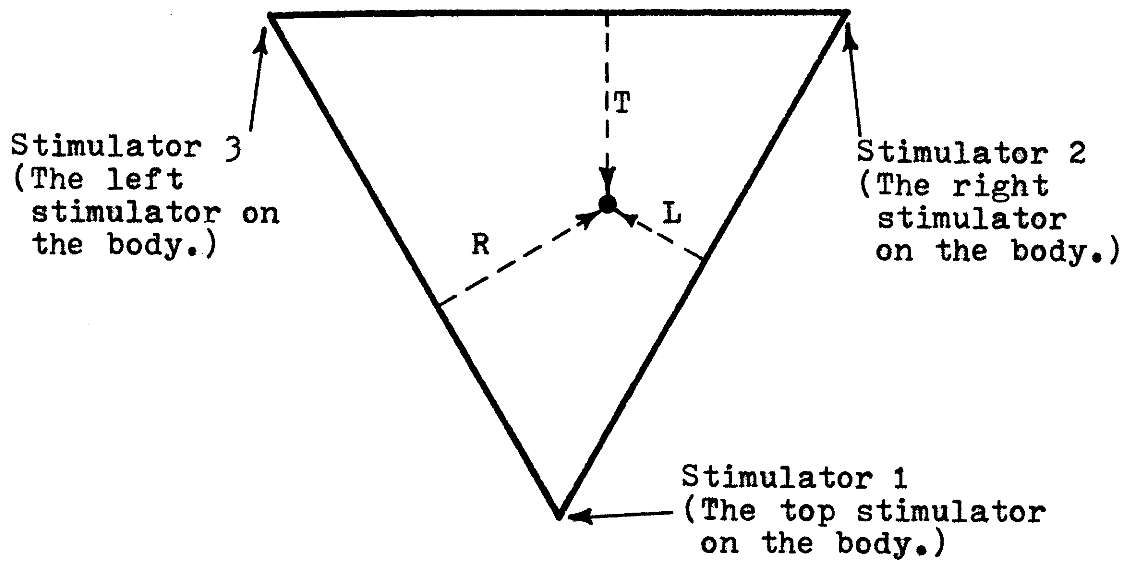


Figure 25-- Coordinate system (R,L,&T) used in the control of each stimulator.

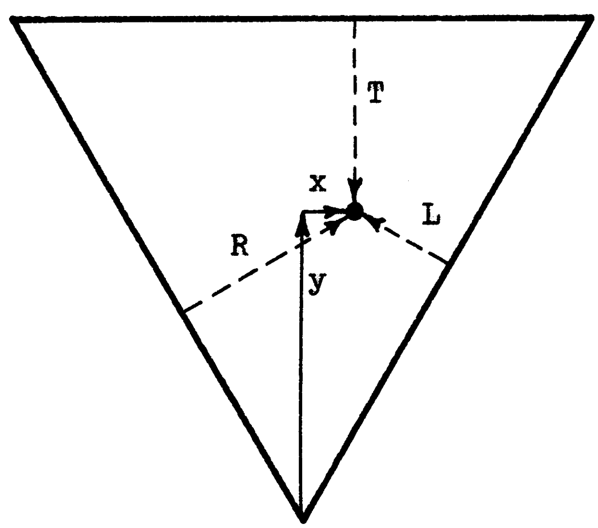


Figure 26-- Geometric conversion from x-y coordinates to the R,L,&T system.

coordinates are really required to specify any position in a plane, one of these coordinates was redundant.

A geometric conversion from x and y coordinates to these R,L, and T coordinates (see Figure 26) gave the following relations:

$$R = x \cos 30 + y \sin 30 \tag{8}$$

$$L = -x \cos 30 + y \sin 30 \tag{9}$$

$$T = A - y \tag{10}$$

Since addition and subtraction of voltages is extremely simple using operational amplifiers, a circuit was designed to model the above conversion equations.

With voltage inputs, it was no longer feasible to use logarithmic potentiometers for the gain control to the vibrators. Three operational amplifiers with diode feedback were used to convert the linear R,L, and T signals to their logarithmic equivalents. Field Effect Transistors operating in their variable resistance range were used to multiply the signal from the pulser and the logarithmic R,L, and T amplitude signals. A pulsed, logarithmically-controlled output to the stimulators was obtained. The overall circuit is given in Appendix 1-C.

D. Amplitude Measurement

An experiment described in Appendix 1-D correlated the amplitude of the vibrators with the d.c. voltage drop across the buzzer coils.

E. Other Circuitry

Two other circuits were constructed for use in the experiments (detailed in Appendix 1-C). One circuit compared the input and output signals and computed the integral of the absolute error. The other circuit was an analog-to-digital quantizer which was used to operate an array of individual stimulators. The individual stimulators were used to provide a comparison to the phantom display.

F. Production of Tracking Tape

A hybrid (digital and analog) computer was used to produce tape recordings of x-y inputs for tracking experiments. A flow chart of the program is given in Appendix 2-B. Basically, the program generated a random number, converted the number to one of the sixteen areas listed in Figure 19, and then commanded the analog computer to x and y voltages representing the area chosen. The system then waited at these voltages for a time corresponding to the appropriate target rate, and then repeated the above process. This continued until the desired number of targets had been produced. A pulse for synchronization was recorded on a separate track.

A method for automatic processing of the tracking experiments was created. This program was later abandoned for reasons to be discussed in Chapter VII.

VI. OPTIMIZATION OF SYSTEM PARAMETERS

Several variables affect the information capacity and resolution of the two-dimensional phantom sensation. This chapter describes these variables and discusses experiments which were conducted to determine their approximate value for optimal information input.

A. The Parameters

An important display parameter is the distance between the stimulators. Figure 3 is von Bekesy's description of the relative area of the phantom sensation and the corresponding intensity as a function of the distance between the vibrators. Alles[1] and Reimers[32] found that the best display distance on the arm was 4 to 5 inches. There was no such data available on the stomach. In the experiments mentioned in Chapter III, the two-dimensional display seemed to work well with a stimulator distance of 4 to 5 inches.

Alles and Reimers also reported that a stimulation frequency of 100 hz was well suited for display on the arm. It was suspected that an appropriate value for the abdomen would be near this value.

More uncertain than frequency was the appropriate "pulsing" or presentation pattern for the stimulation. Reimers used the pattern shown in Figure 27. He reported this pattern was a trade off between information transmission rate and having enough "rest time" to prevent adaption of the skin. The appropriate value for both pulse

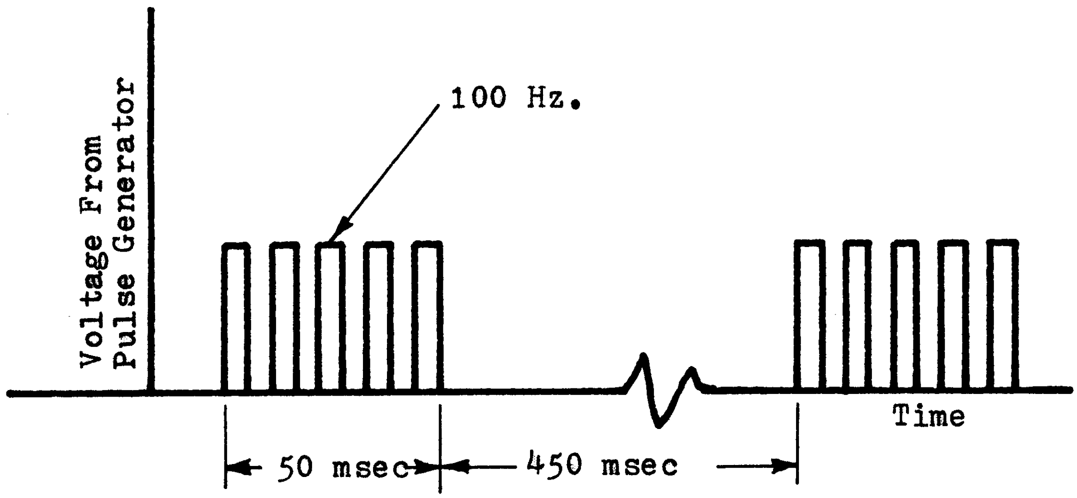


Figure 27-- Vibration pattern used by Reimers[32].

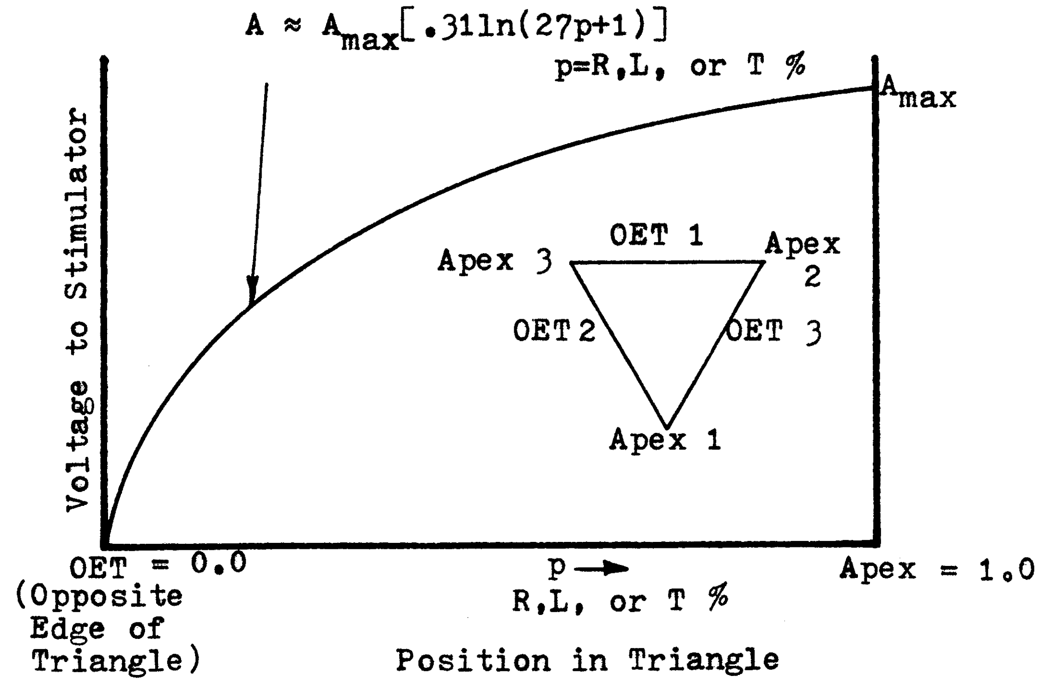


Figure 28-- Initial amplitude increment function.

rate and pulse length were uncertain for the two-dimensional display.

It was suspected, as was discussed in Chapter II, that a logarithmic amplitude function was required in order to provide a uniform intensity of the phantom throughout the display triangle. It, however, was not certain what amplitude function would provide the best localization and, hence, the best information transmission for the display.

B. Optimization Method

These system parameters were investigated by conducting a series of tracking tests in which all parameters were held constant except one. The parameter under investigation was randomly set at different values during the test series. Once an appropriate value for a parameter was determined, the system was updated to that value while the other parameters were tested

A psychological method of experimentation, called the "Within Subjects" method as described by McGuigan[30], was used for these tests. In this method, the same subjects are treated differently at different times, and their scores are compared as a function of the different experimental treatments. There are two basic assumptions in this method: (1) The variables are assumed to be independent, and (2) the order of presentation of the variables does not effect the experimental outcome. None of the parameters in this study have obvious restrictions as to displaying them independently. There probably is dependence on the order of presentation. For example, if the starting value of frequency was orders of magnitude away from the "optimum value", then tests on the other variables would naturally be biased. In these experiments two things were done to minimize the effect from this form of error: (1) The system parameters were set at initial values which were suspected to be close to the optimum values, and (2) the tests were conducted in the order of descending uncertainty. That is, the parameters which were most uncertain were optimized first. The order of optimization was:

1. Stimulator distance.
2. The pulsing rate.
3. The pulse length.
4. The amplitude increment.
5. The frequency of stimulation.

The initial parameters were:

1. The stimulator distance -- five inches.
2. The amplitude increment function -- (see Figure 28) $A_{max} \approx .032$ inch or 30 db above threshold.
3. Stimulation frequency -- 100 hz.
4. Pulse rate -- two per second.
5. Pulse length -- 50 msec.

The integral of the absolute error between the input and output signals was used as the measure of information transmission. Even though the extra error due to the response lag was included, the value of this integral should be an indication of the tracking performance.

Because the experiment was automated, the subject for these experiments was the author. There were several advantages in this choice: Tests could be conducted without scheduling. The previous experience with the display reduced the effects of learning in the tests. The author gained experience with the equipment which was an asset in tests on the information transmission capacity of the display.

C. Equipment

Figure 29 is an overall description of the experimental setup. This consisted basically of an F.M. tape recorder which supplied the x-y input signals, electronic processing equipment to control the amplitudes of vibration, a joy stick x-y control for response of the subject, and a circuit to integrate and measure the absolute error during the tracking task. Ear mufflers were used to mask any audio feedback.

Two x-y tracking tapes were made. In one, the targets were presented in an ordered fashion. This "non-random" tape was used during the training phases of the experiments. In the other tape, the input target areas were random. Each tape had 120 targets which were presented at a rate of one

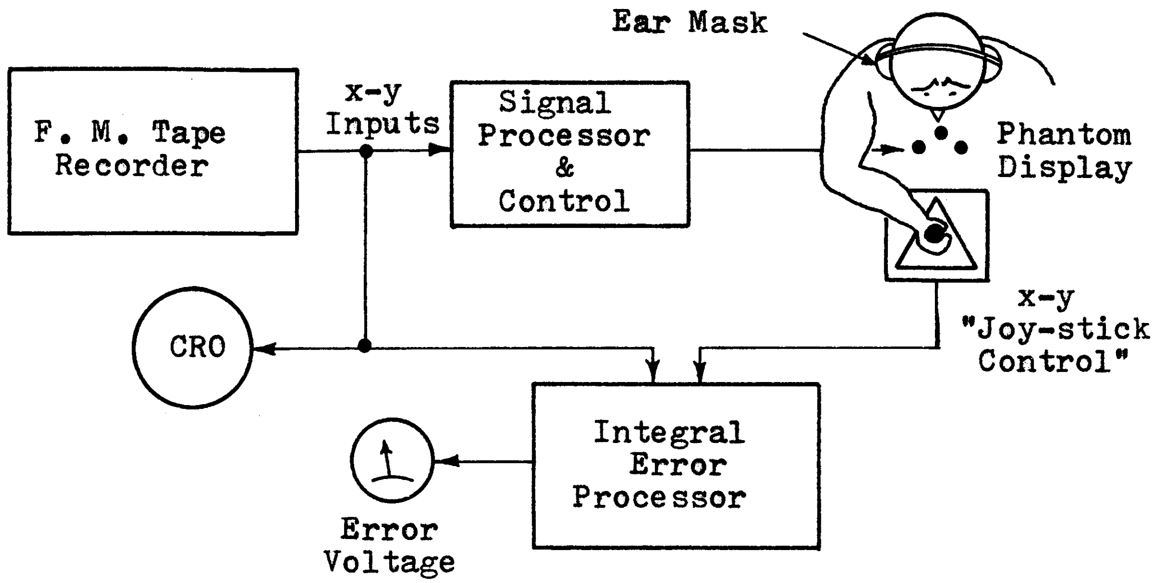


Figure 29-- Equipment used in parameter experiments.

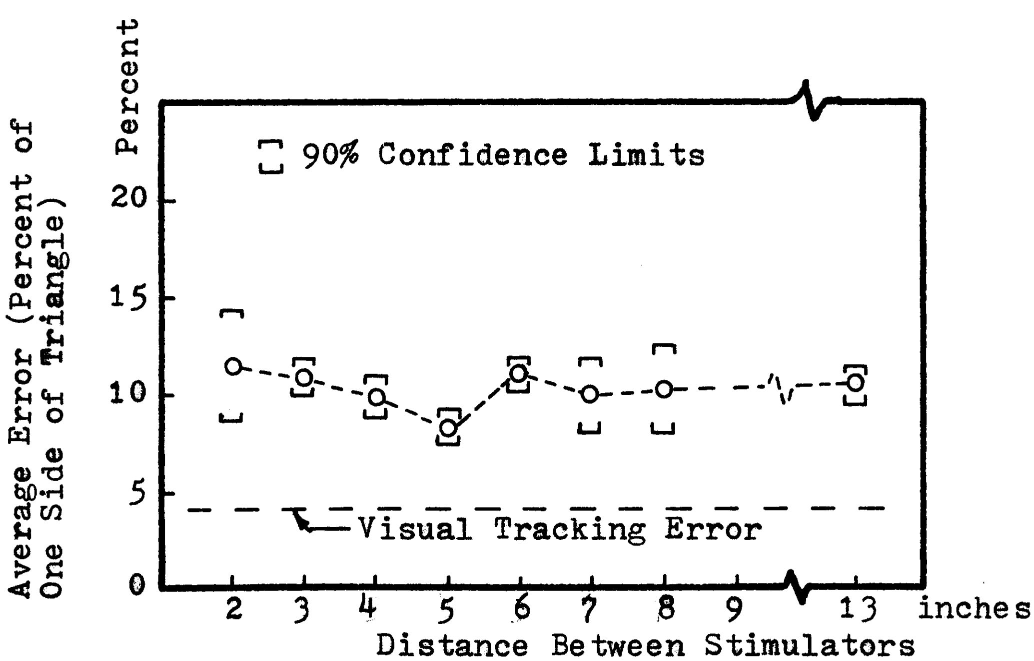


Figure 30-- Tracking error vs. stimulator distance with "non-random" targets.

target every two seconds. The targets were the centers of each area shown in Figure 19.

D. Experiments

The experimentation was started with the subject controlling the phatom sensation with the joy stick. after familiarization with the display, the sensation was driven by the non-random tape input. At first, the subject was able to see* the input on the cathode ray oscilliscope (CRO), but later, after this learning phase, tracking was done only by phantom sensations.

Using the non-random tape, the integral error processor was "calibrated" against perfect tracking (identical signals from the tape input), no tracking (one set of the x-y leads to the processor was at ground), and visual tracking (the subject followed a visual dot on the CRO with the joy stick). Using the value of the integral error at the end of the length of tracking tape, an average percent error was calculated. This percent error was the value of the integral error divided by the voltage equal to the length of one side of the triangle. A sample of this calculation is given in Appendix 3-D. The value for perfect tracking was 0.2 percent, for no tracking was 38.2 percent, and for visual tracking was 4.1 percent.

It was extremely difficult to track the 16 positions precisely. There were only subtle differences between some of the sensations. This was frustrating to the subject.

* Note: The CRO face was marked off into sixteen areas.

