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PERCEPTION OF PATTERNED VIBRATORY STIMULATION:
AN EVALUATION OF
THE TACTILE VISION SUBSTITUTION SYSTEM

by

Lawrence Allyn Scadden

A DISSERTATION

Presented to the Department of Visual Sciences
and the Graduate School of the University of the Pacific
in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

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This dissertation, written and submitted by

Lawrence Allyn Scadden,

is approved for recommendation to the
Graduate Council, University of the Pacific.

Department Chairman or Dean:

Dissertation Committee:

Joseph W. Metz

Carter Collins

Paul Bach y Rita

Benjamin V. White

Douglas W. Matheson

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PERCEPTION OF PATTERNED VIBRATORY STIMULATION: AN EVALUATION OF THE TACTILE VISION SUBSTITUTION SYSTEM

ABSTRACT

By Lawrence Allyn Scadden

Sensory substitution—the replacing of an impaired sensory channel by a properly functioning one—is possibly best manifested today in attempts to provide visual aids for the blind. The tactile vision substitution system (T.V.S.S.) is an example of one such visual aid. The system presents patterned tactile stimulation to the skin of the observer provided by the output of a closed-circuit television system. Research conducted with congenitally blind Ss in evaluation of the T.V.S.S. has provided useful information concerning the potentialities and limitations of the prototype systems, similarities and differences between tactile and visual perception, and the development of "visual" perception in the congenitally blind.

Investigation demonstrated that the congenitally blind Ss can learn to make valid judgments of three-dimensional displays with the T.V.S.S. Such judgments are made on the basis of properties contained in the proximal stimulation—properties analogous to the monocular cues of depth present

in vision, such as linear-perspective, apparent elevation in the visual field, size change as a function of distance, occlusion, and textural gradients.

Similarities have been noted between judgments made by sighted Ss using vision and by blind Ss using the T.V.S.S. on comparable tasks. A display consisting of two slightly displaced alternating lights is perceived in both situations as a single spot of light moving back-and-forth between two display boundaries. A rotating drum made up of alternate black and white stripes is, when stopped, perceived as briefly moving in the opposite direction. External localization of the source of stimulation also occurs with both sensory inputs.

The major differences between the visual and tactile inputs that have been noted have occurred in form recognition tasks. Although blind Ss using the patterned tactile stimulation are able to identify both geometric forms and abstract patterns, accuracy is consistently lower than that of sighted Ss using vision, and the latencies for the blind Ss are significantly longer. It is hypothesized that the longer latencies for the blind Ss using the T.V.S.S. can be accounted for primarily by the need to hand-position the television camera during scanning. A major factor in the lower accuracy for the tactile group is the noted difficulty in detecting and identifying display features located within a mass of stimulation. This difficulty with internal display detail may be a function of sensory inhibition and/or masking.

The research findings support a concept of sensory substitution as well as a theory of perception which stresses the amodality of many qualities contained in visible displays. Further research is needed to determine the significance of sensor movement--either eye movements or camera manipulation--in the perceptual process.

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I

Introduction

The concept of sensory substitution (the replacement of an impaired sensory input channel by a properly functioning one) may best be manifested today in the various research and development projects concerned with providing sensory aids for the blind. Typically in such aids, an ultrasonic beam or ambient light source provides the input for specially constructed sensors which transduce the signals into electrical impulses which, in turn, activate auditory or tactile output units. The sensations received by the observer from these output units contain representations of the input to the sensors. In this way, information from two-dimensional displays or three-dimensional space can be provided for the blind who are trained to use the devices.

Such devices also serve as tools for studying the similarities and differences existing between the sensory modalities as well as for testing theories concerning intermodality connections and cross modality transfer. The following chapters report some findings from research conducted in evaluation of one such sensory substitution device, the tactile vision substitution system (T.V.S.S.). These findings should provide additional information concerning the similarities and differences between the visual and tactile modalities and the learning process that occurs in sensory substitution.

Early investigation with the T.V.S.S. has been reported elsewhere

(Bach-y-Rita, Collins, Saunders, White, and Scadden, 1969; White, Saunders, Scadden, Bach-y-Rita, and Collins, 1970; Scadden, 1969). A closed-circuit television system displays the output of a television camera on the observer's skin by means of a stimulator matrix which delivers patterns of either mechanical or electrical stimulation. Preliminary investigation demonstrated that the congenitally blind were able to learn to identify simple visual patterns with the system. With these encouraging results, later experimentation was directed toward determining the characteristics of the system which might make it more useful for the blind for performing daily activities.

Sensory substitution, such as that reported here, has theoretical support in both neurophysiology and perceptual psychology. Bach-y-Rita (1967) suggested that the senses are plastic, resilient to new information inputs. With time, new neural networks may be developed to enhance the transmission and processing of the sensory information which had formerly been restricted to another sensory input, (e.g., patterned stimuli usually presented visually now presented tactilely). Future neurophysiological investigation will be needed to demonstrate the existence of such neural reorganization and if it is influenced by the introduction of the novel stimuli at some critical age.

The existence of trimodal cortical cells—cells which can be activated by visual, auditory, or somatic stimulation—has long been known (Murata, Cramer, and Bach-y-Rita, 1965; Mayers, Robertson, Rubel, and Thompson, 1971). Such cells have been found in many areas of the brain, cortical and subcortical. The existence of such cells may give support to theories of sensory plasticity and/or theories regarding the unity of the senses (Hayek, 1952).

Von Horngostel was quoted by Ellis (1938) in his description of what he termed "supersensuous sense perception". He stated, "It makes no difference by which sense I know that at night I have blundered into a pig sty." This "supersensuous sense perception" could be anything which could be seen, felt, heard, or experienced through more than one sensory channel. Gibson (1969) used the term "amodal" to refer to such experiences though the term was previously employed by Michotte and his colleagues in a somewhat different way. An amodal percept according to Michotte, Thinès, and Crabbé (1964) is an experience that does not stem from proximal stimulation in the place or time in which the percept occurs. For instance, Michotte referred to the well-known experience of viewing a figure with some central portion missing and still experiencing a solid form. Also, the tunneling effect occurring when a moving target passes behind some occluding structure, but which is seen as a solid moving target with only a shadow on it, was considered to be an amodal experience.

Gibson believed that both von Horngostel's "supersensuous sense perception" and Michotte's "amodal percepts" were higher order perceptual events. This higher order process was not modality specific. Much of perception is amodal in character by this definition. Many events can be experienced by more than one modality and are not modality specific or occur by filling in redundent information when it does not exist in the specific stimulation. Gibson stressed that much of what is generally termed cross-modality transfer is actually amodal in character. The quality of a sensation may vary along some dimension which is common to other modalities. What is experienced is not the sensation but the quality attributed to the stimulation source. Gibson stated that many of the distinctive characteristics of objects and of events are amodal in this way. The distinctive qualities can be experienced through a number of senses.