E. Optimum Distance Between Stimulators

A pre-experiment using the non-random tape was conducted on the distance between stimulators. The tracking tests were at values of 2,3,4,5,6,7,8,and 13 inches between the stimulators. The results of this experimentation are shown in Figure 30. The lowest error was at 5 inches. If the vibrators were closer than this, the fusion of the stimulation into a phantom sensation was good but it was difficult to localize. With the stimulator distance much greater than 5 inches, there was loss of fusion of the phantom sensation and the relative amplitudes of the three stimulators was used to track the input signal.

Experiments were then conducted using random x-y inputs. As before, the error processor was calibrated using this tape. The percent error for perfect tracking was 0.0 percent, for no tracking was 41.9 percent, and for visual tracking was 8.8 percent. The random input caused a higher visual tracking error.

The results from the series of tests on the distance between the stimulators are shown in Figure 31. Again, the curve shows a minimum at a value of five inches. The vibrator distance was now held at five inches while other parameters were investigated.

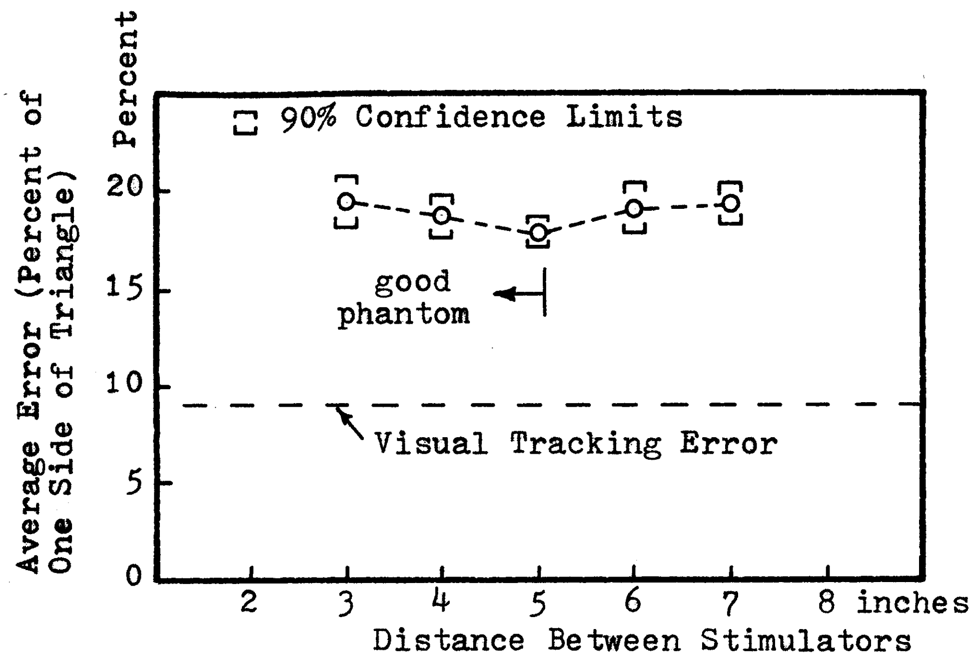


Figure 31-- Tracking error vs. stimulator distance with random targets.

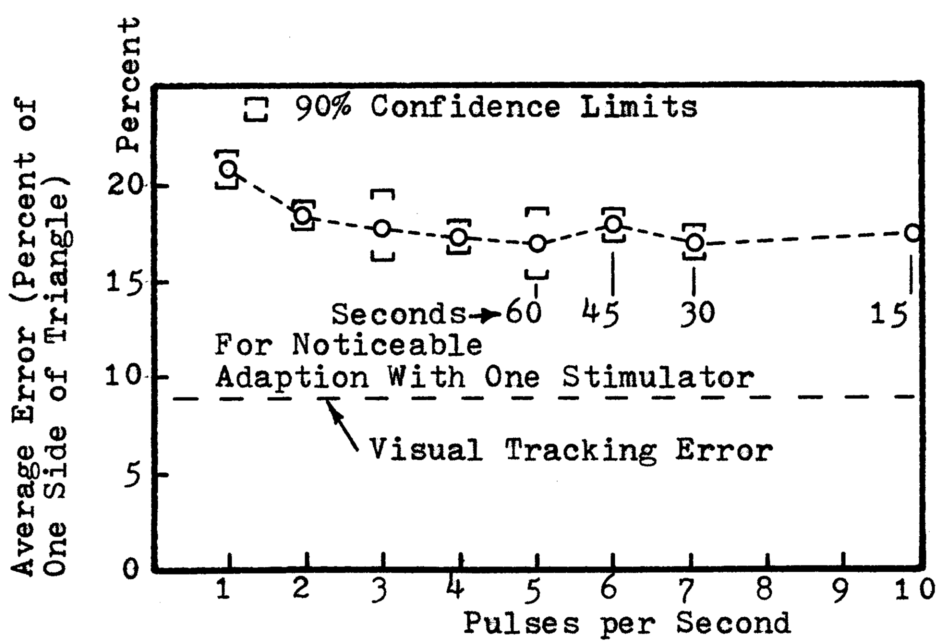


Figure 32-- Tracking error vs. pulsing rate.

F. Optimum Pulse Rate

A series of experiments was conducted on the pulse rate at values of 1,2,3,4,5,6,7, and 10 pulses per second. Results of these experiments are shown in Figure 32. Since adaption of the skin to vibration was noticed at high rates, a simple experiment was conducted using one stimulator to determine the time required to have noticable adaption for the various pulsing rates. These results are also given in Figure 32. These results indicated that four to five pulses per second can be used without serious adaption. Five pulses per second were used in the experiments that followed.

G. Optimum Pulse Length

A similar series of tests was conducted on the pulse length. Again the time required to detect noticable adaption was investigated. The results are given in Figure 33. The lowest percent error was at a pulse length of 75 msec. The data suggested that the appropriate pulsing of the vibration was 75 msec. "on" and 125 msec. "off".

H. Optimum Increment of Amplitudes

The next series of experiments was conducted on the amplitude increment function. First a linear increment as shown in Figure 4-A was tried. This pattern was deemed unfit because the perceived magnitude and localization of the sensation in the central areas was extremely poor. Of several other increments tried, two were found to have

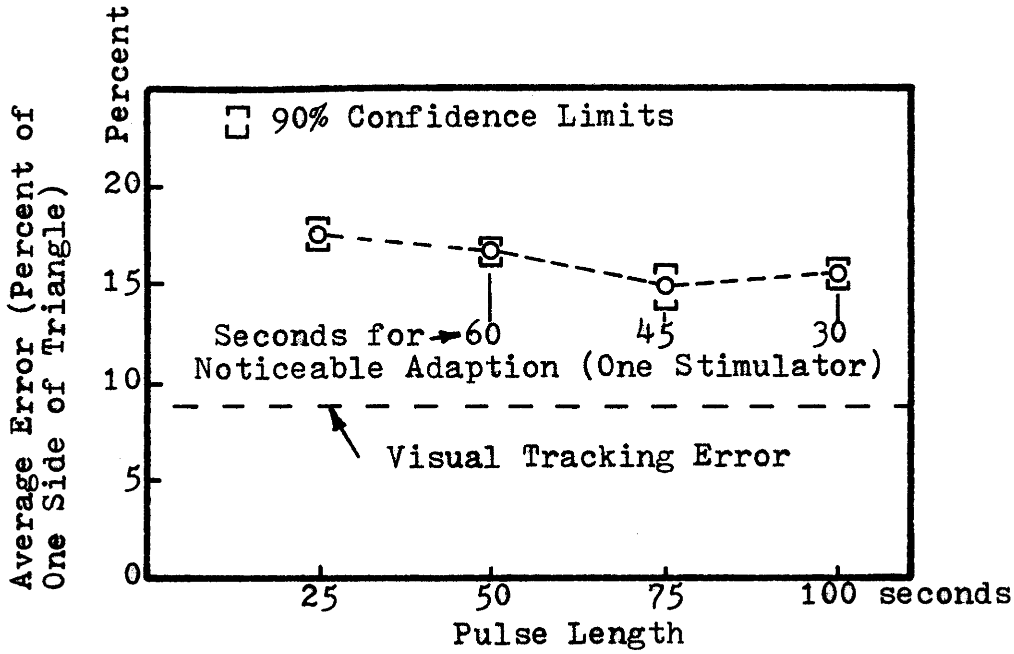


Figure 33-- Tracking error vs. pulse length.

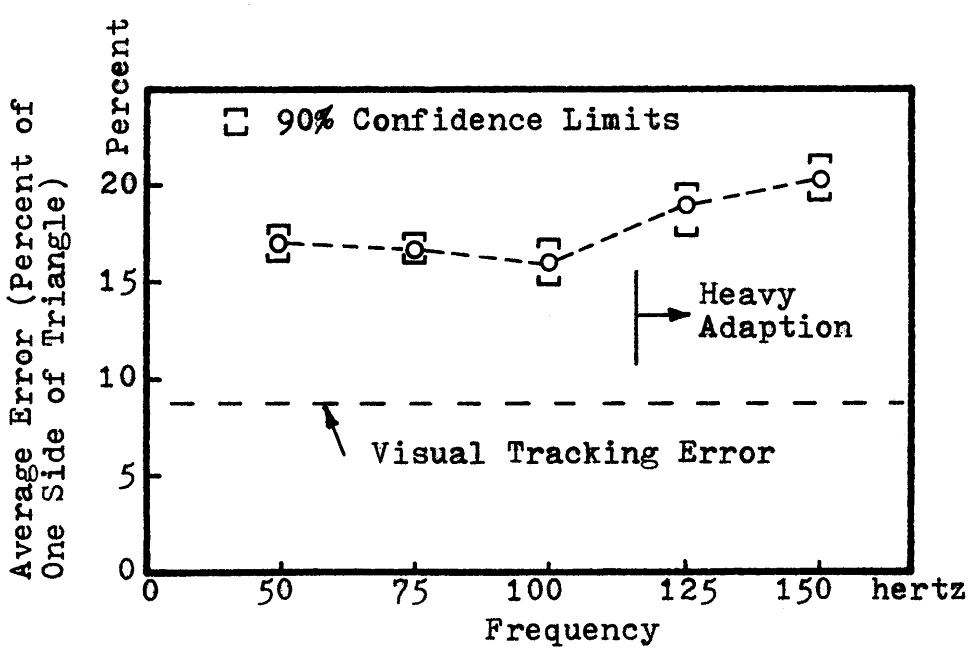


Figure 34-- Tracking error vs. stimulation frequency.

favorable characteristics. The function shown in Figure 35 gave well fused perception of the phantom sensation with equally loud stimulation throughout the area, but localization was poor. This was because a slightly lower intensity in the central areas was an added cue to the subject for localization. Using the function shown in Figure 36, the phantom sensation in the central area was not as fused, but the intensity cues aided the information input. This amplitude increment function was chosen for continued experiments on the two-dimensional phantom sensation.

I. Optimum Frequency

The last series of optimization tracking experiments was conducted using frequency as the independent variable. The error results from these tests are given in Figure 34. The tests indicated that 100 hz is a suitable frequency for input.

J. Review

In review, the experiments described in this section indicated that for "optimum" information transmission via the two-dimensional phantom sensation on the abdomen, the input parameters should be as follows:

1. The stimulator distance should be on the order of five inches. This may be slightly smaller for persons with a small frame.

2. The vibration should be a 100 hz signal pulsed "on" for 75 msec. and then "off" for 125 msec.

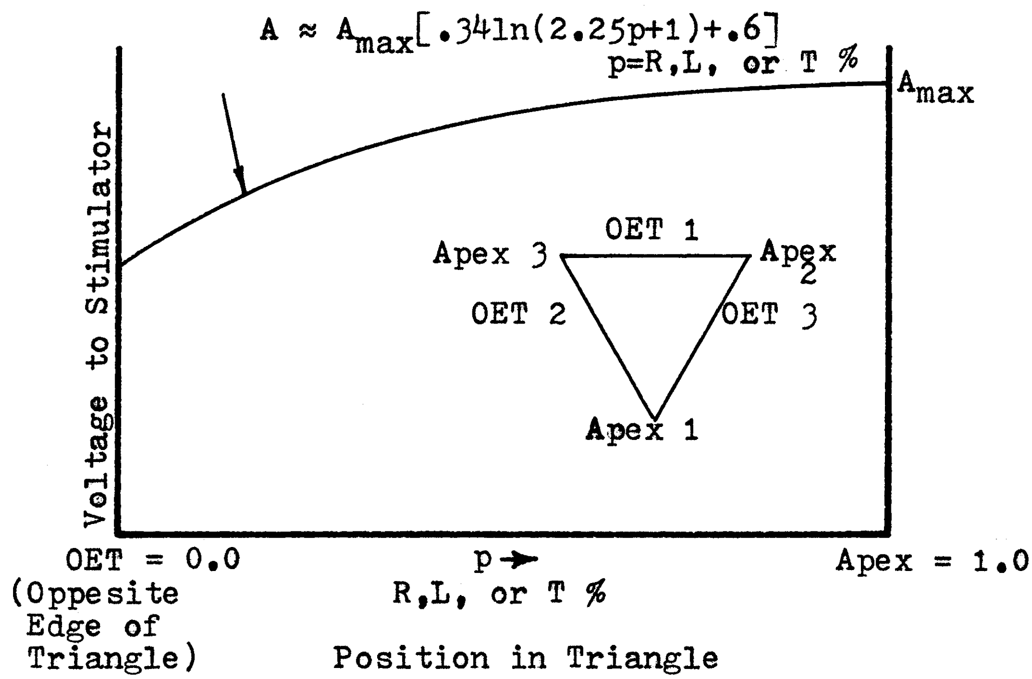


Figure 35-- Amplitude increment function for "best" perception of the two-dimensional phantom display.

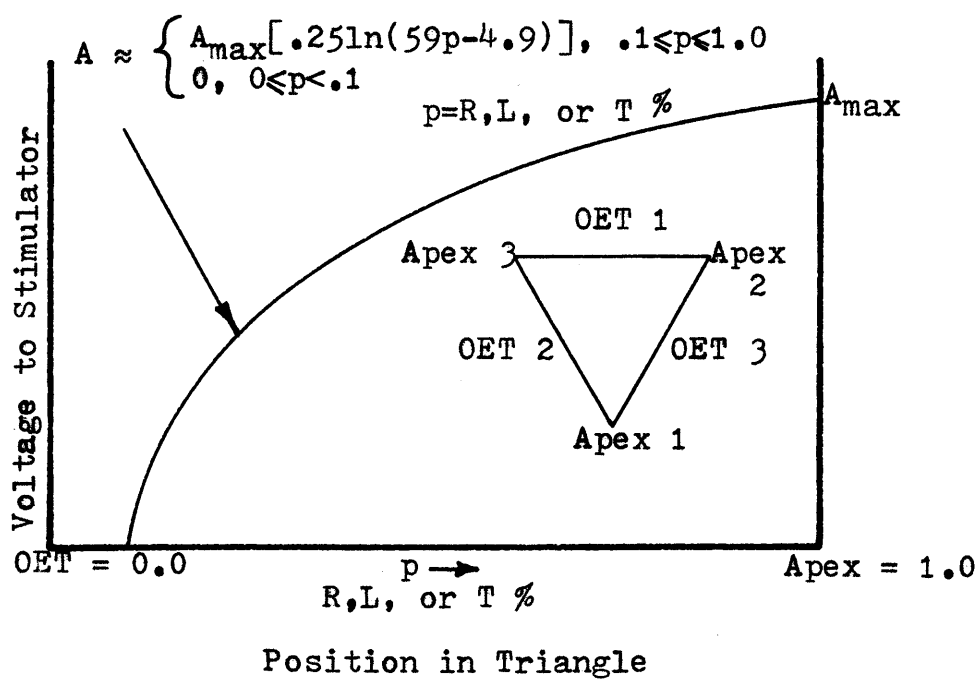


Figure 36-- Amplitude increment function for "best" transmission of information.

3. The amplitude increment function should be like that shown in Figure 36.

VII. INFORMATION RATE, DISPLAY RESOLUTION AND LEARNING

This chapter describes experiments conducted to determine the maximum information transmission rate, the resolution, and the learning associated with the two-dimensional phantom sensation. The theory describing information rate was discussed in Chapter IV. Briefly, as it relates to these tests, it is a measure of how fast a subject can distinguish a randomly chosen input area from a specified number of possible input areas. The resolution of the phantom display is simply an indication of how accurately a subject is able to distinguish this random input area. In other words, it is an indication of how discretely the triangular area in which the phantom exists can be subdivided and still allow discernment of one position from another. As a subject learns to localize the perception of the phantom sensation, there is a point of saturation where further practice will no longer reduce the average errors. Alles[1] reported that subjects receiving the one-dimensional phantom sensation did not improve significantly with respect to error after the first practice session.

A. Self-Paced Experiments

It was the original intent to have the subjects follow taped random x-y inputs and record the in-out experiment. After two practice sessions with two of the three subjects, it was apparent that this method of testing was extremely frustrating to the subjects, almost to the point of harassment. This was not a surprise, since the author also had found it difficult to track the 16-position phantom display. A self-paced method of experimentation was devised which gave not only a more relaxed experiment, but also an experiment which was easier to analyze.

Figure 37 depicts the self-paced experiment. It consisted of an x-y input from a joy stick control, an electronic processor for amplitude control, the two-dimensional phantom display on the subjects abdomen, an x-y joy stick for response by the subject, two flip-flop buttons which were used to control the pace of the experiment, and an F.M. tape system to record the data. The subjects vision was shielded to prevent visual perception of the input. A set of ear protectors was used to mask any auditory perception of the vibrators.

To have a digital computer control such a self-paced tracking experiment requires substantial computer time and equipment. Therefore, the input for these experiments was realized by human manipulation of a joy stick. A triangle with the appropriate grid was drawn on the cathode ray oscilliscope (CRO). This provided visual feedback to the input operator concerning the input signals. During the tracking experiments, the input operator randomly selected one of the input areas and then pushed a button which controlled a flip-flop. When the flip-flop went low (the subject had auditory

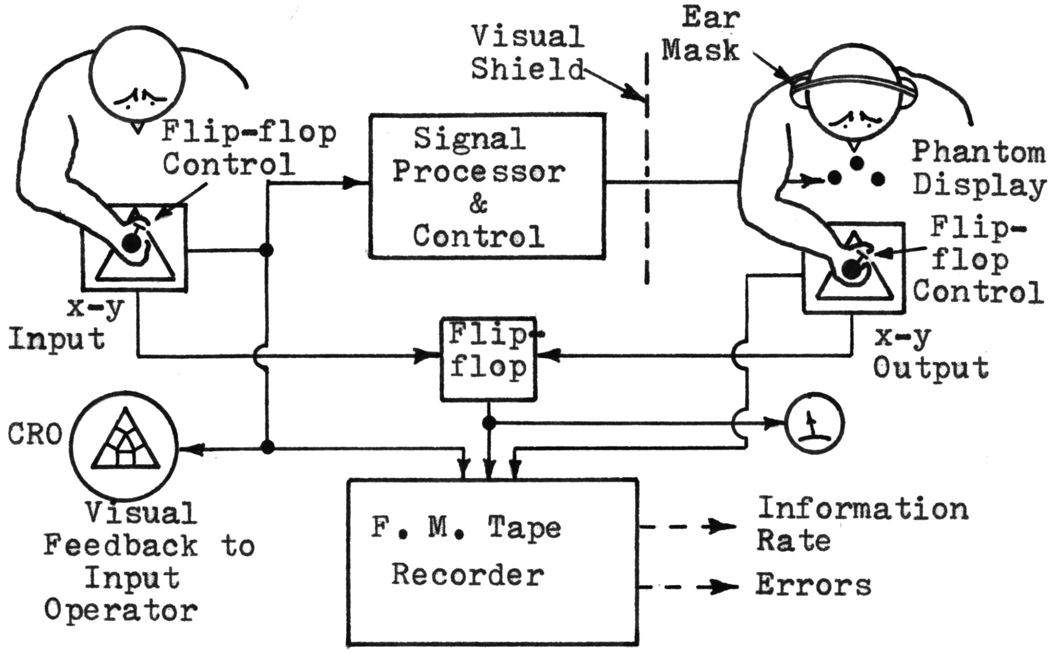


Figure 37-- Self-paced tracking experiment.