Another theory that deals with form perception that may have relevance to the T.V.S.S. stresses the role of eye movements in the perceptual process. This theory states that efferent programs to direct the saccaddic movement through innervation of the extraocular muscles during the process of object identification and form discrimination are monitored as an integral part of the perceptual process. The theory is based on the assumption that eye movements are directed by matching afferent input (primarily the retinal image in this case) with an efferent copy (von Holst, 1964; Held, 1961). Taylor (1962) stated that such programs are learned, learning which results in engrams, or traces, consisting of the proper motor responses for almost any constellation of retinal stimulation. The particular stimulation will determine which program will be selected. Perception, then, is not considered to be an organization of afferent input, but it is considered to be the conscious awareness of the engrams brought into play at any time by the afferent input. The totality of the efferent program engrams brought into play at any moment constitutes the perceptual process. Taylor's theory would account for the fact that filling-in of blank areas in a visual display occurs. Only the distinctive features of a known scene would be needed to elicit the engrams of the process of scanning the entire pattern. Even if the scanning did not take place in its entirety, the percept would be complete.

Festinger, Burnham, Ono, and Bamber (1967) stated that tachistoscopic and stabilized retinal presentations lead to contour analysis without the occurrence of eye movements. Thus, Festinger added the concept of efferent readiness to Taylor's theory; the engram or efferent program can be called into consciousness without the enactment of the efferent program and still result in a valid percept. Later, Festinger (1971) demonstrated that these efferent programs can be for head or limb movement and not exclusively eye movement.

Each of these theories seems to lend support to an attempt to display patterned stimulation on the skin as the observer pans a television camera in the process of discriminating visual images. Certain qualities of the image should have amodal characteristics, and the distinctive features will, with learning, later trigger the efferent programs for camera manipulation. Preliminary results have already been reported (Bach-y-Rita, Collins, White, Saunders, Scadden, and Blomberg, 1969b) which suggest that blind subjects using the T.V.S.S. tend to develop idiosyncratic techniques of camera manipulation during object discrimination learning. Observer controlled camera manipulation is a necessity; movement of the camera by someone other than the observer does not lead to the same performance ability in form discrimination tasks.

The scientific literature has numerous references concerning the similarities and differences between the visual and tactile modalities. Investigation of these two senses had traditionally followed two approaches. First, receptor structure and response characteristics to varied stimuli have been studied; second, active pattern discriminations visually and tactilely have been compared. Many investigators have found similarity in retinal and somatic response to a variety of stimuli. Von Fieandt (1966) reported that relatively accurate positive after-images occur on the skin after fairly prolonged simmultaneous presentations of patterns of pressure. Révész (1934) stated that the Muller-Lyer illusion evoked similar responses visually and tactilely. In the tactile presentation, the illusion was demonstrated by pressing cardboard cut-outs of the Muller-Lyer arrows against the abdomen or thigh.

Dynamic presentations of alternating spots of stimulation on the skin can produce the phenomenon of apparent motion similar to that experienced in vision with alternating lights. Geldard (1960) reported that his associate Sumby had demonstrated this tactile example of the Phi phenomenon by placing two vibrators on the chest of his subject. Benussi (1913) demonstrated that a sequential activation of three simulators arranged in a triangular pattern on the skin produces the sensation of a spot moving circularly similar to that phenomenon experienced in vision with sequential presentation of three lights arranged in the same pattern.

Another form of psychological response to tactile stimulation which is similar to the response to visual stimulation has been reported by von Békésy (1959, 1967). It is well-known that visual and auditory inputs lead to localization of the origin of the source of stimulation external to the body. Von Bekesy, either using two loud-speakers vibrating at low frequencies on the chest or two mechanical models of the cochlea operating beneath the observer's arms, noted that the origin of the sensation would be localized beyond the body at a distance of about three feet, especially when the observer had the opportunity to view the source of the stimulation. But subsequent to the visual feed-back condition, the observer experienced external localization without viewing the source. Von Békésy concluded that this external localization should not be surprising considering similar localization when holding a stick or screwdriver against nearby objects.

A final area of visiocutaneous similarity discovered by direct comparison of response characteristics to visual and tactile stimulation should be noted. Stevens, Mack, and Stevens (1960) reported that judgments of stimulus intensity can be transferred between vision, touch, and audition with high accuracy.

An alternative experimental approach for intermodal study has relied primarily on tasks requiring transfer from one modality to the other in the same pattern discrimination task using active exploration. Piéron (1922) demonstrated that judgments of the length of a line could be made visually or tactilely with equal accuracy. Many investigators have later studied intermodal transfer by having the subjects learn to discriminate certain forms in one modality and subsequently attempt the same task in the other. Rudel and Teuber (1964) in a typical example of this method found that visual-visual matching was superior to tactile-tactile matching in both accuracy and latency, but in tasks requiring cross-modality transfer, transfer did occur. Tactile-visual transfer surpassed visual-tactile transfer in performance. In the former case, forms learned tactilely were more readily recognized visually in a subsequent matching task than were forms learned in the reversed situation. Such a finding has been interpreted by some as supporting the view held by Locke, Molyneux, and Berkeley that things look as they do because they are associated with how they feel; things look round because they feel round and so-forth. However, the lower performance level for tactile-tactile matching in the Rudel and Teuber study contrasted with the higher performance for visual-visual matching does not support this view.

The work of Gaydos (1966) and Holmgren, Arnoult, and Manning (1966) demonstrated that verbal mediators, attaching names or words to forms during learning, assist in cross-modality transfer of form discrimination. However, the work done with animals in cross-modal transfer tasks indicates that verbal mediators are not a necessity for such transfer to occur (Burton & Etlinger, 1960; Davenport & Rogers, 1970).

Two major differences seem to exist between visual and tactile form discrimination. Owen and Brown (1970) stated that tactile form discrimination results in longer latencies compared to visual discrimination. They stressed the acquisition of information is more time consuming tactilely than visually. The speed of saccaddic eye movements compared to hand movements is probably the major factor producing this difference. Owen and Brown (1970) also reported that complexity of forms, such as the number of sides, is directly correlated with latency of discrimination and inversely correlated with accuracy in tactile matching tasks. Gibson (1969) stressed the structural and functional differences in the eye compared to the somatic receptor surface.

> "It is true that both spatial order (and therefore spatial relations) and temporal order (and therefore temporal relations) are available to vision and to the skin. But a wider panorama of space and objects is available to vision. This means, I think, that greater complexity of structure and higher levels of constraint (rules within rules, so to speak) are possible to detect in visual displays." (Gibson, 1969, p. 229).

The technique used for pattern recognition both tactilely and visually seems to be similar, although these modalities may differ in the acquisition of detail and in the speed of recognition. Baker and Alluisi (1962) stated that distinctive features were primary in both visual and auditory pattern discrimination. They contended that an entire figure is not processed when such distinctive features are present. Pick (1965) later found that distinctive features serve as the primary factor in tactile form recognition. The lack of distinctive features in forms produces longer latencies in identification both in vision and in touch (Baker & Alluisi, 1962; Gibson, 1969). Walk (1965) found that such symmetrical forms, or "restrained" figures, were more difficult to discriminate tactilely than visually. This difference suggested that distinctive features may be even more important tactilely than visually.

By relating the findings of the investigators reported above to the theory of amodal perception, certain modes of stimulation and aspects of stimulus patterns may be considered amodal in character. Aspects such as extent and magnitude, qualities of assymmetry, and the phenomena of apparent movement and external localization all seem to be based on dimensions which are not modality specific. This theory of amodal qualities in perception would then seem to support a prediction that a tactile imaging device such as the T.V.S.S. would permit discrimination of displays containing these amodal features.