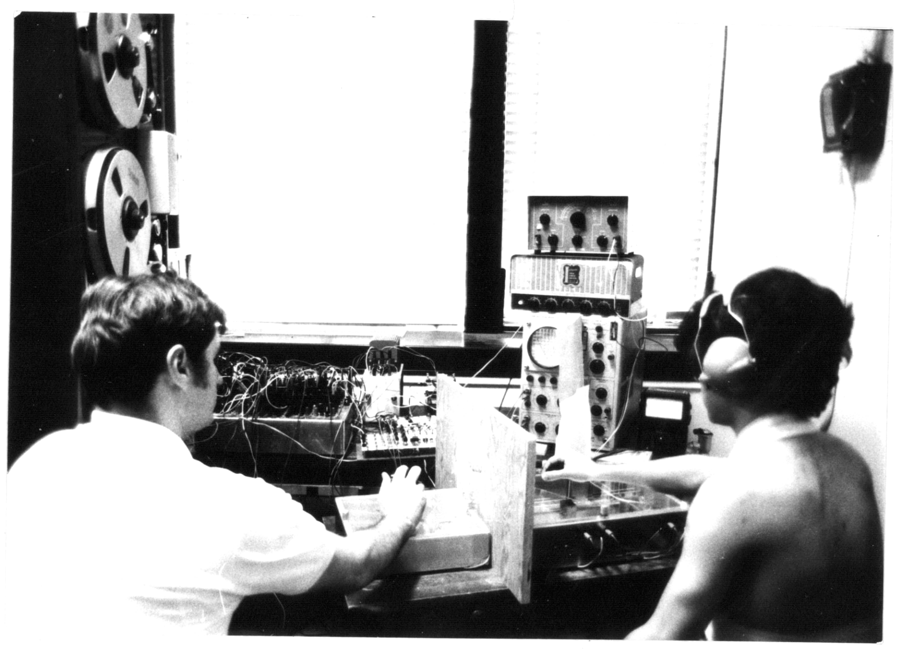


Figure 38-- Photograph of self-paced tracking experiment.

perception of this), the subject knew a position was being presented to him for tracking. After the subject had moved his x-y control to the appropriate area, he indicated his decision by pushing a button mounted on his control handle. This caused the flip-flop to go high. The operator then quickly gave another input target (sometimes it was the same target to keep the target random) and pressed his flip-flop button. This process was repeated for the length of the tracking test which was usually between 100 and 160 targets. A photograph of the experiment is given in Figure 38.

B. Subjects

Three subjects were used for these experiments; two were sighted and one was blind. Subject F was male, 19 years old, 5'8" tall, and weighed 130 lbs. Subject L was female, 25 years old, 5'7" tall, and weighed 124 lbs. Subject V (the blind subject) was male, 44 years old, 5'4" tall, and weighed 155 lbs. He had been blind since age ten.

C. System Parameters

In all the experiments, the system parameters were at the values determined in the previous chapter. Because the stimulator distance was constant, the vibrators were mounted on a nylon screen. The compliance of the nylon, aided by a cloth cushion placed in between the stimulators, was sufficient to eliminate the vibrational transmission. This display, as worn by a subject, is shown in Figure 39. All subjects preferred peak to peak amplitudes around .032 inch, which is approximately 30 db above threshold. At the beginning of each test, the relative magnitudes of the stimulators were adjusted to have equal perceived intensities.

D. Seven Position Phantom Display

Since preliminary tests showed that subjects had difficulty tracking the tape-driven sixteen-area display (this display was discussed in the previous chapter), the self-paced experiments were initialized using the input triangle divided into only 7 areas. This is shown in Figure 40. The dot in each area is the position at which the input was directed during the tracking tasks. Self-paced experiments with the display divided into 16 areas, were conducted towards the end of the series of experiments.

E. Processing of the Experiments

Since the tracking targets were presented at a relatively slow pace, (one in-out event every second), the experiments were processed by displaying the taped input and output records on the CRO and listing the appropriate area numbers as a function of whether the flip-flop record was high or low. The response time of the subject was measured with a stop watch by accumulating the total time the flip-flop was low. This accumulated time, divided by the number of targets in the experiment, gave an indication of the subject's average reaction time.

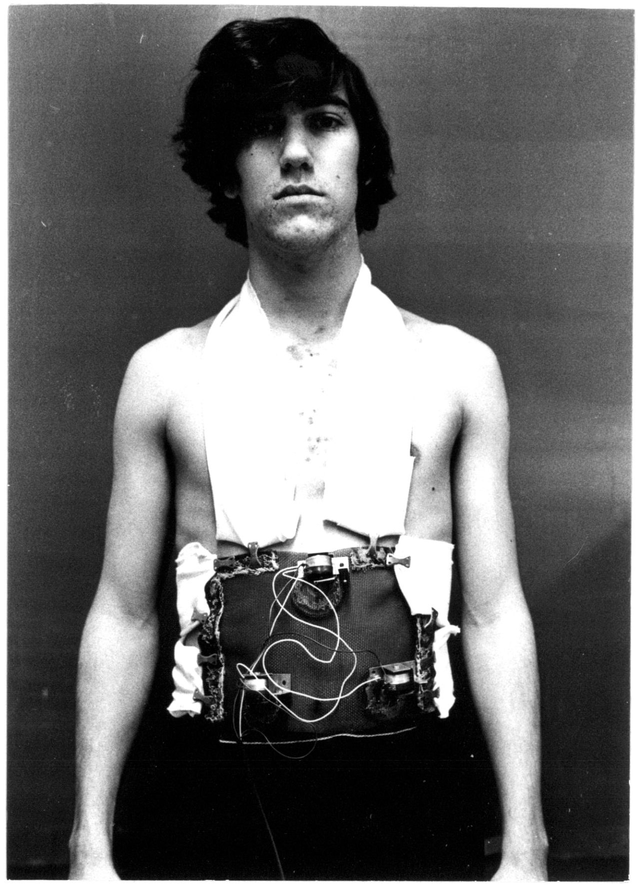


Figure 39-- Photograph of subject wearing phantom display.

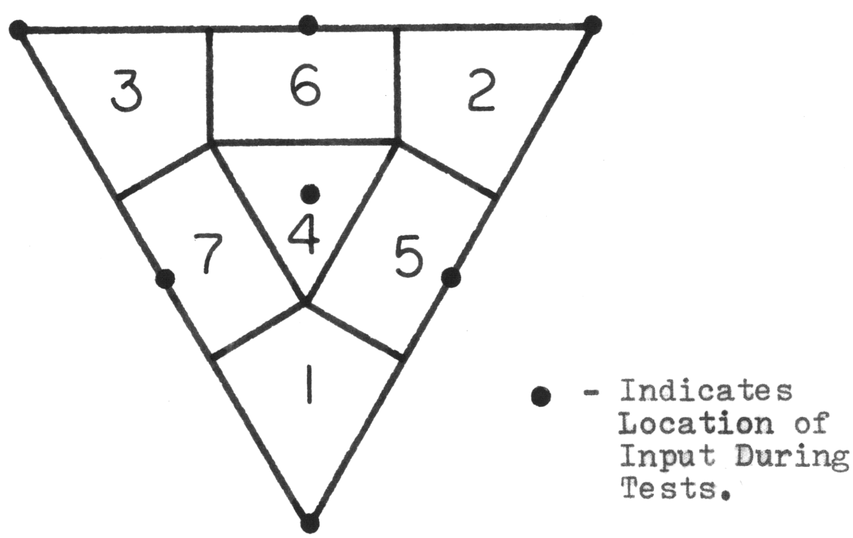


Figure 40-- Division of input triangle into seven quantized segments.

Experiments were conducted to determine the portion of the subjects' response time due to neurological lag and physical manipulation of the x-y output control. Based on previous experience with the phantom display, the time for a visual image to be recognized as compared with the time required for recognition of a phantom image was assumed to be negligible. For each sighted subject, a visual tracking experiment was conducted. The average reaction time for this visual tracking experiment was defined as the average time required to move the x-y control.

For the blind subject, an experiment was conducted in which he followed the input as directed by audio cues. The experiment was similar to the visual tests mentioned above, except the subject was vocally told which area to respond to (he had the number corresponding to each area memorized). Similar audio tracking tests were also conducted on the sighted subjects. The portion of the reaction time for the blind subject which was due to manipulation of the x-y control was extrapolated using the ratio of the audio and visual data on the sighted subjects.

For these experiments, the average time the subject spent examining each phantom target was defined as the difference between the subjects measured average response time and his average muscular response time. Hence, the rate at which targets were sent to the subjects' higher centers was determined, i.e., the target rate.

A contingency table like the one described in Chapter IV was used to calculate the information transmission rates. Equation 2, in Chapter IV was used for these calculations.

F. Error Processing

An indication of the absolute error in the experiments was obtained by examining the in-out record and summing the absolute errors. If the input and output were the same area, no error was recorded; if the input and output areas were different, the absolute distance between the defined locations of the two areas was summed. The average error was computed by dividing this sum by the number of targets. As with the experiments in Chapter VI, these errors were normalized as a percent of the length of one edge of the triangle. Average errors computed this way were smaller than the errors listed in Figures 30 to 34, because the effects of small deviations and also error due to response lag were eliminated.

G. Learning Curves

The error data for these experiments is presented in Figure 41. It can be seen that all three subjects saturated their learning with regard to error in four to six hours of practice with the display. This is about three times the time required for the one-dimensional display.

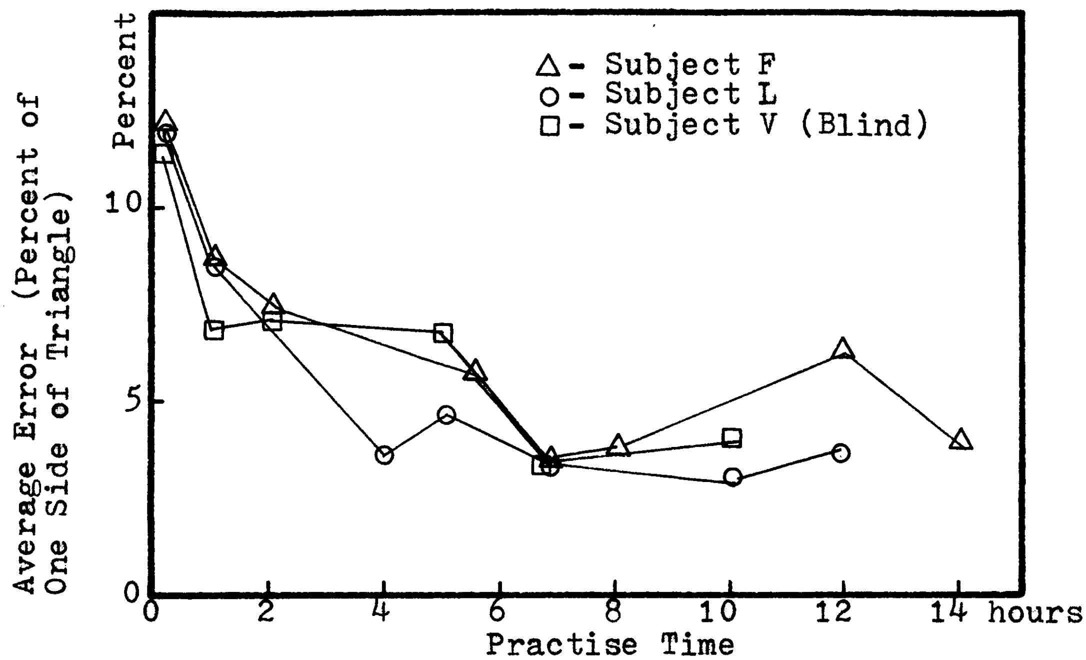


Figure 41-- Error vs. Practise with the two-dimensional phantom display.

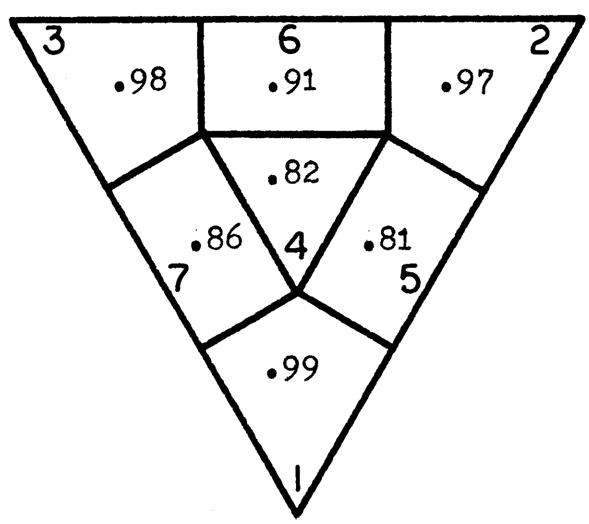


Figure 42-- Resolution of the phantom display. (Fractions indicate the average frequency of occurrence for a correct in-out response.)

H. Resolution of Seven Position Phantom Display

Figure 42 reports the results of the experiments in regard to the acuity or resolution of the display. The number in each area is an estimate of the probability of the subject choosing that area, if that particular area was chosen randomly to be an input. These estimates were obtained by averageing the relative frequencies for correct tracking of the phantom. Only data taken beyond the initial learning phanses was used. As can be seen from the diagram, the subjects had very little difficulty tracking the sensation when located at one of the apexes. Areas 4, 5 and 7 were the most difficult to track. A summary contingency table of this data is given in Appendix 3-A.

I. Maximum Information Rates

The maximum information transmission rate achieved was 3.7 bits per second by subject L. Subject F had a maximum rate of 3.0 bits per second. The blind subject had a maximim of 2.7 bits per second. All three maximums occurred in tests conducted near, but not at, the end of the series of experiments.

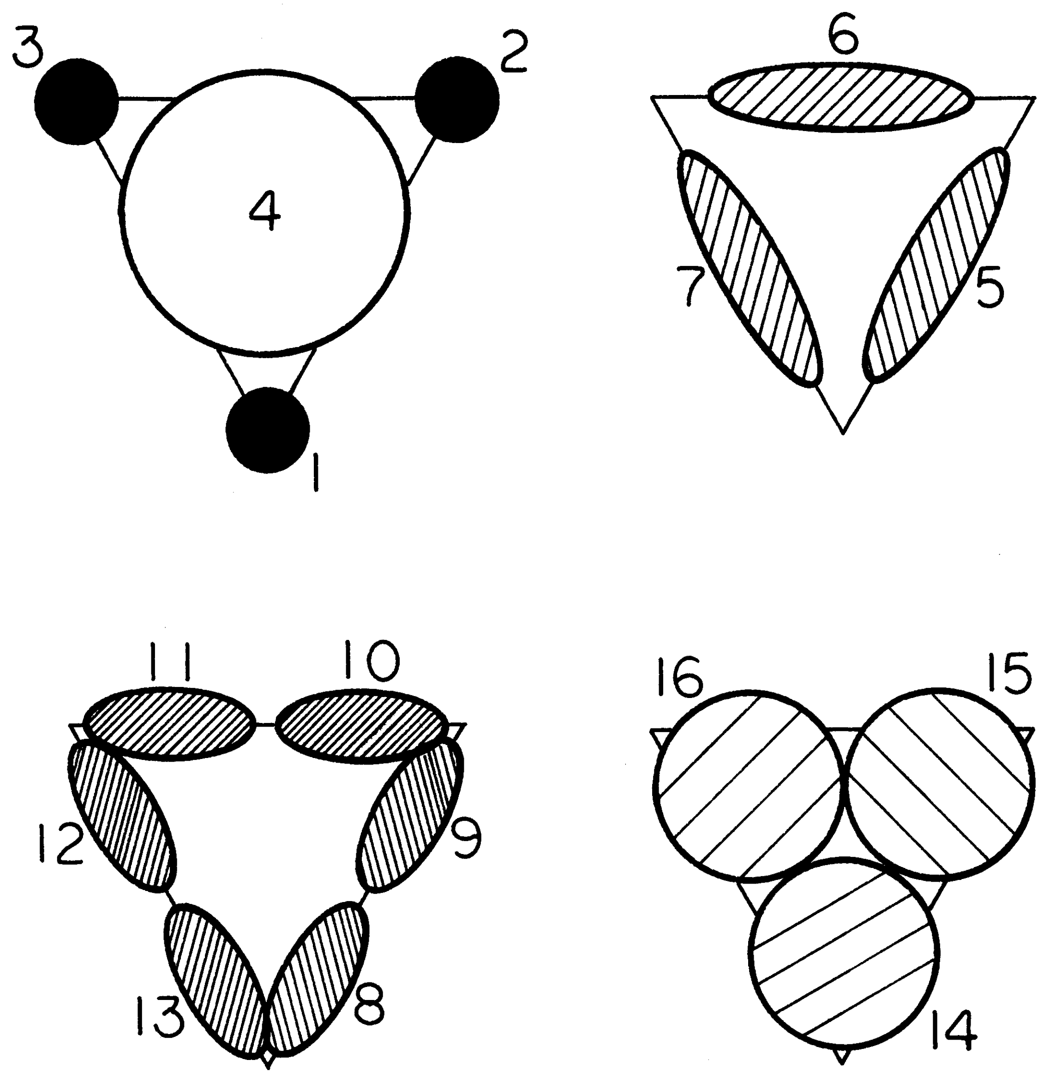
J. Phantom Perception

Subjects reported difficulty maintaining fusion of the phantom sensation, especially in the central areas. About half the time, subjects said they could distinguish more than one vibrator simultaneously. This was true especially if the input traced from one apex through the center to the middle of the opposite side. The sensation was reported to move to the center, becoming softer and more spread, and then split into two sensations. The fused phantom was best observed when the input was traced along an edge of the triangular display. Figure 43 diagrams the intensity and spread of stimulation as a function of input location. This diagram refers to the fused phantom sensation. In the diagram, a darker area represents more intense the stimulation.

K. Experiments with 16 Areas

Toward the end of the tracking tests, a series of experiments was conducted with the input triangle divided into 16 areas as shown in Figure 44. Again, the dot in each area indicates the position to which the input was directed during tracking tests. Two sessions were spent training the subjects to recognize subtle differences between adjacent areas. Again, visual and audio tracking tasks were conducted to determine the neurological and x-y positioning lag times.

Figure 45 presents the estimated probabilities for each of the 16 areas. As before, these numbers represent the probability that the subject will respond to an area if it is given as an input. The data seems to indicate that the resolution of the display is inadequate to accurately distinguish the 16 positions. Again, the apexes were accurately perceived, but the response to the central areas was rather poor. The information transmission



Darker Shading Indicates
More Intense Stimulation

Figure 43-- Perceived intensity and lateral spread of the two-dimensional phantom display for the various input locations.

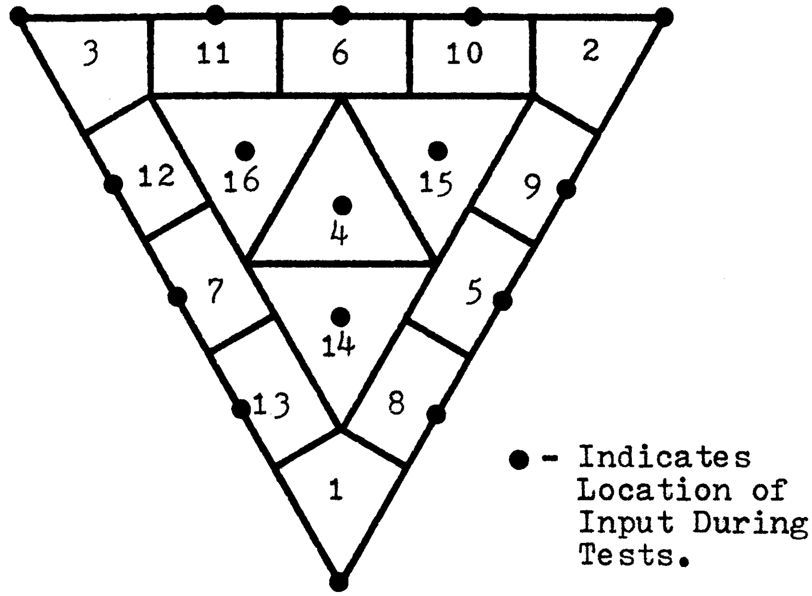


Figure 44-- Input locations for tracking tasks with 16 quantized areas.

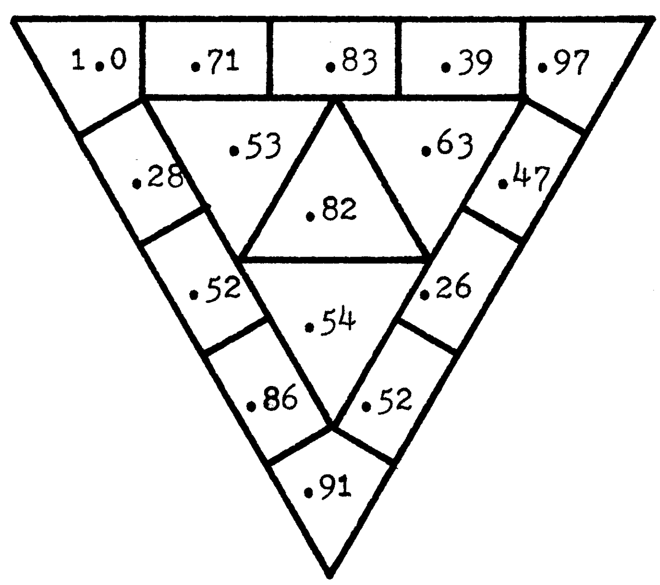


Figure 45-- Resolution of 16 area tests. (Fractions indicate the average frequency of occurrence for a correct in-out response.)

rate was also low. This was due both to slow tracking and poor resolution. Intense concentration was required to decide which of the 16 areas was being stimulated. The maximum rates were: Subject F --.89 bits per second, Subject L --.81 bits per second and Subject V --.69 bits per second. The contingency table is in Appendix 3-B.

L. Continuous Tracking Experiments

An experiment was conducted in which the input to the system was moved slowly and continuously through the area of the triangle. Subjects were asked to follow the input as closely as possible. The subjects tracked well as the input moved along any of the edges. When the input traversed through the center of the display, the subjects often hesitated slightly at the last position or moved a short distance along an edge before following the input through the center. The maximum speed of motion in these experiments (using the length of one side of the triangle as a basis) was about one side length per second.

The two signals were processed by the integral error processor (discussed in the previous chapter), with the input signal delayed so that the two signals coincided as close as possible. Since the F.M. tape recorder had two playback heads, the delay was realized by threading the tape through spools which created an adjustable length loop between the heads. (This mechanism is shown in Appendix 1-C, Figure A-13). The average percent error for these tests was 9.2 percent for Subject F, 8.9 percent for subject L and 9.7 percent for subject V. These values are higher than those shown in Figure 41 because they account for the continuous, rather than quantized error. On the average, these numbers indicate tracking within the area was fair.

M. Experiments with an Array of Vibrators

For comparative purposes, a quickly designed series of experiments using an array of seven stimulators was conducted. The obvious question was: Would an array be better? The equipment for these tests consisted of an input x-y joy stick, a switching circuit that directed power to only one of the seven stimulators at a time (this circuit is discussed in Appendix 1-C-6), the array of tactile stimulators, and the output x-y control for response of the subject. The array of stimulators were arranged in a triangular pattern identical to the area divisions created for tracking the 7 area phantom display. (See Figure 46). The stimulators were small electro-magnetic speakers with a skin contactor glued to the cone. (See Figure 47). The input stimulation was a 100 hz sine wave with motion perpendicular to the skin. Tests were conducted in a manner similar to those for the self-paced tests on the phantom display.

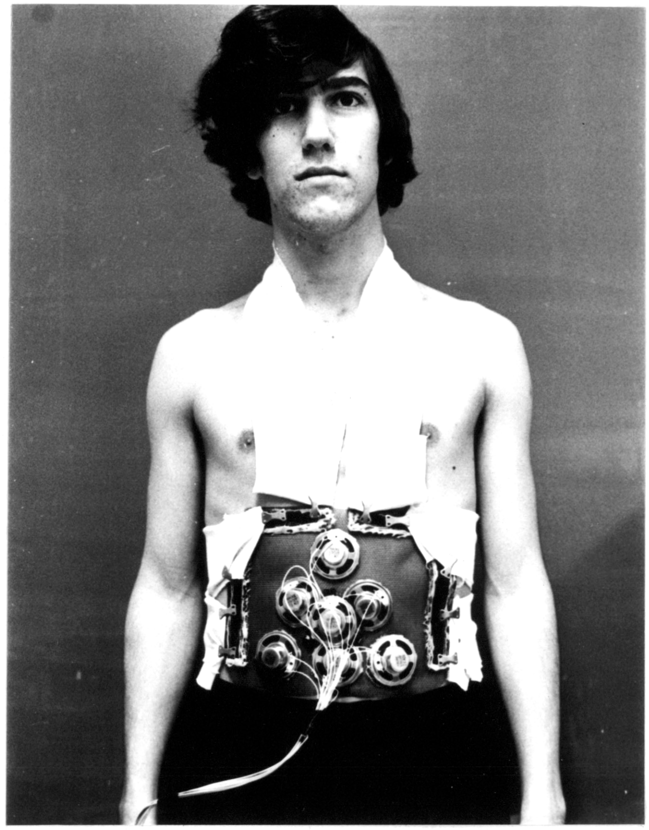


Figure 46-- Photograph of subject wearing the array of seven vibrators.

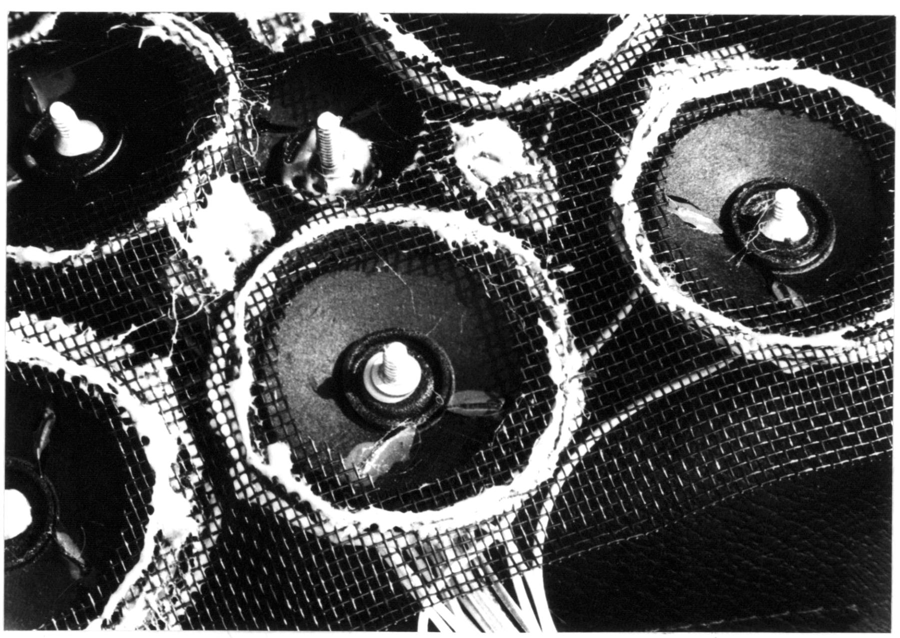


Figure 47-- Close-up view of stimulator used in the array of seven vibrators.

Subjects reported that there was essentially no learning time involved in localizing the area stimulated. They also reported a jerky (haptic) motion when the input control was moved rapidly through the display area. Initially, all three subjects felt this array was easier to localize than the phantom sensation. After the series of tracking tests, they were undecided as to which display was better. The array lacked a reference frame and subjects often confused the inputs. The three vibrators associated with the phantom display had outlined the display area and provided an automatic frame of reference.

Figure 48 presents the results for the array of seven vibrators. The probabilities were uniformly distributed but were lower than anticipated. This was, no doubt, caused by the lack of a reference frame. The information transmission rates were higher for two of the subjects. The information rate for the blind subject did not improve with the array. The maximum rates were: Subject F -- 5.2 bits per second, subject L -- 4.9 bits per second and subject V -- 2.6 bits per second.

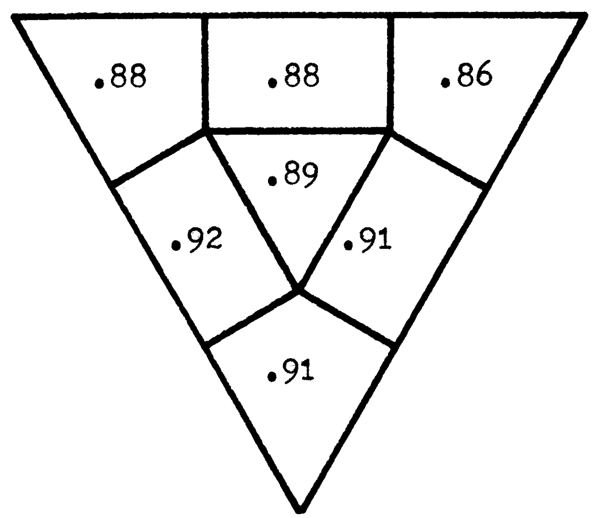


Figure 48-- Resolution of the display using seven stimulators. (Fractions indicate the average frequency of occurrence for a correct in-out response.)

N. Comparison of Alles' Equipment

It was wondered whether the lack of permanent fusion of the phantom display on the stomach was caused by the apparatus. To provide a check on this question, the one-dimensional stimulators used by Alles and Reimers (shown in Appendix 1-A) in their studies was tried both on the stomach and the upper and lower arm. An identical experiment was performed using two of the stimulators which were constructed for this study. Without exception, the subjects received a better one-dimensional phantom sensation using the stimulators built for this study. The problem, therefore, was not the equipment.

O. Two-Dimensional Phantom Sensation on the Arm

A short test was conducted using the two-dimensional phantom sensation on the upper arm. Subjects reported a more fused phantom sensation. The perception of the stimulation splitting into two sensations as the input moved from an apex through the center to the middle of the opposite edge still existed. A tracking task conducted on subject L showed no marked improvement over the information transmission capacity of the abdomen.

VIII. DISCUSSION OF RESULTS

The results (as discussed in Chapter VI) of the parameter optimization experiments closely correlated with the work done by Alles[1] and Reimers[32]. Two differences should be mentioned. In order to prevent adaption, Reimers used pulsed stimulation (two pulses per second) with a ten percent duty cycle (vibration only ten percent of the time). As shown by the results in Figures 32 and 33, this pattern of stimulation was not "optimum" with regard to information input via the two-dimensional display on the abdomen. A pattern with more frequent pulsing (5 per second) and with a higher duty cycle (37 percent) was found to be best in this study. This was partly due to the fact that the stimulation was divided between three vibrators instead of two. On the average, each skin location received about 17 percent less stimulation. Another difference between this study and the work done by Alles and Reimers was the function used to control the vibrational amplitude. They used a function much like Figure 35. A result from this study was that more information could be presented by increasing the amplitude by the function shown in Figure 36.

The experiments in Chapter VII showed that more information was transmitted by the two-dimensional display than by the one-dimensional display of Alles and Reimers. About eight positions (2.98) bits could be transmitted in two dimensions on the abdomen while only about 4 to 5 locations (2.11 bits) were discernible using the Alles display on the arm.

The biggest discrepancy between this study and the Alles study was the loss of fusion of the phantom sensation as the display traversed through the central areas (discussed in Chapter VII). The problem may have been caused by pushing the display to its limits to gain maximum information transmission instead of seeking the conditions for the most fused phantom sensation. The problem was not equipment. All subjects preferred the phantom sensation produced by the stimulators used in this study over the sensation produced by Alles' vibrators. This lack of fusion might have been caused by insufficient practice time. However, all subjects had two to three weeks experience with the display which, according to Alles, should have been sufficient time to smooth the reception of the display. The location chosen for input is another possible explanation. The abdomen is less sensitive than the upper arm to vibration. There also may be less neural interconnections at the midline of the torso. The problem however, may be inherent in the display. Even when the two-dimensional display was presented on the arm, there was a loss of fusion as the input was traced from one apex through the center to the opposite side.

Figures 42, 45, and 48 show the subjects' abilities to perceive the various displays. The phantom sensation when divided into 16 positions was extremely difficult to track. However, if the display was more coarsely divided (7 positions), the discernment of the phantom was relatively good when compared to an array of seven individual stimulators.

In comparing the performance of the blind subject to the sighted subjects, the primary difference was the rate at which the information was received. The sighted subjects had rates about 20 percent higher. This may, in part, be due to the difference in ages of the subjects. The blind subject was twenty years older. There was no significant difference in the abilities to discern the position of the phantom sensation. It simply took the blind subject longer to react to the phantom display.

An important question for this thesis is: Can the two-dimensional phantom sensation be used as an information input in a mobility aid for the blind? The answer to this question depends on what the mobility aid is intended to do. If it is required to pin-point the exact location and shape of multiple objects in the path of travel, the phantom display is not the correct input. If, however, the mobility aid is intended to simply augment the long cane, giving only a general indication of the position of objects in the path of travel, the phantom has good potential. Note that the experiments in this study describe a "worst case" for the type of information transmitted. In real situations objects seldom jump randomly throughout the path of travel; instead, they move continuously through the area. In other words, real mobility situations may be less random than the tracking tasks described in Chapter VII. Perhaps the blind would be able to follow the phantom even better in real mobility situations.

The average maximum information rate (3.1 bits per second) suggests that an object detector should have a minimum range of ten to twelve feet to provide adequate warning to a blind traveler using the phantom display. This range was based on a walking speed of six feet per second. Before this (or any tactile display) will be accepted by the blind, the cumbersome aspects (such as vibrator weight and awkward methods of strapping stimulators to the body) must be eliminated.

IX. FUTURE WORK

Based on this study, four suggestions for future work are listed:

1. A simulation of actual travel situations should be attempted. This could be done using a computer to provide various travel situations and various scanning rates for control of the phantom sensation.

2. A less cumbersome method for stimulation of the skin should be found.

3. The two-dimensional phantom sensation should be tried at other locations on the body in an attempt to gain a more fused sensation as it traverses central areas.

4. The mathematical model of mobility which is listed in Appendix 5 should be examined experimentally.

APPENDIX 1

A. Threshold Test Equipment

Figure A-1 diagrams the equipment used in the threshold experiments. The stimulator (shown in Figure A-2) used in these experiments was used by Alles[1] and Reimers[32]. A variable capacitor system (shown in Figure A-3) was used to measure the amplitudes. Calibration of the amplitude measurement system was accomplished by visual measurement of the amplitude under stroboscopic light using a hairline microscope.

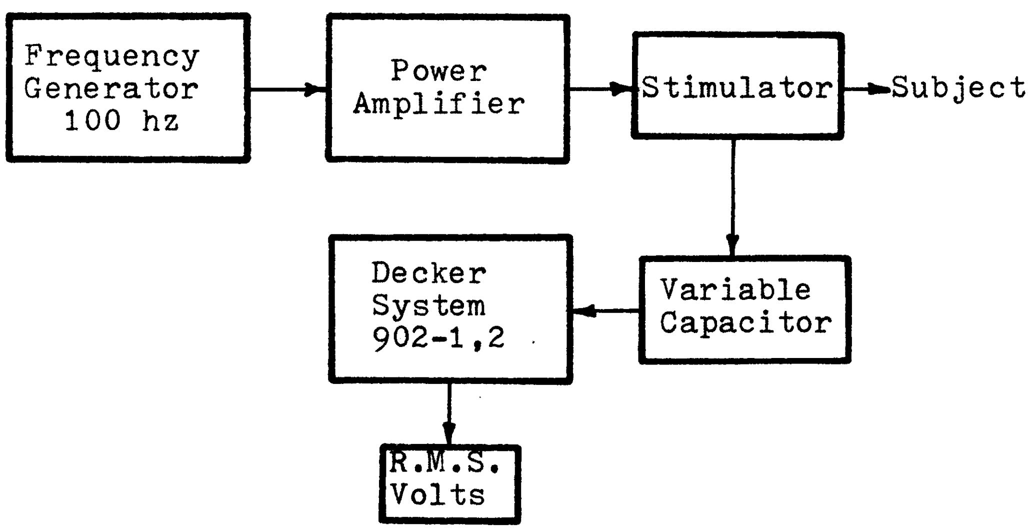


Figure A-1-- Equipment used in threshold experiments.