The literature surveyed here would also seem to predict that comparison of discrimination performance with visual and tactile displays containing comparable information should result in similar accuracy with simple displays. Increasing display complexity should lead to decreasing accuracy for tactile discrimination. The latencies for tactile discrimination would necessarily be expected to be longer than for visual discrimination as long as hand movement was needed in the former condition.

Using congenitally blind subjects in experiments designed to evaluate the T.V.S.S. permitted the investigators to observe adults learning to interpret pictorial information for the first time. No attempt has been made to generalize from these observations to the learning and perceptual processes existing in sighted infants. Wherever possible, the findings have been interpreted within the framework of theories of form perception and intermodal relationships presented above.

II

Perception of Depth

The judgment of absolute or relative distance by using depth information from monocular vision would seem on the surface to be based on a solely modality specific quality. The output of a standard television system displays a two-dimensional representation of a three-dimensional scene similar to that viewed monocularly. Experimentation was conducted to determine whether congenitally blind Ss would be able to learn to make valid judgments of three-dimensionality when the output of the T.V.S.S. was displayed on the skin in a pictorial, tactile pattern. It was first necessary to determine which of the "monocular cues" were most readily presented by this low resolution system. Here, the term "monocular cues" refers to the characteristics of a display which can be viewed monocularly and without regard to their origin, innate or acquired. Subsequently, experiments were conducted to compare judgments made with the tactile system and those made visually when the visual display was reduced in resolution to match that of the tactile display.

The presentations were made with the T.V.S.S. A complete technical description of the system has appeared elsewhere (Collins, 1970). The apparatus consisted of a matrix of 400 electromechanical stimulators arranged in a 10-inch square array and mounted as the back-rest in a dental chair. When a television camera was focused on a bright region, the stimulators in the corresponding area of this tactor array were activated, each vibrating at 60 Hz. In the first model of this system, the bulky camera was mounted on a tripod and was positioned by manually turning two wheels. The camera was equipped with a zoom-lens to permit variations in the angle subtended by a display. A 400 point visual display, analogous to the tactile display, was provided on an oscilloscope.

The first attempt to quantify judgments of distance with the T.V.S.S. was in a project utilizing size change as a function of distance. A vidio-taped sequence of 40 randomized presentations of a 6-inch circle, appearing at four incremental distances from 5 to 20 feet, was shown to one naive sighted and two blind Ss experienced in the use of the system. Each of the three Ss observed the sequence with the T.V.S.S. and reported which of the four distances was being displayed. Following a brief training interval of 10 trials, in which the distances were reported by E, the Ss each attained 95% accuracy or better on judgments of target distance. It was concluded that relative size of a familiar object was a depth cue readily discriminated with the T.V.S.S.

Linear-perspective and clarity of display were studied simmultaneously by presenting, in various slanted positions, a 6-inch white square divided into quadrants by thick black lines. Twenty randomized trials were presented to five experienced blind Ss who were asked to report the direction of slant. Two cues were present in the display; first, the convergence of the exterior and interior lines toward the direction of slant, and second, the clarity of resolution provided by laboratory illumination which made the distant side appear less clear (stimulators in areas with inadequate illumination responded intermittantly rather than at constant 60 Hz., producing a "fuzzy" rather than a sharp image). In addition, the fore-shortening of the display through paralax when positioning the square on a slant served to immediately demonstrate whether the square was rotated in the vertical or horizontal plane. Following a 10 trial warm-up interval which served as a training sequence, the Ss attained a mean accuracy of 90% for direction of slant and 100% for plane of slant.

A second sequence followed which utilized uniform illumination for the entire field, thus eliminating the cue of clarity of display. As in the previous sequence, the five blind Ss were asked to report the direction of slant. The mean accuracy for this sequence was 75% for direction of slant and 100% for plane of slant.

This second investigation suggested that linear perspective provided the primary information for judgments of slant but that clarity of display provided additional useable information.

Descriptive information concerning the monocular cues used by blind Ss to make judgments of distance with the T.V.S.S. was gathered by using complex arrangements of familiar objects. Seven blind Ss learned rapid recognition of a vocabulary of 25 objects—telephone, pyramid, cup, toy animal, and so-forth. Several of these objects were repeatedly placed on a small, black felt covered table 4-feet in front of, and 20-degrees below the gaze-line of, the camera. White lines were placed around the perimeter of the tabletop for reference. Ss were asked to identify each object and to report its relative position and distance from the others as well as the cues used for these judgments.

Ss were able to identify partially occluded objects by using distinctive features such as telephone cord, cup handle, watering-can spout, and so-forth. The cue most frequently reported for judging relative distance was the apparent elevation of the object in the field.

Ss spontaneously reported that near objects appeared lower in the field than more distant objects. This feature is analogous to the positioning of images from more distant objects on the lower area of the inverted retinal display. This cue of distance was subsequently controlled experimentally by placing the object array on a surface which tilted down and away from the S at an angle of 20-degrees, thus compensating for the camera-table angle. In this experimental situation, Ss had difficulty in making distance judgments unless they could rely upon occlusion when it existed or minimal size change as cues.

After demonstrating that judgments of three-dimensionality could be made on the basis of monocular cues presented by the tactile display, it was considered important to compare such judgments made tactilely and visually. Information concerning the relative resolving capability of the retina and of the skin if both displays were comparable was desired. Two experiments were conducted for such comparison. The first was designed to compare the groups and the second to compare judgments of three-dimensionality.

Method

Subjects

Six congenitally blind college students were selected for preliminary evaluation of the T.V.S.S. on the basis of their satisfactory motor and verbal abilities. Each received extensive training with the apparatus (an average of 40 hours) designed to familiarize them with the techniques of camera manipulation, stimulus analysis, and form recognition. Six sighted Ss participated as a control group.

Apparatus

The congenitally blind group performed the assigned tasks with the T.V.S.S. tactile display and the sighted control group with the analogue visual display. Both groups were permitted free manual manipulation of the camera.

Stimuli

The displays consisted of six 35-mm. slides. Five of the slides consisted of sets of parallel black and white lines. Each of these slides varied in the number of line pairs from 4 to 12 pairs. The sixth slide was made by photographing a checkerboard pattern tilted at an angle of 70-degrees from the frontoparallel position. Each slide could be rotated in the projector so that the patterns might be presented in any desired orientation. Only the center portion of the checkerboard pattern was photographed so that rotation of the slide did not produce fore-shortening of the external contour that might serve as a cue to the plane of slant. For the line orientation task, the zoom lens was set so that the entire display could be encompassed within the camera angle, but for the checkerboard slant task, Ss were given freedom of lens setting.

Procedure

Forty randomized presentations of the grid patterns were presented in either vertical or horizontal orientation. Ss were asked to report the orientation of each. E reported verbally to S the accuracy of the report on each trial. Subsequently, 40 randomized presentations of the checkerboard pattern were made with S asked to report the direction of slant, which side was furthest away. E reported the accuracy of the report. Accuracy and latency of each trial were recorded. The means for the two groups for accuracy and latency were compared for both tasks by the use of t-tests.

Results

The two groups did not differ significantly in performance of the orientation of the grid pattern task (See Table 1, p. 17). Both groups were able to judge the orientation rapidly and without camera movement. The sighted control group was significantly more accurate on the checkerboard slant task, 97.5% to 82.9%, $p < 0.01$. Latencies for the sighted group on this task were also significantly shorter than those of the blind group, $p < 0.001$.