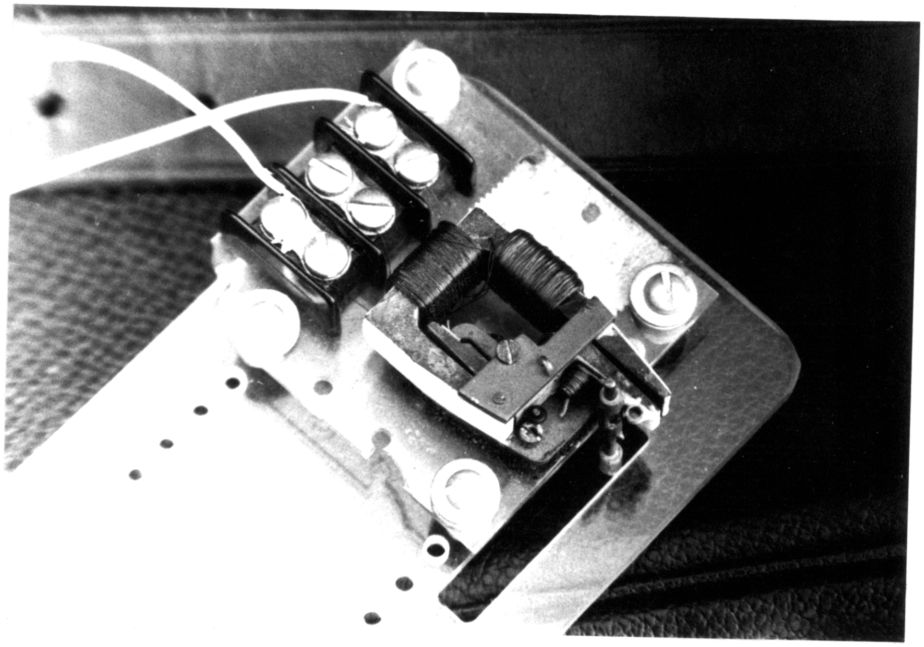


Figure A-2-- Stimulator used by Alles[1] and Reimers[32].

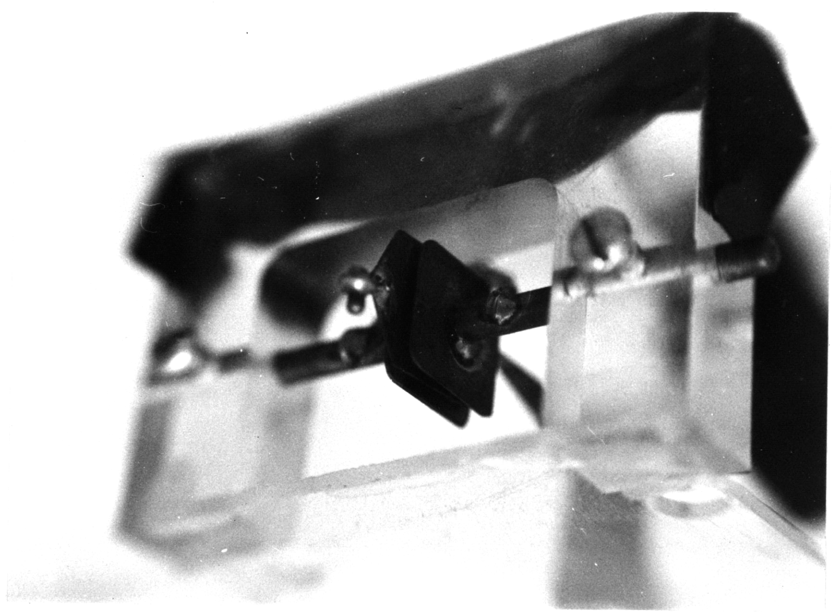


Figure A-3-- Variable capacitor plate used to measure threshold amplitudes.

B. Vibrators

Figure A-4 is a photograph of the bimorph reed stimulator which was investigated as a possible input. Figures A-5 and A-6 are photographs of the Potter-Brumfield BU Buzzer which was adapted for use as a stimulator. The natural frequency of the vibrator was about 115 hz which allowed strong 100 hz stimulation at relatively low power. Since the skin is spring dominated at 100 hz the total skin-vibrator system did not operate at resonance.

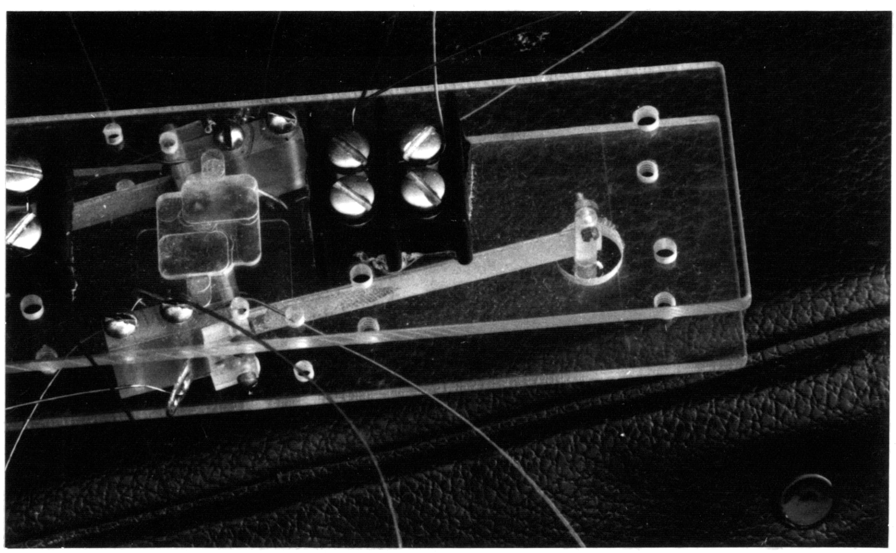


Figure A-4-- Photograph of bimorph reed stimulator.

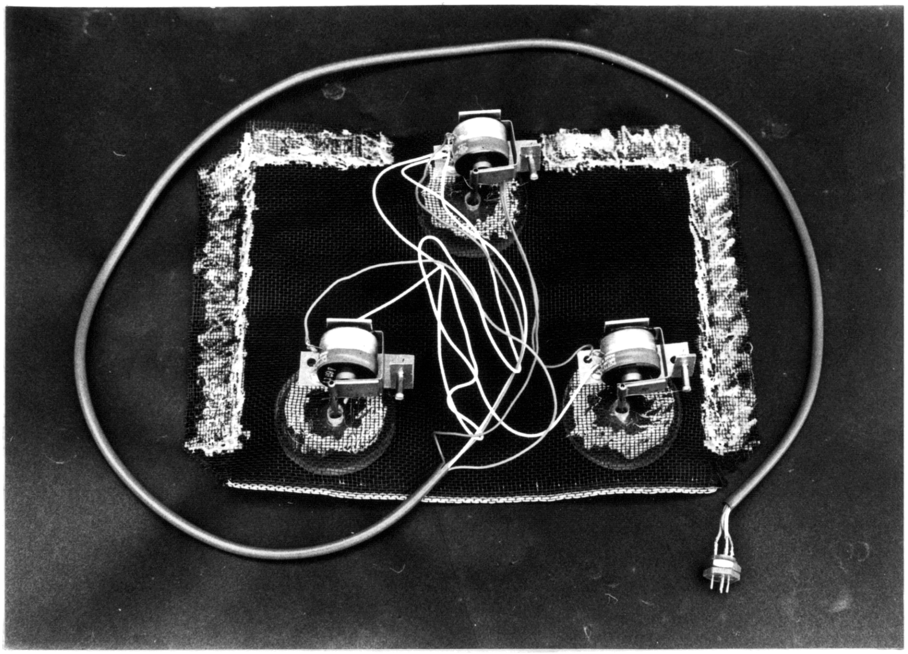


Figure A-5-- The stimulators used in the two-dimensional phantom display.

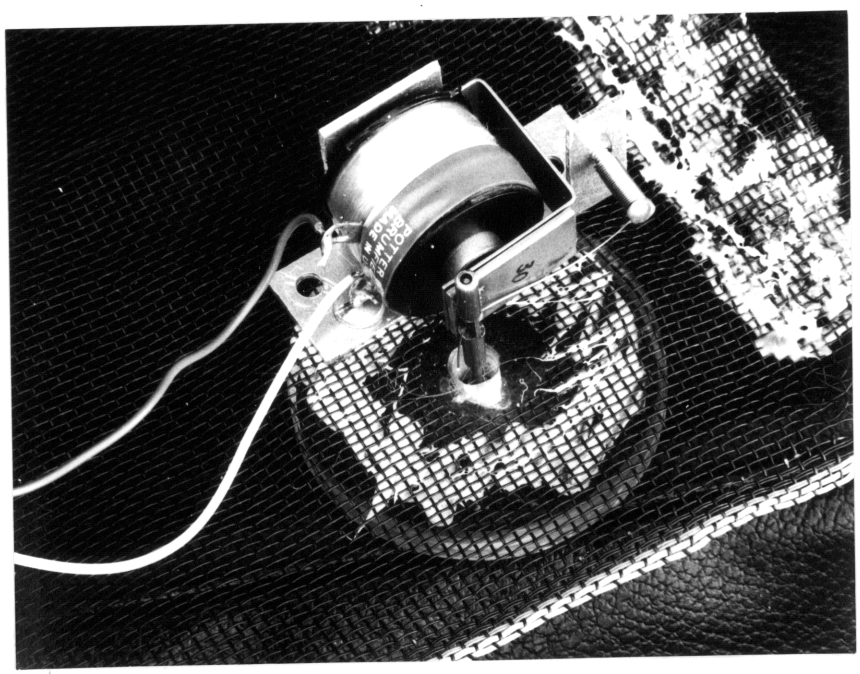


Figure A-6-- Close-up view of stimulator.

C. Electronics

1. Initial Electronics

The electronic circuit used in the initial tests (Chapter III) is presented in Figure A-7. Figure 15 in Chapter III is a photograph of this equipment.

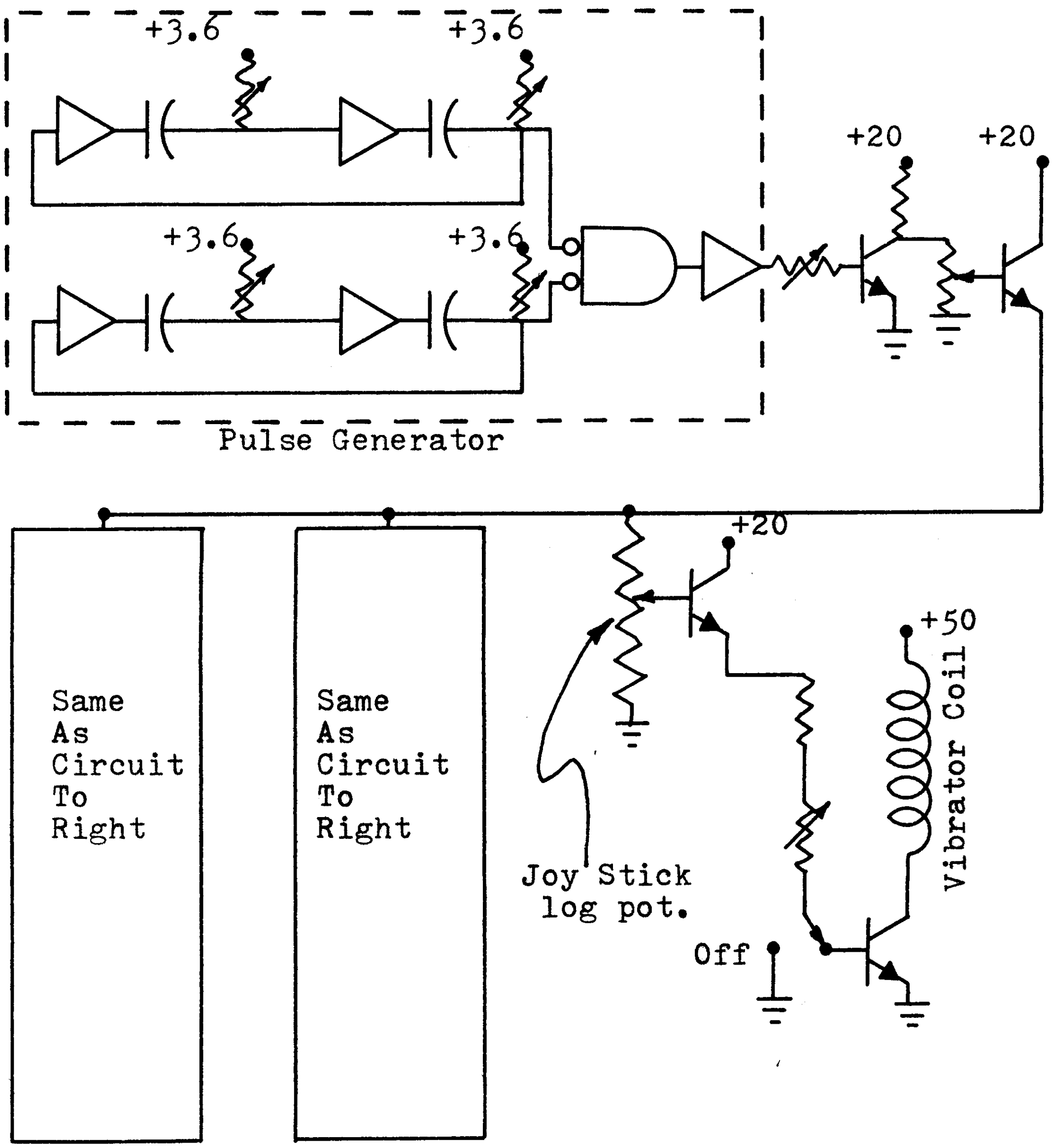


Figure A-7 Initial electronics circuit.

2. <u>Final Electronics</u>

A photograph of the final electronic equipment is shown in Figure A-8. Figure A-9A is the circuit diagram for conversion of x-y voltages to R,L, and T voltages. Figure A-9B is the circuit which controlled the stimulators using the R,L, and T voltages. The primary advantage of this circuit was that the pulsed vibration could be controlled logarithmically by an external linear voltage.

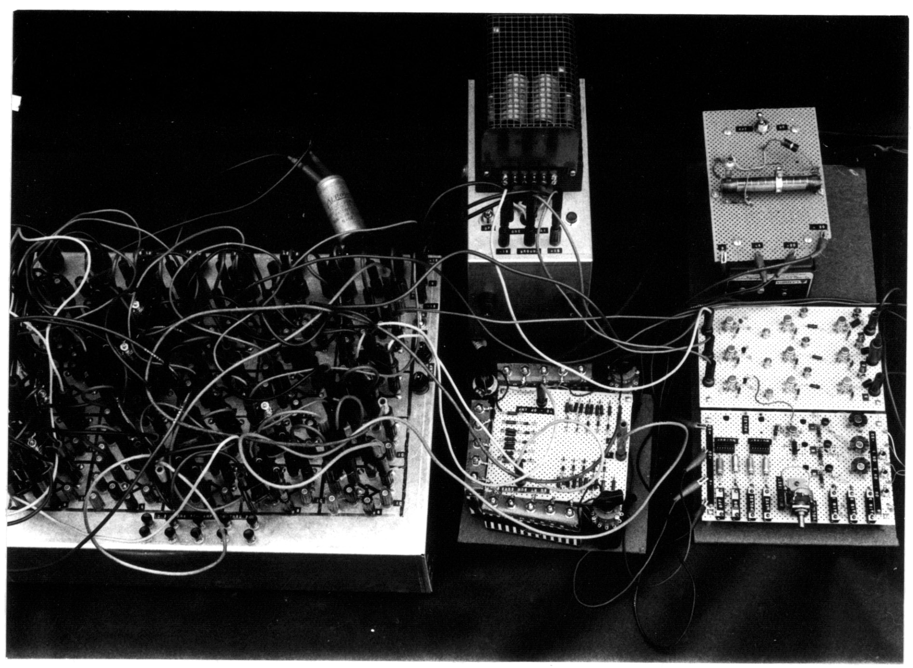


Figure A-8-- Photograph of final electronic equipment.

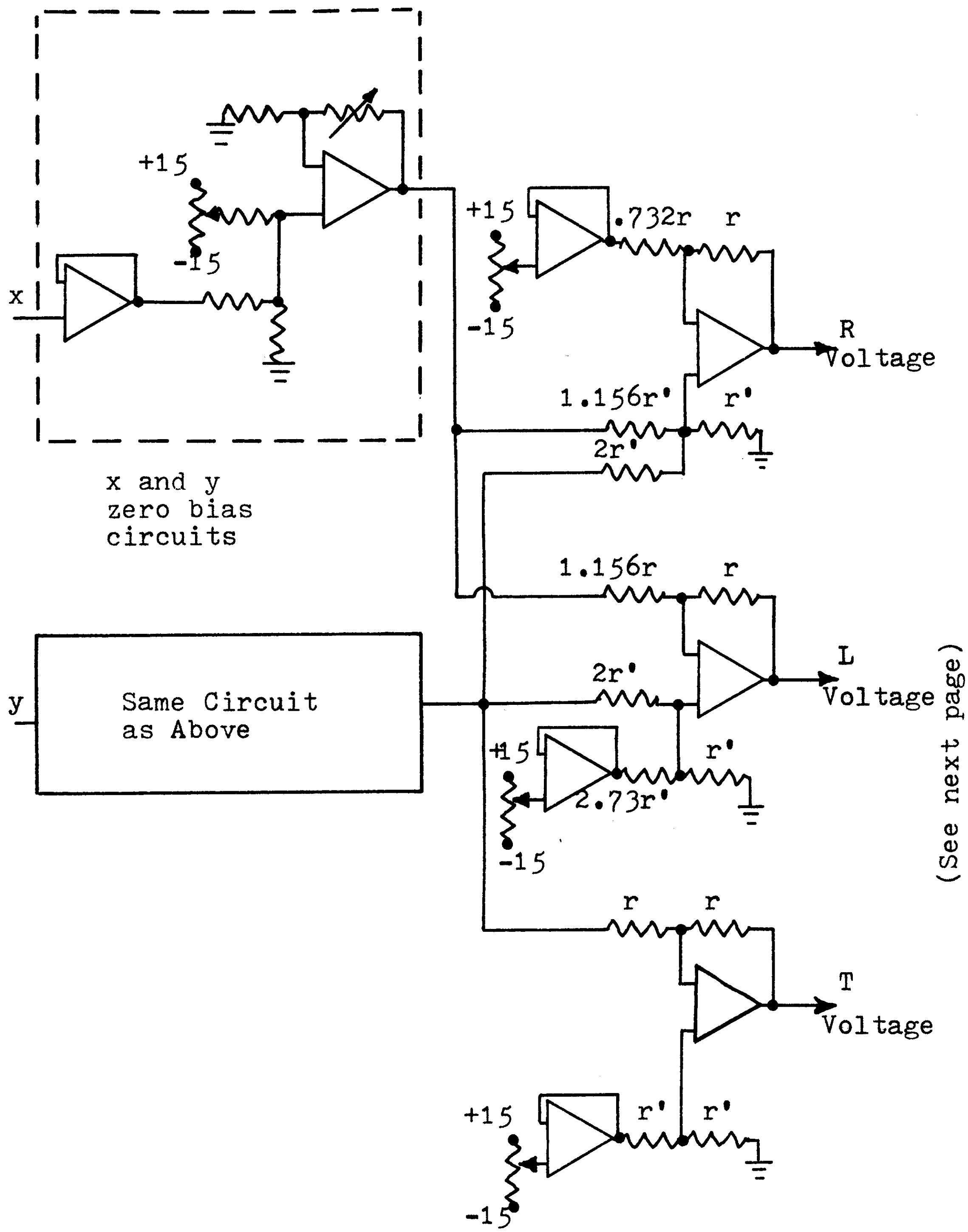


Figure A-9A-- Final electronic circuit for conversion of x-y voltages to R,L, and T voltages.

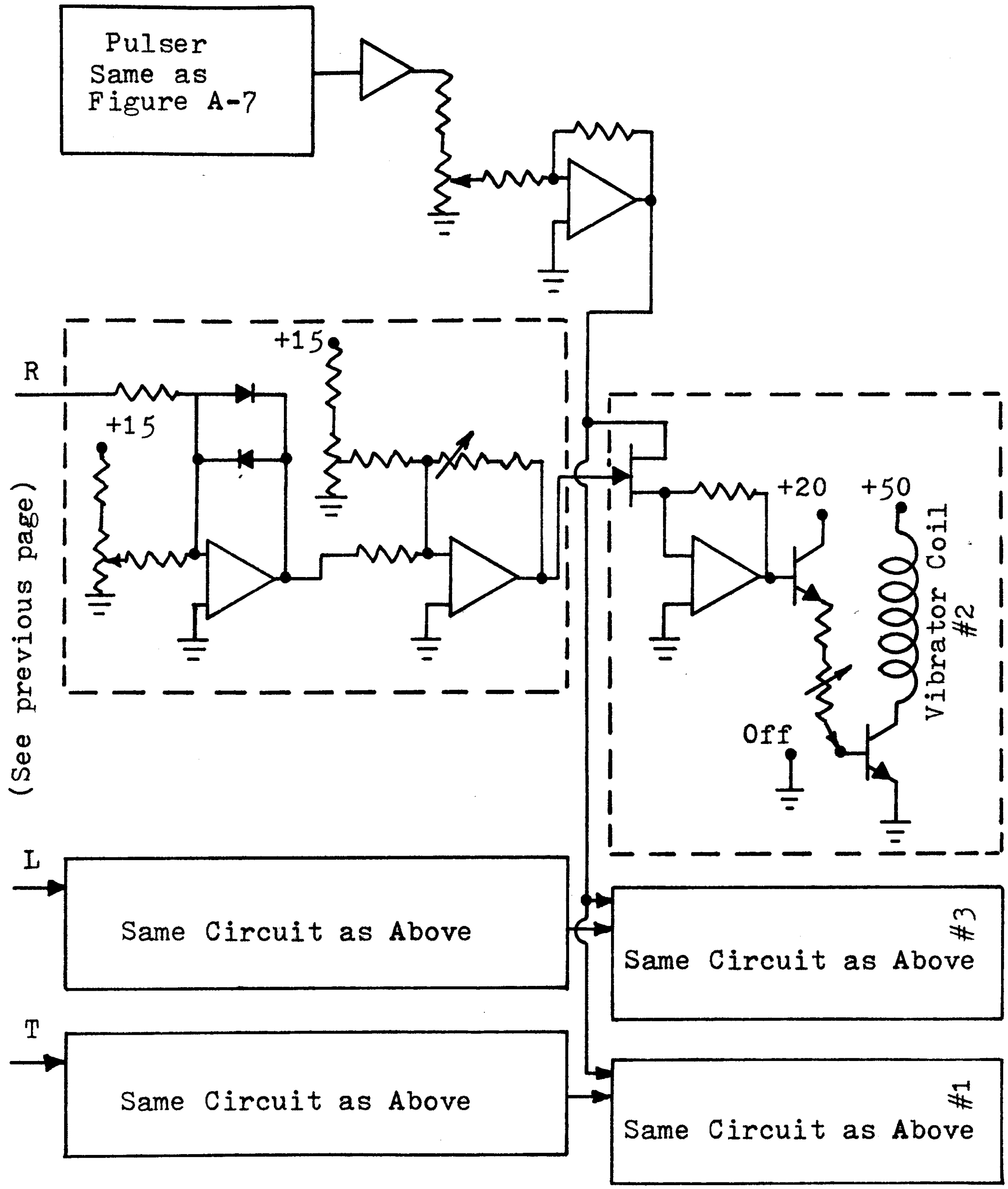


Figure A-9B-- Circuit for pulsed, logarithmic amplitude control from an external voltage.

3. <u>Analog Manifold</u>

Figure A-10 is a photograph of the analog manifold constructed for this study. It was an array of 20 operational amplifiers which could be wired in any configuration desired. The system also had eight potentiometers that could be used as desired. Manual switches allowed input of initial conditions to amplifiers used as integrators. A typical circuit is shown in Figure A-11.

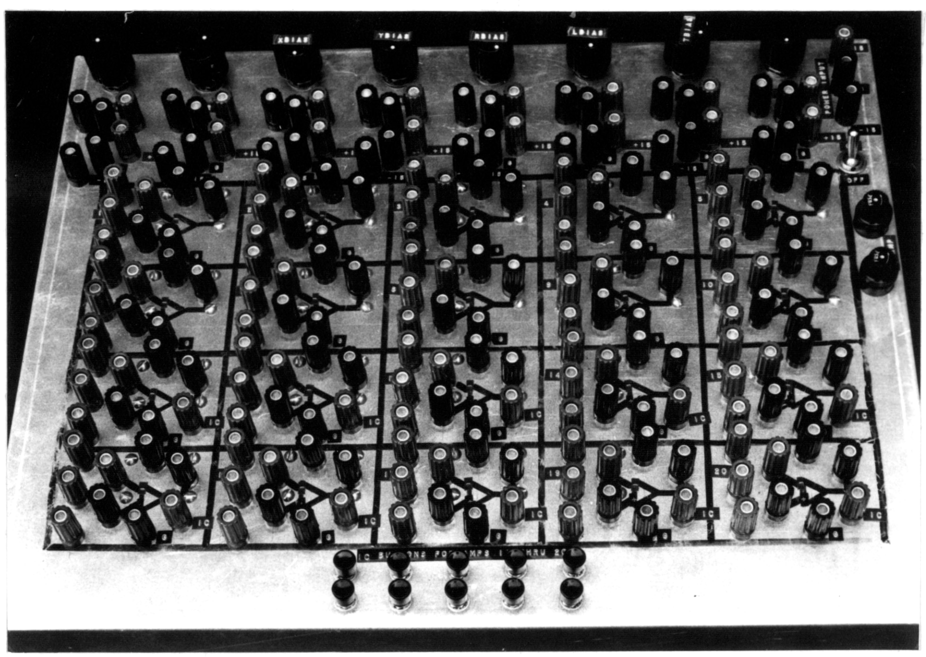
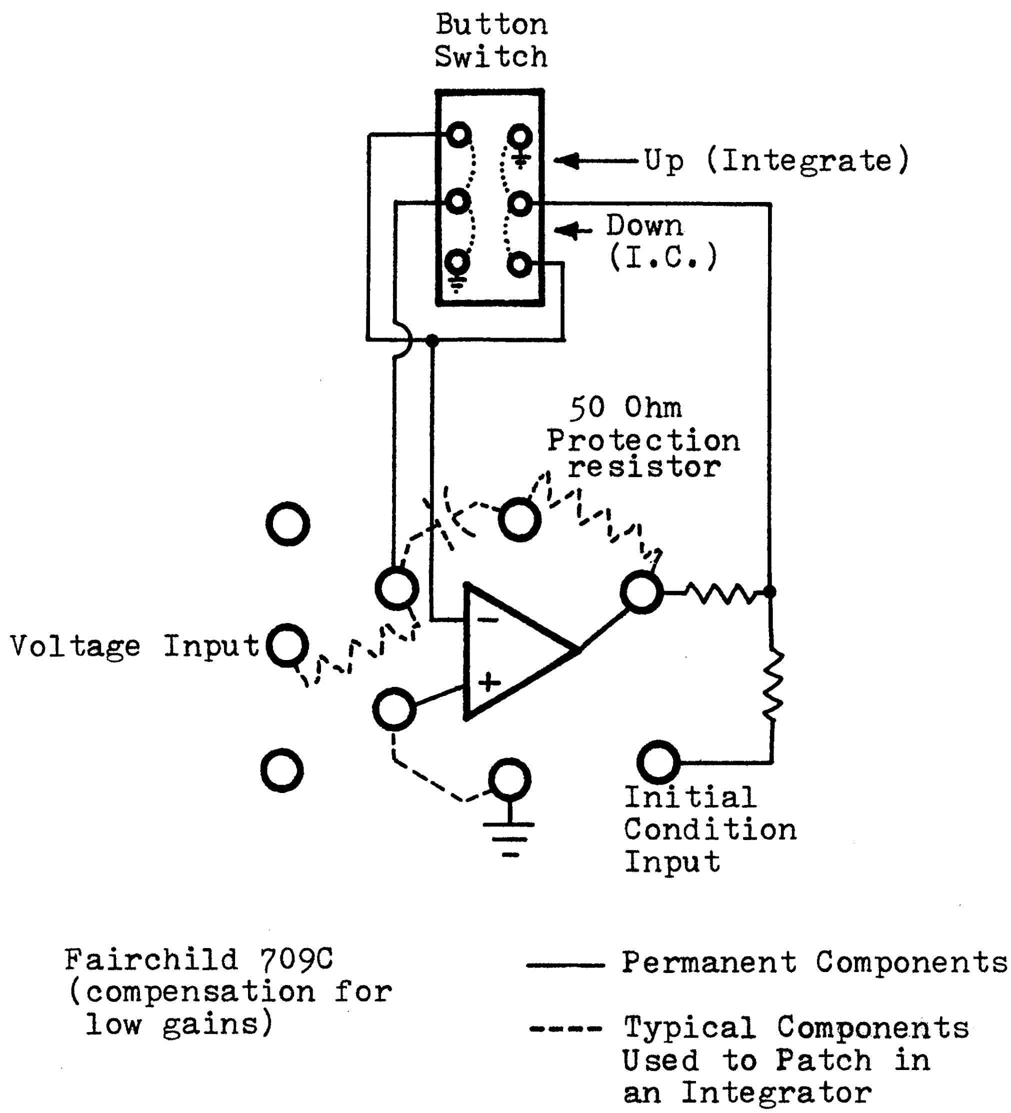


Figure A-10-- Operational Manifold.



Note: With no voltage input to the integrator, the integrator can be used as a track and store unit; button up = store, button down = track. The I.C. input is the signal being tracked or stored.

Figure A-11-- Basic amplifier circuit with initial condition switch.

4. Integral Error Processor

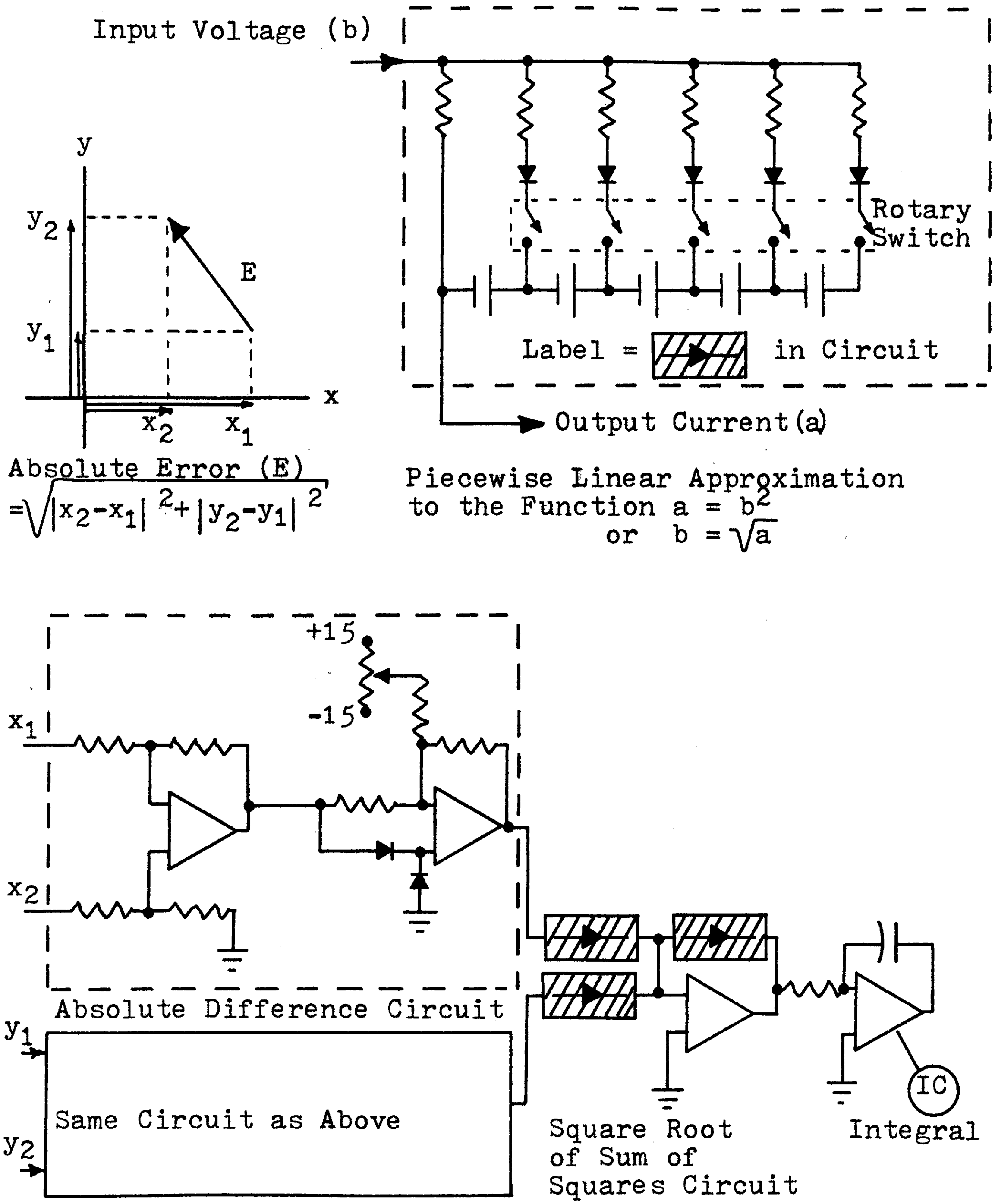


Figure a-12-- Circuit diagram for integral-absolute error processor.

5. <u>Tape Delay Mechanism</u>

The tape delay mechanism was used to eliminate the subject's response lag during integral error processing of direct tracking experiments. A photograph is presented in Figure A-13.

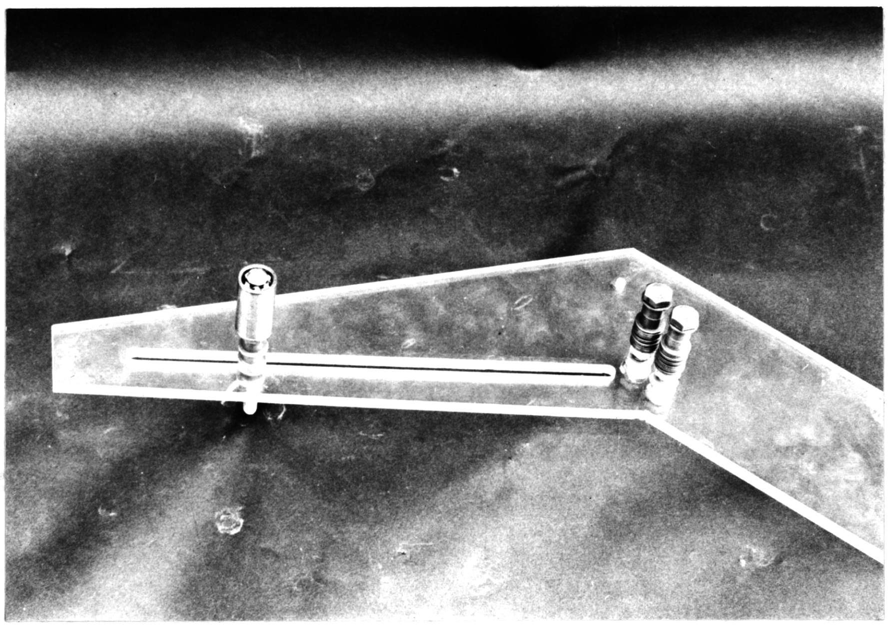


Figure A-13-- Tape delay.

6. <u>Analog to Digital Quantizer</u>

This circuit was originally intended to be used in an audio comparison to the phantom sensation. The input triangle is split into 15 positions. Seven of these areas, as shown in Figure A-14, were used to run the array of seven stimulators which were described in Chapter VII. Figure A-15 is the logic diagram.

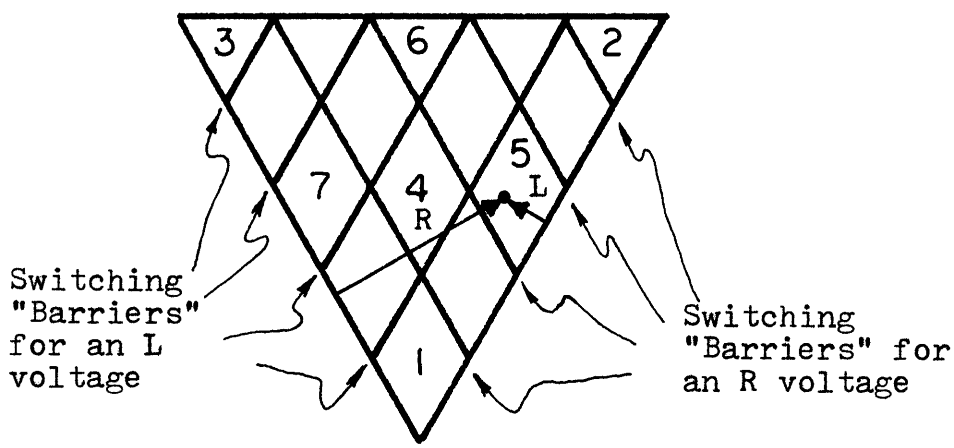


Figure A-14-- Seven areas used of the 15 area quantizer.