Discussion

The difference in latency in the checkerboard slant task is more easily understood than the accuracy difference. The sighted Ss could scan the oscilloscope image rapidly with their eyes while keeping the camera stationary whereas the blind Ss were restricted to manual manipulation of the camera in order to scan the tactile image across their skin. Secondly, the complexity of the internal detail of the checkerboard pattern was such that Ss with limited experience with the system and with the mode of presentation found it somewhat difficult to detect rapidly the small stimulus differences. The latency difference then seems to be related to information acquisition time similar to that previously reported by Owen and Brown. The similarity in performance

Table 1

Accuracy and latency means for six blind and six sighted Ss on line orientation and checkerboard slant tasks with comparable 400 point displays visually and tactilely.

	Line Orientation		Checkerboard Slant	
	Accuracy	Latency	Accuracy	Latency
Tactile	99.6%	1.2 sec.	82.9% SD 10.4%	8.4 sec. SD 2.9 sec.
Visual	100%	1.1 sec.	97.5% SD 1.5%	2.8 sec. SD 0.7 sec.

between the groups on the grid orientation task suggests that information concerning line orientation can be acquired without movement of the lines across the receptor surfaces of the skin or eye.

Three possible explanations for the slant accuracy differences must be considered. First, the difficulty in discriminating internal detail of the display by the Ss with limited experience with the system may have contributed to a lower performance level by some of the Ss. Second, four hours experience with the pattern may have been too short a training period to enable blind Ss to equal the performance of sighted Ss using an accustomed modality. Third, the visual system may be better equipped for processing detailed patterned stimuli than the tactile system. The performance of the sighted group demonstrated that judgments of slant could be made rapidly and efficiently when vision is limited to 400 points; and the 82.9% accuracy of the blind group demonstrated that similar judgments can be made when the same information is presented tactilely.

A follow-up study was conducted to attempt to determine the role of visual experience in judgments of three-dimensional displays. Six naive blindfolded sighted Ss were compared with three naive blind Ss on the two tasks described in the previous section. The two groups did not differ significantly on judgments of line orientation or checkerboard slant. Both groups averaged near 90% accuracy for line orientation and 55% accuracy for direction of slant. Latencies for line orientation were approximately 20 seconds, and for direction of slant, three minutes. The verbal reports of the sighted Ss indicated that transfer from visual experience would be available for judgments of three-dimensionality with the T.V.S.S. These Ss reported that they were searching for particular cues such as degree of clarity or convergence of lines. The blind Ss seemed confused by the task, but verbal reinforcement of correct or incorrect guesses in the early trials seemed to initiate improved performance suggesting that learning was occuring. For both groups, the limiting factor for accuracy and latency seemed to be the difficult internal detail of the display. Ss needed more experience with the T.V.S.S. for thorough and rapid analysis of such a display.

One final observation should be noted in the discussion of the slant judgment task. The sighted group, using the visual display, reported most often that judgments were based on the convergence of the internal lines of the checkerboard pattern toward the direction of tilt. The blind Ss, using tactile stimulation, most frequently referred to the change in "texture". The near side of the pattern appeared to these Ss to have distince divisions which passed through gradations of "texture" until the pattern merged into a relatively uniform mass. The method used by the blind Ss to make the judgments of three-dimensionality in this task may be related to the textural gradient slant cue known in vision.

It can be concluded that some of the depth cues associated with monocular vision can be presented by a tactile imaging device to the skin and still provide useful information. Evidence to date seems to indicate that the utilization of these cues, when presented tactilely, must be learned by the congenitally blind but may be transferred from visual experience by sighted observers. For the blind, in early training, the judgment process may have an intermediate step of relating the stimulus pattern to a rule concerning depth analysis. Some subjective observations suggest that this process subsequently becomes more immediate and possibly less dependent on an intermediate step. In either case, depth perception based on monocular cues is not modality specific. Information contained in such displays may be considered to relate to some higher order process of space perception and as such may be considered to be amodal in character.

In summary, the studies reported in this chapter investigated the translation of visual monocular depth cues into patterned tactile stimulation by the T.V.S.S. Experienced blind Ss were able to make valid judgments of depth and distance by using cues of relative size, clarity of display, occlusion, apparent elevation in the field produced by camera-table angle, linear perspective, and coarse textural gradients. A comparison was made between tactile stimulation and vision in judgments of orientation and slant when the same information was presented. Sighted Ss, viewing a visual display, and blind Ss, receiving tactile stimulation, performed these tasks at levels significantly above chance. The sighted group performed significantly better than the blind group in accuracy and latency of slant judgments.

III

Internal Detail and Display Grain

The complexity of internal detail in the checkerboard pattern was mentioned as a possible deterent to higher performance by the blind Ss in the slant detection task. Ss in that and other studies conducted with the T.V.S.S. had frequently reported that the detection and identification of small areas of quiescence and areas consisting of a small amount of stimulation embedded within a mass of stimulation were more difficult than the detection and identification of regions of stimulation located in a quiescent surround. Research was needed to determine whether this discrepancy of performance was caused by masking from a mass of stimulation. This investigation was conducted in conjuction with research geared to determining the answer to another question of primary practical significance to the development of a useful tactile imaging device for the blind. The 20 line image presented by the first system was not sufficient for displays containing fine detail. The needed display grain would require packing the stimulators into the matrix with an inter-stimulator separation much less than the 12-mm. stimulator separation currently used. It was first necessary to determine whether experienced Ss could resolve the existing separation. The design of the apparatus made it possible to deactivate half of the stimulators leaving a 10-inch square matrix of 200 stimulators with lateral and vertical stimulator separation of 24-mm. and diagonal separation of 17-mm. By comparing the two display matrices, it was possible to determine whether the 12-mm. separation was being resolved. If it was not being resolved, the 200 point matrix would permit performance equal to that of the 400 point matrix. Further, if a mass of stimulation masked embedded areas of quiescence, the matrix of 200 widely spaced vibrotactors would permit a higher level of performance on tasks requiring detection or identification of embedded areas. The matrices were compared on two experiments. One was designed to determine the minimum size of a detectable silent area within a mass of stimulation. The second was designed to determine the relative difficulty of form identification when the forms differed in mode of presentation—either consisting of stimulation with a silent surround or of an area of silence within a mass of stimulation.

Experiment 1

Method

Subjects

Five congenitally blind college students served as Ss. There was no reason to expect that blind Ss would differ from sighted Ss in performance of the task, but to this point, only blind Ss had received extensive training with the apparatus. Ss had from 70 to 120 hours of experience with the system.

Stimuli

Five annuli differing in internal diameter were made from white felt circles, 3-inches in external diameter, and mounted on black cardboard. The internal diameter of the annuli varied from 1/4 to

1-1/2 inches. The largest annulus presented an area on the tactile matrix equivalent to 25 silent stimulators with the 400 point display and approximately 13 silent stimulators on the 200 point display. In both cases, the area covered on the skin by the silent area was approximately 6.25-square inches. The smallest annulus presented one silent stimulator on both matrices. A solid white circle, 3-inches in diameter, was used as a control target. The control circle activated 115 stimulators on the 400 point matrix and approximately 58 with the 200 point matrix.