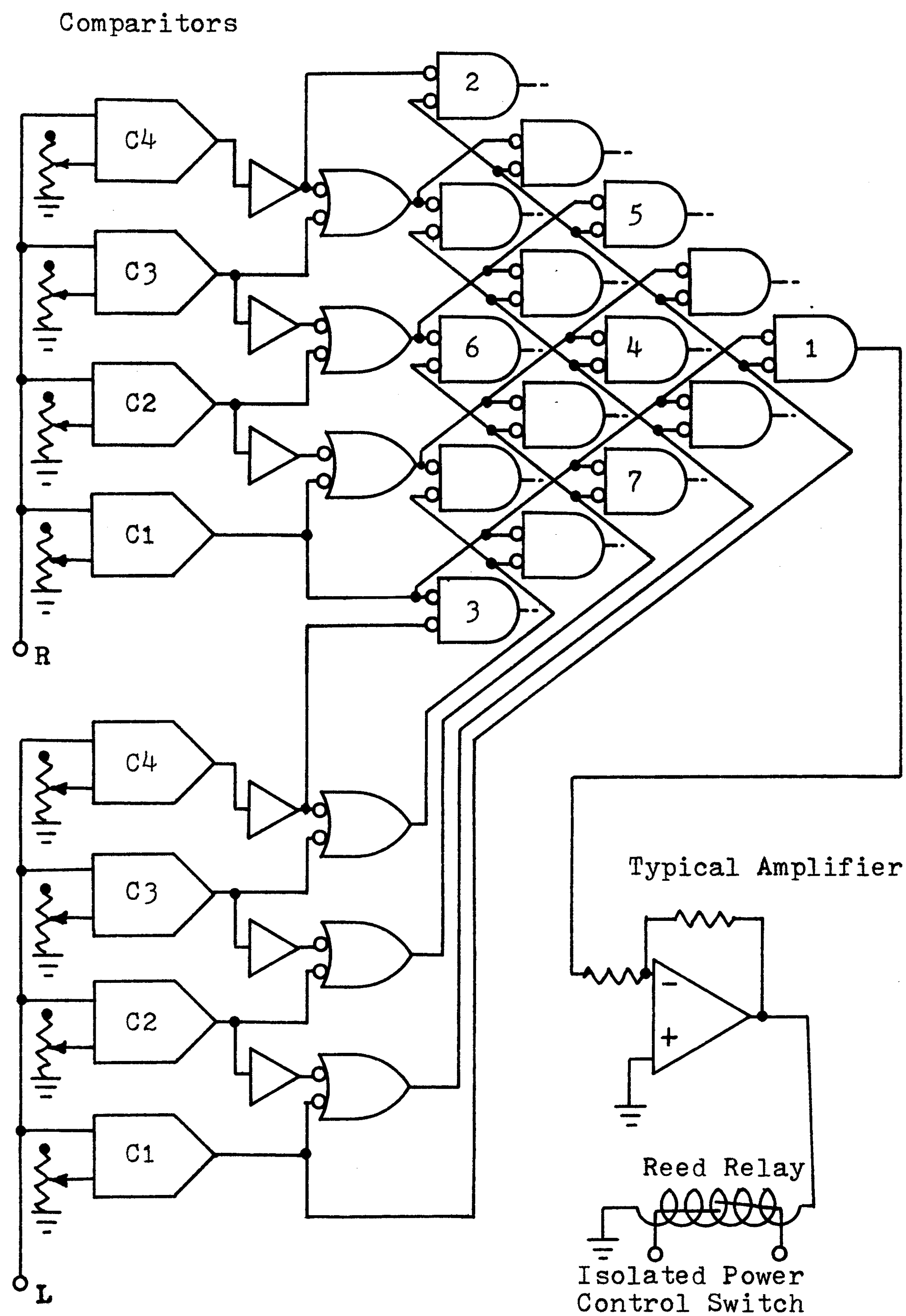


Figure A-15-- Logic diagram for 15 area quantizer.

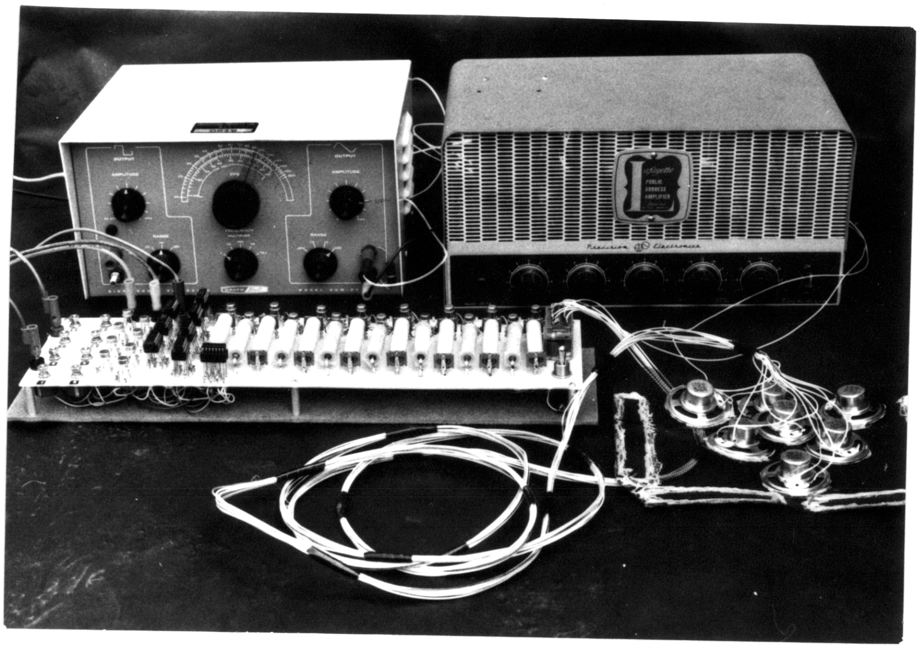


Figure A-15B-- Photograph of equipment used with the array of seven stimulators.

D. Amplitude Measurement

A calibrated microscope and stroboscopic light were used to measure the vibration amplitude with the stimulator impeded by fleshy skin. The amplitudes were correlated to the d.c. drop across the vibrator coil. The experiment is diagramed in Figure A-16. The results are shown in Figure A-17.

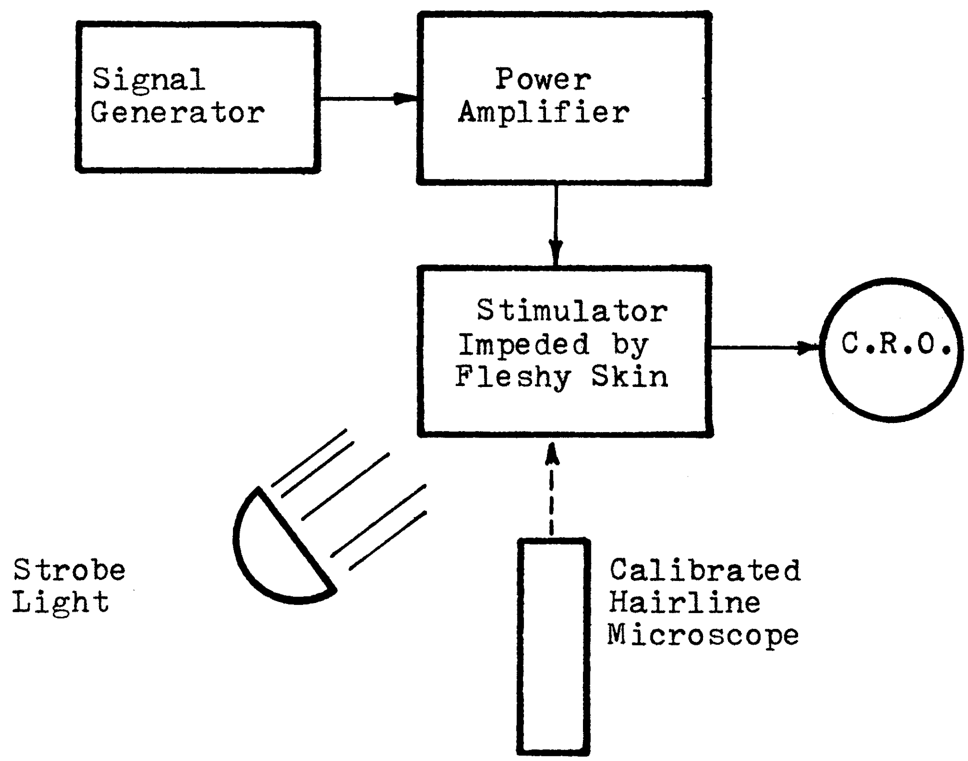


Figure A-16-- Experimental measurement of vibrational amplitude.

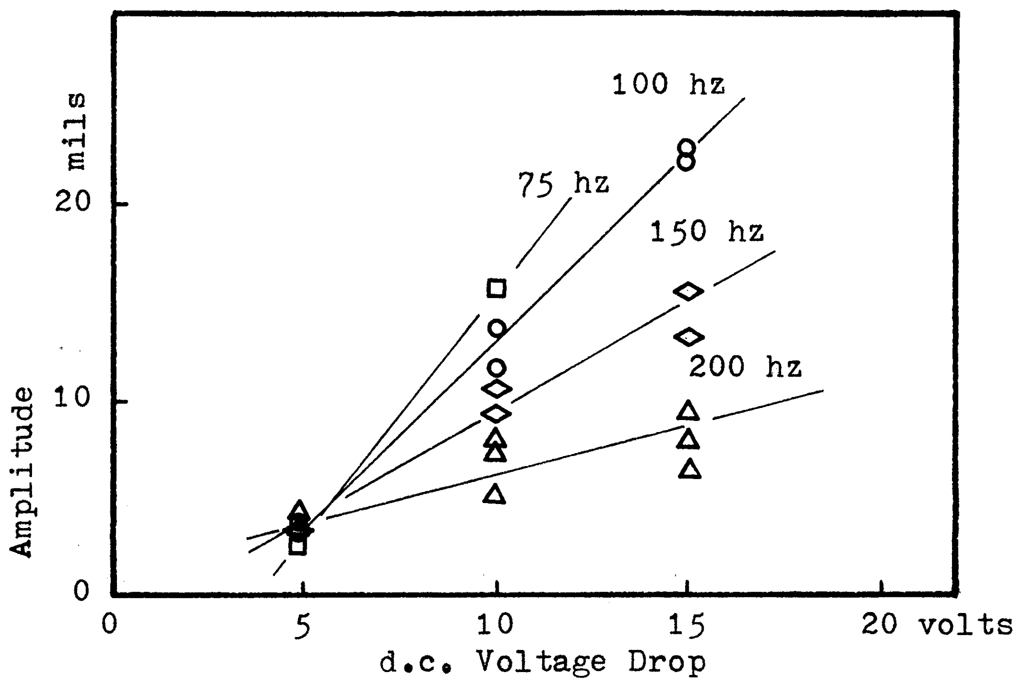


Figure A-17-- Vibrator amplitude versus d.c. drop across stimulator coil.

APPENDIX 2

Information Theory

The basic information contained in answer to a yes or no question, assuming yes and no have the same probability of occurrence, is one bit. If, in order to specify a given outcome from among several equal possibilities, a series of k yes or no answers is required, then the information is k bits. For example, if the task is to choose between 8 items, then three yes or no questions, which divide the sample space into smaller and smaller segments, will eventually specify one item. The formula for the information (H) is:

$$H = \log_2 N \qquad \text{(bits)} \qquad \text{(A1)}$$

When choosing from among N equal possibilities at a fixed rate ($\dot{n}$), the information rate ($\dot{H}$) is:

$$\dot{H} = \dot{n} \log_2 N \qquad \text{(bits per second)} \qquad \text{(A2)}$$

The situation when outcomes have unequal probability of occurrence is best explained by a simple example: N items are divided into a group of n_1 items of the first type and n_2 items of the second type.

Group 1 n_1 } N items
Group 2 n_2

If we know the bits required to specify which group the item is in, then what is the additional total information required to specify one of the items? It is the probability of being in one group times the bits in that group. In mathematical terms:

$$\begin{pmatrix}\text{Bits to}\\ \text{determine}\\ \text{which}\\ \text{group}\end{pmatrix} + \begin{pmatrix}\text{Chance}\\ \text{of}\\ \text{being in}\\ \text{group 1}\end{pmatrix} \cdot \begin{pmatrix}\text{Bits to}\\ \text{determine}\\ \text{which}\\ \text{item in}\\ \text{group 1}\end{pmatrix} + \begin{pmatrix}\text{Chance}\\ \text{of}\\ \text{being in}\\ \text{group 2}\end{pmatrix} \cdot \begin{pmatrix}\text{Bits to}\\ \text{determine}\\ \text{which}\\ \text{item in}\\ \text{group 1}\end{pmatrix}$$

$$= \begin{pmatrix}\text{Bits to}\\ \text{determine}\\ \text{item if}\\ \text{ungrouped}\end{pmatrix}$$

or:

$$H_G + (n_1/N)\log_2 n_1 + (n_2/N)\log_2 n_2 = \log_2 N \qquad \text{(A3)}$$

Solving for H_G and rearranging:

$$H_G = -\log_2 \frac{n_1^{\frac{n_1}{N}} \cdot n_2^{\frac{n_2}{N}}}{N} \qquad \text{(A4)}$$

Using the identity, $1 = \dfrac{n_1 + n_2}{N}$:

$$H_G = -\frac{n_1}{N}\log_2 \frac{n_1}{N} - \frac{n_2}{N}\log_2 \frac{n_2}{N} \qquad \text{(A5)}$$

Or, since $\frac{n_1}{N}$ is simply the probability of being in group 1, the information in a situation with outcomes of unequal probability is:

$$H = - \sum^{i} P_i \log_2 P_i \qquad (A6)$$

As before, if there is a rate ($\dot{n}$) associated with the process:

$$\dot{H} = -\dot{n} \sum^{i} P_i \log_2 P_i \qquad (A7)$$

To measure the information in a continuous signal, the signal is quantized into just recognizable amplitude levels. The information in the signal is then the logarithm of the total levels. To reconstruct any continuous waveform, samples need to be taken at two times the maximum frequency present in the signal. Using this fact, the information rate for a continuous signal is:

$$\dot{H} = 2 f_{max} \log_2 N \qquad (A8)$$

When the amplitude levels have varied probability of occurrence the information rate is:

$$\dot{H} = -2 f_{max} \sum^{i} P_i \log_2 P_i \qquad (A9)$$

The information transmission process via some communication channel was described in Chapter IV. Equation 1 models this process:

$$T(in,out) = H(in) + H(out) - H(in,out) \qquad (1)$$

Derivation of equation 2 of Chapter IV is presented here. Referring to the contingency table listed in Figure 18 of Chapter IV, the sum of a column is the relative frequency of a particular input event. Likewise, the sum of a row is the relative frequency of a particular output event. Using these frequencies, the associated probabilities can be estimated by dividing by M, the total number of in-out events in the experiment. Hence, the information for input and output using equation A6 is:

$$H(in) = -\sum^{i} \frac{n_i}{M} \log_2 \frac{n_i}{M} \qquad (A10)$$

$$H(out) = -\sum^{j} \frac{m_j}{M} \log_2 \frac{m_j}{M} \qquad (A11)$$

$$H(in,out) = -\sum\sum^{ij} \frac{n_{ij}}{M} \log_2 \frac{n_{ij}}{M} \qquad (A12)$$

Using equation 1 the transmitted information can be computed easily with the aid of a computer. However, if the following transformation of the above equations is made, calculation of the information transmission is easy to do with the aid of an adding machine. Rearranging equation A10:

$$H(in) = \sum^{i} \frac{n_i}{M} \log_2 N \; - \sum \frac{n_i}{M} \log_2 n_i \qquad (A13)$$

Or, since $\sum^{i} \frac{n_i}{M} = 1$:

$$H(in) = \log_2 M - \frac{1}{M} \sum^{i} n_i \log_2 n_i \qquad (A14)$$

Similar transformation can be made for equations A11 and A12. The information transmission now is:

$$T(in,out)=\log_2 M-\frac{1}{M}\left[\sum^{i} n_i \log_2 n_i+\sum^{j} m_j \log_2 m_j-\sum\sum^{ij} n_{ij}\log_2 n_{ij}\right] \quad (2)$$

The tables of $\log_2 n$ and $n \log_2 n$ listed in the appendix of reference 2 make information calculations simple with an adding machine and equation 2.

B. Tracking Tape Production

Figure A-18 is a simplified flow diagram of the hybrid computer program used to create the tracking tapes used in optimization of the system parameters.

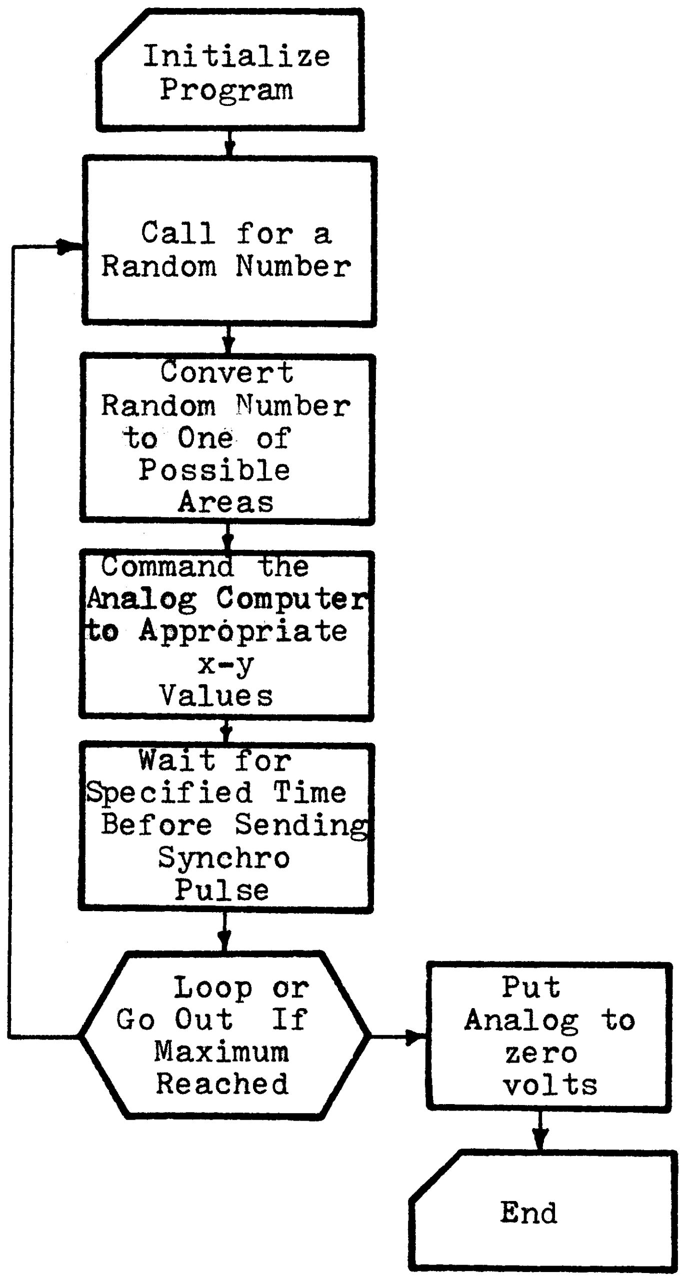


Figure A-18-- Tracking tape flow diagram.

APPENDIX 3

Data

Contingency tables have been used to present the total record of the tracking experiments. There are three positions in each square of the tables. The top numbers are data from Subject F. The middle numbers are from Subject L. The bottom numbers are from Subject V (the blind subject).

TABEL 3-A

Seven Area Phantom Display

Output \ Input	1	2	3	4	5	6	7	Total
1	157 106 95		1		 1 9		5 6 6	163 113 110
2	1	155 94 102		1	8 7	1		166 101 102
3			150 85 88	4 1		 4	15 4 2	169 89 95
4	1			133 127 124	18 4 14	24 3 6	3 5 6	179 139 150
5	 1	1		4 6 5	103 89 85	5		113 95 91
6		 8	 2	13 10 4	1 3 2	160 98 106		174 111 122
7	1 1		 2	14 7 18	1		117 98 87	133 106 107
Total	160 107 96	156 94 110	151 85 92	169 150 152	131 104 110	190 101 116	140 113 101	1097 754 777

TABLE 3-B: 16 Area Phantom Display

Input (columns) / Output (rows)

Output	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total
1	8 12 18							1 1									9 12 19
2		10 14 17							3 1	1 1 1							14 16 18
3			10 10 18				2				2 1	5 4 1	1			1	21 15 19
4				6 12 10		1			1			1		2 2 2	1 1	1	10 16 14
5	2			1	2 2 1			2 1 2	1 3								4 6 7
6						11 7 11				5 4 6	3				1 2	1	18 11 22
7				3			2 4 6					1 6	1	1			3 5 16
8					1 8			5 2 3	1					1			5 3 13
9					2 1 2			1	1 2 6								3 4 8
10		1				1				3 2 7					1 1		4 3 9
11						1 1 1	1			1	5 4 6					1 1	8 7 7
12							1 1 4					1 6				1 1	2 2 11
13							2						5 2 6	1		1	6 3 8
14				1				1						3 5 4			4 5 5
15				1											2 5 5		2 5 6
16						1								1		1 3 5	1 3 7
Total	8 14 18	10 15 17	10 10 18	7 12 15	4 4 11	12 9 14	5 6 12	8 4 7	5 4 10	10 7 14	7 5 9	7 4 14	6 3 6	6 7 9	5 6 8	4 6 7	114 116 189

TABLE 3-C

Results for Array of 7 Vibrators

	Input 1	2	3	4	5	6	7	Total
1	46 56 43			3 5 1	 1		1 1 1	50 62 46
2		35 39 28			1 7 2			36 46 30
3			28 41 32	 1 		1 1 	5 1	34 43 33
4	 3 4			51 73 50		4 1 8		55 77 62
5	 5 	2 12 1		 2 	42 54 27			44 73 28
6		 2		1 4 1		29 45 34	1 	31 49 37
7	1 1 		 7 7	1 3 	 1		25 69 30	27 80 38
Total	47 65 47	37 51 31	28 48 39	56 88 52	43 61 31	34 47 42	32 70 32	277 430 274

D. Sample Calculations

Average Percent Error from Integral Error

Let:

E = Integral error
$e(t)$ = absolute tracking error
e_{av} = average error equivalent to $e(t)$

By definition:

$$E = \frac{1}{RC} \int_0^T e(t)dt$$

For e_{av} to be equivalent to $e(t)$:

$$E = \frac{1}{RC} \int_0^T e_{av}\, dt = \frac{e_{av}T}{RC}$$

or:

$$e_{av} = \frac{RCE}{T} \qquad \text{(A15)}$$

Dividing by the voltage equal to the length of one side of the triangle (V_1) we obtain the defined percent error:

$$e_{av}\% = \frac{RCE}{T\ V_1} \cdot 100 \text{ percent} \qquad \text{(A16)}$$

Average Error from the Contingency Tables

The errors representing each in-out event produced an error matrix with a zero diagonal (correct response). The dot product of this error matrix and the contingency table gave the estimated total error. The average error was this number divided by the total number of in-out events in the tracking experiment. As above, this average error was used to compute the percent error.

APPENDIX 4

A Possible Mobility Aid

Since the objective of this thesis was not to create a mobility device, little of this work was done. However, a simple hypothetical model of such a device was created. As shown in Figure A-19, the device perhaps would be some type of sensor that scans a triangular area (from left to right) in front of the blind person. Suppose there were two objects in the path as shown in the figure. As the sweep occurred, there would be no sensation until the scanner detected the first object. A phantom sensation would occur in the triangle on the abdomen corresponding to the location of the object. The sensation would stop after the scanner passed this object. A similar excitation would occur to indicate the other object. If the scanning were done at the proper speed, the blind traveler should feel two phantom sensations; one corresponding to the location of each object.

Hopefully, a simple object like a wall directly in front of the traveler would be felt as a continuous movement of the phantom sensation. An open door or a clear path would be indicated by the absence of the sensation.

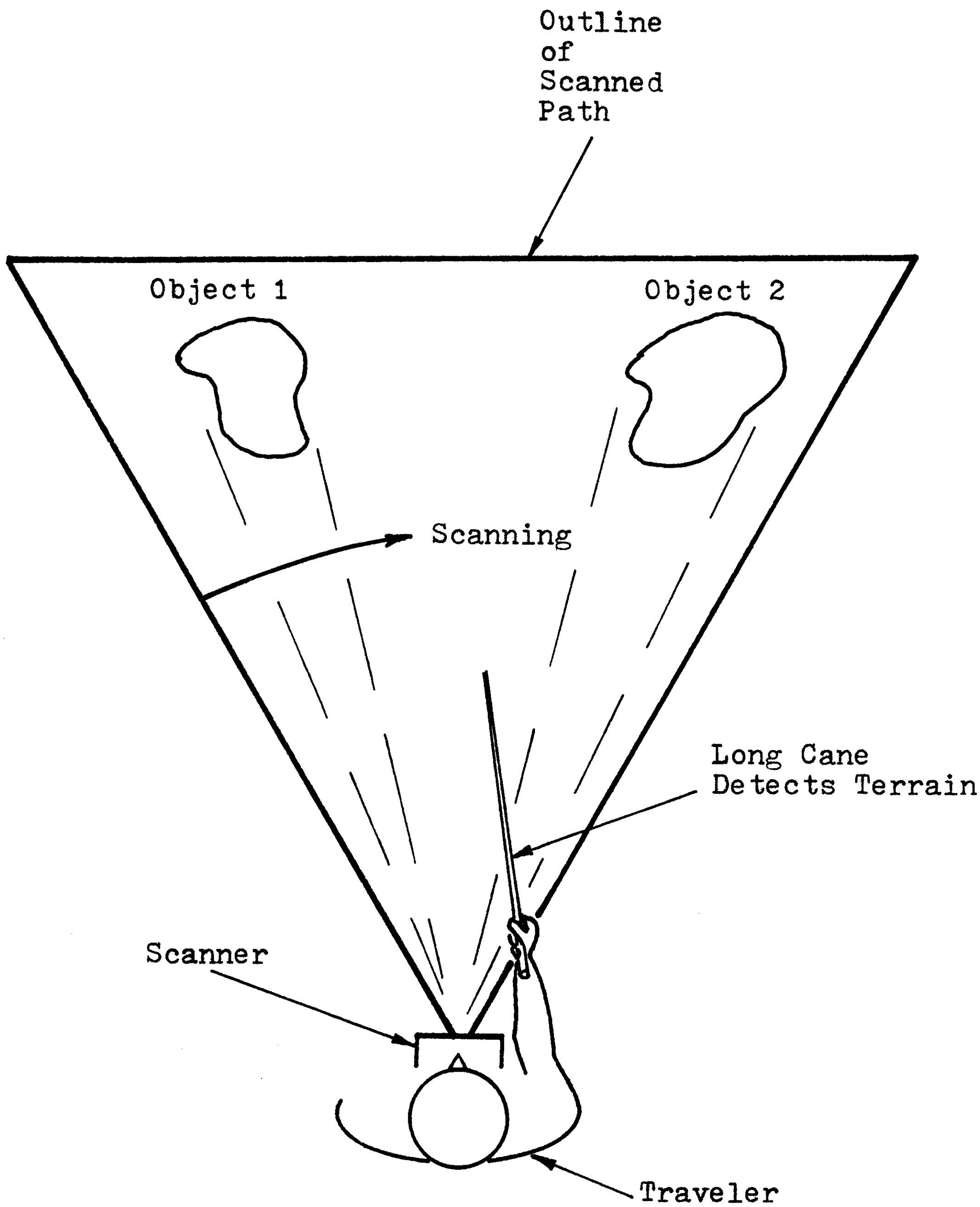


Figure A-19-- A possible mobility aid for the blind.

APPENDIX 5

Mathematical Model of Mobility

Krigman[26] developed a model of blind mobility based on the assumption that a traveler "uses" the information in a small area directly in front of him. During the course of the thesis, an improved model was developed. Because this topic is not part of the stated thesis objectives, it is presented here.

Figure A-20 represents a rectangular area in front of a traveler. The model just as well could be a volume, but an area is simpler to visualize. The outline also need not be rectangular. Again, this was done for simplicity.

In the discussion that follows the terms are:

- v = velocity, a constant for this model
- s = scanning rate (area per unit time)
- k = an efficiency factor in viewing an area
- R = the range of the scanner
- w = the width of the field scanned
- b = depth of a small area used for the "decision to continue"
- r = distance in front of the traveler at which decisions about his travel are made
- t = time that area wb has been in the field of view
- t* = time that the traveler has spent viewing area wb
- T = time required to stop or make a maneuver
- p = percent of the decision field information required for travel
- n = information density (bits per unit area) uniform and constant in this model
- N = information in the decision area (wb)
- H = information that is known at the decision center about the decision area (wb)
- $\dot{H}$ = the maximum information rate of the channel

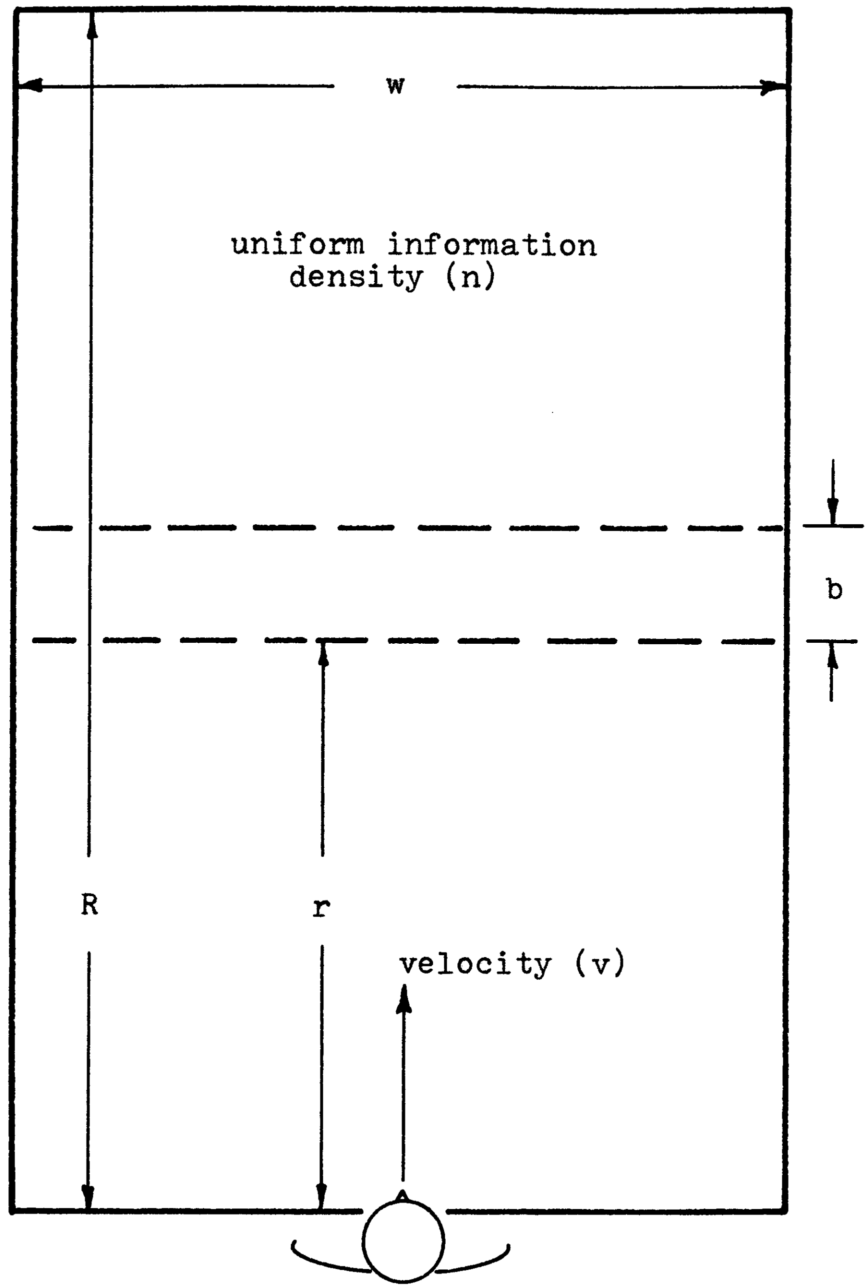


Figure A-20-- Rectangular field of view in front of the traveler.

The model assumes that our senses receive information by scanning small areas at a time, much like reading a book. The limiting factor on the velocity of travel is assumed to be the knowledge about a specified "decision field" (wb) at a distance (r) in front. For example, when we drive a car, we unconsiously make our decisions about stopping or turning by the knowledge we have about an area at some distance in front of the path of travel. If we can't see very far (a foggy night) or if our reaction time is long, we have to go slower. That is:

$$\begin{pmatrix}\text{Required} \\ \text{Information} \\ \text{in the} \\ \text{Decision Area}\end{pmatrix} \leq \begin{pmatrix}\text{Information} \\ \text{about the} \\ \text{Area at the} \\ \text{Decision} \\ \text{Center}\end{pmatrix} \qquad \text{(A17)}$$

The information rate to the decision center is modeled in Figure A-21.

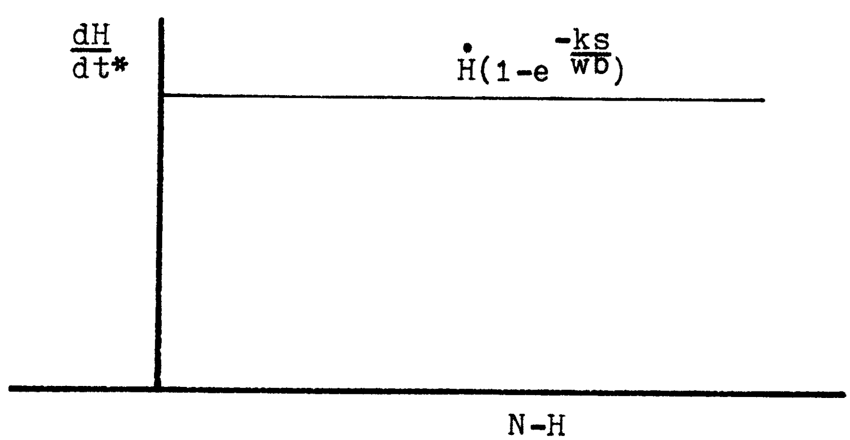


Figure A-21-- Model of information inflow to the decision center about a small decision field (wb).

The equation of the model is:

$$\frac{dH}{dt^*} = \begin{cases} (1 - e^{-\frac{ks}{wb}})\, \dot{H} & , \quad N-H > 0 \\ 0 & , \quad N-H \leq 0 \end{cases} \qquad (A18)$$

Solving equation A18 using the appropriate initial conditions:

$$H = \begin{cases} (1 - e^{-\frac{ks}{wb}})\dot{H}t^* & , \quad N-H > 0 \\ N & , \quad N-H \leq 0 \end{cases} \qquad (A19)$$

The information in the decision field required for travel is pnwb. As stated in equation A17, this must be less than or equal to the information at the decision center (equation A19). Note that t* can be written in terms of the velocity and the proportion of time ($\frac{b}{R}$) that the "scanner" has been looking at area bw.

$$t^* = \frac{b}{R}\, t = \frac{b}{R}\,(\frac{R-r}{v}) \qquad (A20)$$

The human reaction time (T) will specify at what distance (r) the decision must be made, so:

$$r = Tv \qquad (A21)$$

Therefore, equation A20 becomes:

$$t^* = \frac{b}{R}\,(\frac{R-Tv}{v}) \qquad (A22)$$

Using equations A17, A19, and A22:

$$pnwb < \begin{cases} (1-e^{\frac{-ks}{wb}})\dot{H}\frac{b}{R}\left(\frac{R-Tv}{v}\right) & , N-H > 0 \\ nwb & , N-H \leq 0 \end{cases} \qquad (A23)$$

Putting the appropriate quantities into the (N-H > 0) inequality, the effects of the information upon the velocity of travel can be better visualized:

$$N-H > 0 \qquad (A24)$$

or:

$$nwb - (1-e^{\frac{-ks}{wb}})\dot{H}\frac{b}{R}\left(\frac{R-Tv}{v}\right) > 0 \qquad (A25)$$

Solving for v:

$$v > \frac{1}{\frac{nw}{\dot{H}(1-e^{-\frac{ks}{wb}})} + \frac{T}{R}} \qquad (A26)$$

This shows that the velocity is independent of any information if it is slow enough for appropriate conditions. When inequality A26 is the case, the velocity is limited by the upper portion of equation A23. Using the equal sign as the limit and solving for the velocity:

$$\boxed{v = \frac{1}{\frac{pnw}{\dot{H}(1-e^{\frac{-ks}{wb}})} + \frac{T}{R}}} \qquad (A27)$$

Table 5-A shows the effects on the velocity as the various parameters go to their limits. It would be interesting to examine these predictions experimentally. Notice that, contrary to Krigman's model, this model (equation A27) relates that the velocity is a function of the information density. This seems more logical.

TABLE 5-A

Velocity as Parameters are Taken to Limits

Parameters	Parameter Limit	Associated Velocity Limit
p, n, or w	0	$\frac{R}{T}$
T	0	$\frac{\mathring{H}(1-e^{\frac{-ks}{wb}})}{pnw}$
$\dot{H}$, k, s, or R	0	0
b	0	$\frac{R\dot{H}}{pnwR + \dot{H}T}$
p	1	$\frac{1}{\frac{nw}{\dot{H}(1-e^{\frac{-ks}{wb}})} + \frac{T}{R}}$
n, w, b, or T	∞	0
$\dot{H}$	∞	$\frac{R}{T}$
R	∞	$\frac{\dot{H}(1-e^{\frac{-ks}{wb}})}{pnw}$
k or s	∞	$\frac{R\dot{H}}{phwR + \dot{H}T}$

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