Procedure

The Ss scanned the displays with the T.V.S.S. by manually cranking the tripod-mounted television camera. The annulus with the largest internal diameter was placed beside the solid control circle on a stand in front of the camera. S was asked to scan the displays with the camera and to report which circle was solid, the right or left. The procedure was repeated for 20 trials with randomized positions for the displays. The task was first performed with the 400 point matrix and then repeated with the 200 point matrix with a new randomized position sequence. Each trial was limited to a maximum of 30-seconds. The procedure was subsequently repeated for the four smaller annuli in descending order of size. The frequency of correct responses was counted for the five Ss for each annulus and for each matrix. Comparison of performance for each annulus on both matrices was compared by use of t-tests.

Results

Table 2 (p. 24) presents the frequency of correct responses for

Table 2

Detection of annuli by five blind Ss using 400 and 200 point T.V.S.S. matrices, number of correct responses and size of skin area covered by the silent region of the annulus. N equals 100 observations.

Annulus Size	400 Points	200 Points
6.25 $in.^2$	100	100
4.0 $in.^2$	99	98
2.5 $in.^2$	97	95
1.0 $in.^2$	92	89
0.25 $in.^2$	66	65

100 observations made for each annulus with 400 and 200 stimulator matrices. A linear relationship between size of annulus and frequency of correct responses existed, with the four largest annuli being detected at levels far exceeding chance for all Ss. The smallest annulus, consisting of one silent stimulator, was detected by two Ss at levels far above chance, 100% and 90%, but near chance levels for three Ss.

The performance of the Ss was consistently better with 400 stimulators than with 200, but the difference was too slight to reach a level of statistical significance for any annulus.

Experiment 2

Method

Subjects

The five Ss participating in the first experiment acted as Ss for this experiment as well. Each of these Ss had previously approached 100% accuracy on a form recognition task involving a solid square, circle, and triangle, each covering approximately 64 square-inches of skin area when presented with the T.V.S.S.

Stimuli

The displays consisted of geometric forms--square, circle, and triangle--with areas of 1.75 square-inches, the area of the largest annulus used in the first experiment which had been detected without error by all Ss. These forms were presented in two modes--as a solid white form on a black background displayed by the T.V.S.S. as a pattern of stimulation surrounded by silence, and as a black form with a white background displayed as an area of silence within a mass of stimulation. For convenience, the solid white forms were referred to as external forms and the black forms as internal forms. All of the patterns consisted of 25 stimulators, either active or silent, on the 400 point matrix. Each form then would be equivalent in size on the skin to 6.25 square-inches. The internal forms were mounted on white cards of 9 square-inches in size. Thus, with the 400 point matrix, the internal forms appeared as 25 silent stimulators within a field of 90 active stimulators spread over 22.5 square-inches of skin surface. With the 200 point matrix, the skin surface covered by a form or field of stimulation remained constant, but in the case of the internal forms, only 45 stimulators were active, and with external forms, the forms consisted of approximately 13 active stimulators.

Procedure

Sixty randomized presentations of the forms were placed in front of S who had 30-seconds in which to identify them by scanning with the television camera. This procedure was first conducted with the external forms with the 400 point matrix and subsequently with the 200 point matrix. The procedure was repeated with the internal forms. The frequency of correct responses was tabulated and latencies recorded. As a control group, five sighted Ss performed these tasks viewing the oscilloscopic display of the 400 point matrix. In this visual display, the external forms consisted of the activated green dots against the darker background, and the internal forms were dark areas within the green lighted area.

Results

The sighted Ss all completed the tasks without error with a mean latency of 0.1-second demonstrating that the tasks did not differ in difficulty visually. Table 3 (p. 28) presents the results for external and internal form recognition and the corresponding latencies for the blind Ss with 400 and 200 point matrices. Although embedded areas of this magnitude were detected without error by these Ss previously, the relative performance on form recognition in this experiment demonstrated the difficulty of identifying small forms tactilely, at least with a system of this low resolution. The mean accuracy for external form recognition was significantly higher than that for internal form recognition with the 400 point matrix, and the corresponding latencies were significantly shorter t-tests producing p-values of < 0.05 for both measures.

Performance with 400 stimulators again exceeded that for 200 stimulators for each of the four measures recorded. The difference was again too small to reach the 0.05 level of significance on any of the measures.

Performance with the two matrices was compared with nine separate measures in the two experiments. Except for the first task of Experiment 1 in which both matrices permitted 100% accuracy for all Ss, the 400 point matrix provided consistently higher performance than the 200 point matrix. With the use of a nonparametric sign test, the probability of this consistency occuring by chance is minimal, $p < 0.01$. This method of analysis suggested that 400 vibrotactors were significantly better on the assigned tasks than 200 widely spaced vibrotactors.

Table 3

Means and SDs for external and internal form recognition latencies and frequency of correct responses for five blind Ss using 400 and 200 point T.V.S.S. matrices. N equals 60 trials per task for each S.

	400 Points	200 Points	Totals
Accuracy:			
External	41.8 SD 3.63	37.6 SD 5.64	39.7
Internal	31.6 SD 7.75	30.2 SD 9.40	30.9
Totals	36.7	33.9	
Latency:			
External	15.1 sec. SD 3.48 sec.	16.3 sec. SD 3.58 sec.	15.7
Internal	18.1 sec. SD 4.66 sec.	19.0 sec. SD 4.76 sec.	18.6
Totals	16.6 sec.	17.7 sec.	

Discussion

The 12-mm. separation of the stimulators in the 400 point matrix apparently was resolved by these experienced Ss. The consistent improved performance of the Ss with the 400 point matrix over that demonstrated with the 200 point matrix suggests that the higher resolution matrix did provide additional and useable information. The major factor producing better performance with the 400 point matrix over that of the 200 point matrix may have been the improved sharpness of contours displayed by this matrix. The checkerboard-like design of the 200 point matrix displayed irregular contours of all images presented. Contours would not have been sharpened in the 400 point matrix if the 12-mm. separation had not been resolved.

Form recognition was significantly more difficult when the form was a silent area within a mass of stimulation rather than an area of stimulation with a silent surround. Pattern recognition depends largely upon contour analysis, visually and tactilely. An edge formed by a line of vibration on the skin can easily be detected, but the determination of its shape and orientation is impaired when it is observed as the trailing edge of a mass of stimulation moving across the skin.

Two neurophysiological differences between the retina and skin must be considered in attempting to explain the difference between visual and tactile form recognition in this experiment. The possible absence of "off" fibers in the somatic system as exist in the vision system and the relatively slow decay time following stimulation on the skin compared to that in vision (von Békésy, 1959) may impair the determination of the orientation of a trailing edge of vibration.

The difficulty in detecting and identifying internal, or silent areas, apparently is not caused solely by masking from large amounts of stimulation. The reduction of "on" stimulators at any time, without reducing the skin area comprising the image, did not improve performance in detecting or identifying annuli or embedded forms as might be anticipated if masking were the primary deterent. Masking may be a factor, but its influence apparently was out-weighed by the increment of information provided by the higher resolution matrix.

A major question left uninvestigated concerns the necessary size of a recognizable pattern. The research reported here demonstrated that simple geometric forms consisting of 25 stimulators, covering 6.25 square-inches of skin surface, can be identified at levels significantly above chance with the 400 point matrix. The question remains whether the number of stimulators or the skin area is more important in form recognition. A more densely packed stimulator matrix will be needed to investigate this problem.

The results in these experiments suggest that a small embedded area of silence can be detected, but the area must be of sufficient size before its pattern can be identified. The existing 12-mm. inter-stimulator separation was resolved, but the increment of improved preformance over a lower resolution matrix for the assigned tasks was small.

IV

Visual and Tactile Response Characteristics

Analysis of visual and tactile response characteristics to comparable displays was necessary in the complete evaluation of the prototype T.V.S.S. Such analysis would provide information relevant to assessing the relative resolving capabilities of the retina and the skin. Also, by comparing the responses of Ss with different visual histories--normal sight, congenital blindness, and adventitious blindness--it would be possible to make judgments regarding the origin of the responses to patterned, tactile stimulation--innate, learned, or transferred from visual experience.

Earlier chapters contained three studies which compared visual and tactile performance on similar tasks. Three observations were made: 1) The determination of the orientation of parallel lines in visual and tactile displays seems to be equivalent in difficulty in the two modalities. 2) Judgments of the direction of slant of a checkerboard pattern can be made either visually or tactilely, but the visual input provides more rapid and accurate judgments. 3) The detection and identification of internal detail seems to be significantly more difficult tactilely than visually. Three corresponding conclusions were drawn from these observations: 1) Line orientation is a dimension which is not modality specific and does not seem to require new learning by any group of Ss tested when the displays are presented with the T.V.S.S. 2) The perception of slant is not modality specific and (based on the reports of sighted subjects) benefits from past visual experience. The congenitally blind must learn the display characteristics which indicate slant. 3) The complexity of detail within a display, especially details comprised of silent regions, are more readily processed by the visual system than the somatic system, at least when the displays are presented tactilely to Ss with a maximum of 200 hours of experience with the T.V.S.S.

Four additional visual-tactile comparitive studies were conducted utilizing the T.V.S.S. and the analogue visual display. The resulting data and observations were analyzed in light of the conclusions listed above.

The work of Sumby and others was reported in the introductory chapter in which a tactile analogue of the apparent movement perceived visually in the Phi phenomena was produced on the chest. Two slightly displaced vibrators were alternately activated producing the sensation of one spot moving between the two regions of stimulation. A similar result was obtained with the T.V.S.S. using a visual display of alternating lights placed in front of the television camera. Approximately 40 blind and blindfolded Ss reported the movement of a "spot" of stimulation of the back. Only one blind S failed to report a moving "spot" even at higher frequencies of alternation.

Another visual display, consisting of four lights, was used for visual-tactile response comparison. The lights were arranged so that they constituted the corners of a square. The lights were flashed alternately in pairs, each pair consisting of the two lights located at diagonal corners of the square array. This arrangement was designed to permit a variety of responses. If the Ss were to perceive a "double"

Phi phenomena (two spots moving between two points on the skin), the apparent movement of the two dots could be perceived in either a vertical or horizontal direction. The investigation was conducted to determine whether spontaneous reversal of perceived display movement would occur on the skin. Five congenitally blind and fifteen blindfolded sighted Ss observed the display with the T.V.S.S. One blind S (who had over 300 hours of experience with the T.V.S.S.) reported two moving spots, first moving vertically, and then spontaneously reversing to horizontal movement. Four blind Ss reported that a horizontal line seemed to sway, moving in a see-saw fashion, with the center remaining stationary. Upon subsequent questioning, two of these Ss reported that they could "make" the see-sawing "bar" appear vertical. The 15 blindfolded sighted Ss divided evenly, by classes of response, into three groups of five. One group reported feeling two dots moving in a vertical direction; a second group felt two dots moving horizontally; and a third group reported a horizontal line moving in the see-saw fashion. None of these sighted Ss reported spontaneous reversal of the display. However, it must be stressed that the five blind Ss participating in this study were experienced with the system and the mode of presentation whereas all of the sighted Ss were naive to the T.V.S.S. The experience of the blind Ss may have provided a more relaxed situation thus producing less rigid perceptions. Approximately 10 sighted Ss have viewed this display visually with the analogue 400 point oscilloscopic matrix. Each S reported a "double" Phi phenomena with spontaneous reversal of direction.

The perception of two simultaneously moving dots, in a display such as that just described can occur both visually and tactilely according to these observations. The visual display was apparently more striking than the tactile display based on the relative proportion of the responses from the two modes of presentation. The major difference in response seemed to be related to the apparent closure occuring tactilely. The frequently reported erroneous perception of a continuous line of stimulation connecting the two discrete dots was not reported with visual stimulation. This discrepancy may be related to the difficulty with areas embedded within tactile displays. Such regions seem to be ambiguous as to the presence of further stimulation. Also, in this situation, Ss did not have control of camera manipulation. The tactile group then could not scan the display to reduce ambiguity in the same way as the visual group could scan with eye movements. A higher resolution tactile matrix would be needed to eliminate the necessity to lock the camera in position for presenting the relatively small display. This situation might eliminate some of the discrepancy in reports from tactile and visual presentations of this display.

In another experiment, two pegs were rotated in the horizontal plane in front of the T.V.S.S. camera in an attempt to determine whether the kinetic depth effect could be perceived on the skin. Approximately 25 congenitally blind Ss were presented the display. None of these Ss reported perceiving a three-dimensional movement. Most of these Ss reported feeling two vertical lines which moved together and then retreated in a cyclical manner. Three blind Ss reported that the lines came together and passed one another before reversing direction. All of the blind Ss were later shown tactilely (by hand exploration) the peg display. On subsequent presentations of the display over a two-year period, these Ss never failed to identify the rotating pegs.

Whether this identification demonstrated a similar experience by these Ss of that of a sighted person viewing the display is not known, but in any case, the rudiments of learning were observed.

Two studies were conducted with sighted Ss using the same rotating peg display in an attempt to determine whether the inability of the blind Ss to detect three-dimensional rotation was based on lack of visual experience or the nature of the display itself presented with a 400 point matrix. First, 43 college students observed the display with the T.V.S.S. tactile matrix. Thirteen of these Ss were unable to perceive the cyclical motion of two vertical pegs which left thirty responses for analysis. Subsequently, 30 sighted Ss viewed the display on the 400 point visual matrix.

Table 4 (p. 36) presents a summary of the responses of the 30 blindfolded sighted Ss observing the rotating peg display tactilely and the 30 sighted Ss viewing the display visually. Both groups were divided into three sub-groups on the basis of response classification--perceived rotation, perceived bouncing of two vertical lines, and perceived crossing of one another by the two lines. The latter two classes of response were identical to the perceived two-dimensional display reported by the blind group. The data obtained from the sighted and blindfolded sighted Ss were analyzed by the use of a Chi-Square test with a resulting p-value of 0.001 demonstrating significant difference in responses. The results suggest that a 400 point display matrix is not ideal for perception of the kinetic depth effect, but it is sufficient for the perception by some Ss both visually and tactilely. The visual display was again apparently more conducive to an interpretation of three-dimensionality than was the tactile display. The few rotation

Table 4

Frequency of response categories to a rotating peg display by 30 blindforded sighted Ss receiving tactile stimulation by the T.V.S.S. and 30 sighted Ss viewing an analogue visual display.

	Bouncing	Crossing	Rotating
Tactile	24	3	3
Visual	10	10	10

$X^2 = 29.6$ DF = 2 $p < 0.001$

responses by blindfolded sighted Ss and the lack of such responses by blind Ss suggests that transfer from visual experience is possible and may be necessary for the first observation of such a display. It can be predicted that additional T.V.S.S. experience with dynamic, three-dimensional displays would lead to a higher percentage of valid responses of rotation both by the blind and blindfolded sighted Ss.

The waterfall effect (Teuber, 1960) was also studied with the T.V.S.S. A black drum with 14 vertical white stripes was used for the display. Approximately 40 blind and blindfolded sighted Ss observed a continuous series of vertical lines moving horizontally across their backs when the T.V.S.S. camera was focused on the rotating drum. Each trial lasted for 30-seconds. When the drum was stopped, leaving stationary vertical lines on the skin, S was asked to report his experience. One blindfolded sighted and two blind Ss reported a brief tendency of the lines to move in the opposite direction. Later, random dots replaced the lines in the display. In the judgment of two of the Ss who experienced the phenomenon previously, the subjective tendency of the dots to move in the opposite direction upon stopping the drum seemed to be more marked than that of the lines. Judgments made from the visual display confirmed that the dots made a more convincing reversal of direction. However, the visual displays, both lines and dots, were more consistent in producing the effect than was the tactile display. Tentatively, it can be concluded that the waterfall effect can be perceived with tactile stimulation.

The final tactile-visual comparitive study reported here consisted of a form discrimination task. The Witkin Embedded Figures Test (Witkin, 1968), designed to be administered tactilely by active exploration was revised especially for this investigation. In the original test, S was handed a simple tactile design to explore with his fingers. Subsequently, S was handed a complex design which contained the simple form, and was asked to trace on it with his finger the outline of the simple form. The test revision called for the placement of the simple form along side of four complex forms, one of which contained the simple one. Four congenitally blind Ss were presented the 14 trials of the revised test to be performed with their hands and subsequently with the T.V.S.S. Four sighted Ss performed the task by using the oscilloscopic display. All Ss were free to manipulate the camera when performing the task with the T.V.S.S.

Table 5 (p. 39) presents a summary table of a one-way, one-by-three analysis of variance performed to compare accuracy and latency results of a revised Embedded Figures Test. F-values indicated significant differences in performance latency, $p < 0.01$. Table 6 (p. 40) presents the mean accuracy and latency scores for Ss performing the revised Embedded Figures Test under three conditions. A t-test was used to compare performance under the two tactile conditions. The blind group using their hands performed the task more accurately and more rapidly than when using the T.V.S.S., $p < 0.05$ for both measures. The visual group performed the task significantly faster the T.V.S.S. group, $p < 0.01$. Other performed t-tests produced p-values below statistical significance. Performance with the hands and with the 400 point visual display did not seem to differ greatly in either accuracy or latency.

The results suggest that the group performing the task with the T.V.S.S. tactile display were again impaired by the complexity of embedded features of the display. Also, the long latencies required

Table 5

A summary table of a one-way, one-by-three, analysis of variance performed on accuracy and latency scores obtained from a revised Embedded Figures Test performed under three conditions.

Accuracy

Sources	SS	df	MS	F
Between-groups	26	2	13	
Within-groups	42	9	4.67	
Totals	68	2/9		2.78

Latency

Sources	SS	df	MS	F
Between-groups	3,973,296	2	1,936,648	
Within-groups	617,512	9	68,612	
Totals	4,590,808	2/9		29.0

Table 6

Number of correct responses, N = 56, and mean latencies for scores obtained on a revised Embedded Figures Test performed under three conditions.

	Correct Responses	Latency
Tactile (hands)	50	303 seconds
Tactile (back)	36	1459 seconds
Visual	48	182 seconds

to perform each trial placed a heavy stress on memory under each condition. It can be concluded that both the hands and eyes are better suited for analysis of complex designs.

In summary, the results from these four investigations support the findings from earlier visual-tactile comparisons. Simple displays, such as the two alternating lights, are perceived in the same way visually and tactilely. More complex displays, such as the display with four lights and the Embedded Figures, produce differences caused primarily by difficulty, when using the T.V.S.S., to process display features located within the boundaries of the display. Three-dimensionality can be perceived both visually and tactilely, but previous experience, either visually or tactilely, with such displays seems to be a requirement if accurate percepts are to be produced. The congenitally blind do learn to identify three-dimensional displays on the basis of display features comparable to that used by sighted Ss viewing visual displays.

V

Form Recognition and Body Loci

The future development of a T.V.S.S. practical for the blind will require selection of a body surface which provides adequate receptor area and optimal sensitivity for tactile form recognition. The back was selected as the original receptor surface for the T.V.S.S. because it provided a relatively large area of skin which was somewhat flat and which held its shape fairly well during other body movement. The original apparatus, containing large and heavy components, required selection of a body surface which met these requirements. Selection of the back was made even though the sensory literature indicated that the back was less sensitive than other body areas on absolute and two-point threshold measures.

After demonstrating that tactile form recognition was possible on the back with the T.V.S.S., it became of interest to determine whether other body loci would have greater sensitivity for this task especially with Ss who had received extensive training with the T.V.S.S. display on the back. The literature did not seem to have any comparative studies which would be of immediate relevance to this question. For this reason, experimentation was conducted to compare form recognition on three areas of the body—back, abdomen, and inner-thigh. Primarily, this comparison would be of value in the decision process regarding development of improved models of the T.V.S.S. Secondarily, such a comparison should provide data concerning the sensitivity of the skin in different body loci and a means of evaluating the possible change of sensitivity after experience with this mode of stimulation on one body locus.

Method

Subjects

Five congenitally blind college students participated in this investigation as Ss. Each had received over 100 hours of practice with the T.V.S.S.

Apparatus

A 5-inch square matrix containing 100 electromechanical stimulators on 12-mm. centers served as the tactile display surface in this experiment. The matrix was mounted on a dental-chair mechanism to permit ease of raising and lowering the unit. The matrix displayed the output of the T.V.S.S. camera which was manually manipulated by the S by hand movements. The camera was suspended from a bar in front of S. Two ball-joint pivot units were attached at either end of the suspending bar to permit free movement of the camera.

Stimuli

All 26 of the block capital letters were used as displays. The letters were made of plastic strips embedded with magnetic material to permit displaying on a metal plate. The zoom-lens was set so that the letter images were 5-inches in height on the skin. These Ss had previously worked with letter images no smaller than 8-inches in height on the skin.

Procedure

Three sequences consisting of 40 randomized presentations of the letters were presented to each S. Each sequence was presented with the display matrix placed against a different body region. The sequences were presented to all Ss in the same order—on the abdomen, inner-thigh, and back. The letters were presented to both the abdomen and back so that the left side of the images appeared on the left side of the trunk. The images appeared on the right inner-thigh with the left side of the images located near the front of the leg. These image positions were selected after preliminary evaluation had demonstrated that these positions seemed natural and that relearning would not be necessary as a result of left-right reversal, as produced optically in vision (Taylor, 1962). S was asked to identify each letter. Accuracy and latency for each trial were reported. Data analysis included the performance of a one-by-three, one-way analysis of variance and the necessary t-tests.

Results

Table 7 (p. 45) presents the summary of a single factor analysis of variance with repeated measures, and Table 8 (p. 46) presents the means and SDs for accuracy and latency on the letter recognition task performed by five Ss with the T.V.S.S. matrix placed against three different body loci. The F-values indicate significant differences in performance for both accuracy, $p < 0.01$, and latency, $p < 0.05$. The subsequent t-tests demonstrated that performance on the abdomen was significantly more accurate than on the back, $p < 0.01$. The latency for performance on the abdomen was significantly shorter than that on

Table 7

A summary table for a single factor analysis of variance with repeated measures performed on data obtained from a letter recognition task performed with a T.V.S.S. matrix placed against three body loci.

Accuracy
(Number correct in 40 trials)

Sources	SS	df	MS	F
Between-groups	85.72	4	21.43	
Within-groups	504.68	10	50.46	
Body Locus	473.20	2	236.6	
Interaction	31.48	8	3.93	
Total	590.40	14	42.17	60.20 (2/8) $p < .01$

Latency

Sources	SS	df	MS	F
Between-groups	455.28	4	113.82	
Within-groups	1299.12	10	129.91	
Body Locus	793.2	2	396.6	
Interaction	505.92	8	63.24	
Total	1754.4	14	125.31	6.27 (2/8) $p < .05$

Table 8

Means and SDs for accuracy and latency on a letter recognition performed by five Ss with a T.V.S.S. matrix placed against three body loci.

	Accuracy	Latency
Abdomen	82.5% SD 5.57%	15.6 seconds SD 3.8 seconds
Inner-thigh	64.3% SD 9.1%	16.17 seconds SD 12.10 seconds
Back	48.6% SD 9.73%	33.0 seconds SD 12.17 seconds

the back, $p < 0.05$. Performance with the matrix placed against the inner-thigh fell between that attained on the abdomen and back, but the level of difference did not reach the level of statistical difference in comparing inner-thigh performance with that achieved on the other loci on either accuracy or latency measures.

Discussion

The significantly better performance achieved on the abdomen compared to the back has both practical and theoretical importance. The practical consideration centers on the fact that the abdomen permitted good letter recognition with images too small to permit adequate recognition on the back with a 100 point matrix. This apparent increase in form recognition sensitivity should have relevance to future T.V.S.S. development. It is hypothesized here that inter-stimulator separation could also be reduced further on the abdomen than on the back, at least with electromechanical stimulation. One possible explanation for the discrepancy in performance should be considered. The body structure underlying the skin surface may influence the spread of vibration and thus cause possible interference with adjacent areas of the skin. The bony structure beneath the skin of the back may serve to spread vibration further than the soft tissue of the abdomen. The use of electrocutaneous stimulation of these two body loci in future comparisons of form recognition should provide means of investigating this possibility.

The theoretical implications of the study stem from the improved preformance achieved with an "untrained" body locus over that attained with a locus which had received extensive training. Theories of periphery and central neural organizations which are activated by specific proximal stimulation would predict that the trained surface would provide better performance than the untrained surface (Hebb, 1949). Further, these theories would hold that relearning would be needed when the locus of stimulation was shifted. However, the immediate transfer of performance skills learned on one locus to a novel locus cannot support these theories. Instead, these data support a theory of intra-modal transfer of performance skills. Assuming that much of the learning which had previously occurred involved camera scanning techniques, it is reasonable to expect that these learned movements would be used wherever patterned stimulation was applied to the skin as long as specific neural networks had not simmultaneously been developed between specific peripheral regions and central motor control areas. In the light of these supporting data, it might be hypothesized that any existing connections between learned motor responses to particular image features involve solely central regions of the nervous system. For this reason, it is tentatively concluded here that intra-modal transfer, as well as inter-modal transfer, is based on higher order processes involving non-modality specific, central structures and centrally controlled responses.

It is known from the literature as well as the investigation with the T.V.S.S. that practice improves performance with tactile stimulation. It can be expected then that additional practice with the tactile display placed against the abdomen that performance on form recognition tasks would improve. Future investigation is needed to test this prediction.

VI

Summary and Conclusions

In the preceding chapters, sensory substitution was investigated by experimentally presenting patterned stimulation to the skin by the T.V.S.S. Performance with comparable visual and tactile displays was compared in an attempt to assess the similarities between the two modalities. The three predictions made in the introductory chapter, in light of the literature surveyed, were supported by the results subsequently obtained.

The first prediction was that displays containing features considered to be amodal would be discriminated with the T.V.S.S. The results obtained with the display consisting of two alternating lights supported this prediction and the amodal character of apparent movement. Also, the form recognition performance displayed with geometric forms, letters, and the Embedded Figures Test, may support the amodality of asymmetry in that identification was made on the basis of distinctive features. Using the previously presented definition of amodal characteristics (features which can be experienced by more than one modality), the list of amodal features should be lengthened on the basis of the findings reported here. Orientation of lines and monocular depth cues should be listed with extent and magnitude, asymmetry, apparent movement, and external localization, as features which are amodal in character. Of course, the aspects in the displays containing monocular depth information are generally distinctive and asymmetrical, but the resulting percept is qualitatively different from that experienced in mere form recognition. The added dimension, so to speak, in perception of three-dimensional space cannot adequately be encompassed in the same classification. Considering that external localization of a source of stimulation occurs in vision, audition, and touch, and that depth information can be contained in visual and tactile displays, it may be fair to speak of spatial perception, as well as form perception, as being amodal in character.

The second prediction stated that simple displays would produce equal performance visually and tactilely. The equivalent performance visually and tactilely on the line orientation task supports this prediction. The simplicity of the task is demonstrated by the fact that this task was the only one which did not require camera movement by the tactilely stimulated group. The remaining tasks required camera movement for pattern recognition, and in each case, accuracy for the tactile performance was below that for visual performance. Three possible explanations for the accuracy differential for the two modalities must be considered--first, the longer latencies required (to be discussed later) placed a burden on memory; second, the possibility that the visual system is better equipped for form recognition with the existence of specialized feature detectors which may not exist in the somatic system; and third, the overwhelming difficulty of handling internal details of a display. There is little doubt that the rapid saccaddic eye movements in vision permit nearly immediate summation of small parts of an image into a "whole" image. The relatively slow scanning required when manually manipulating a camera does not seem to lead to the same percept suggesting that the limitations of short-term memory storage is a factor in lower accuracy performance with the T.V.S.S. Placing the camera on the head should improve performance, but even head movements may not equal the 700-degrees per second achieved by saccaddes, and therefore tactile performance still may not equal that of vision. Concerning the relative capabilities of the visual and somatic systems of processing patterned displays, it is known that the retina does organize much of the received stimulation before it is passed through the optic tract. Much of this organization concerns the presence or absence of stimulation. Whether this processing occurs in the skin receptors is unknown, but if it does not occur in the skin, the visual system would necessarily be better equipped to deal with complex forms. The ability to perceive line orientation (moving and stationary) would seem to eliminate the necessity to consider specialized edge detectors, existing in vision, as a possible reason for improved performance visually. It would seem that the most likely difference in the two systems which might produce discrepancy in performance is lateral inhibition. Lateral inhibition, both in the retina and skin, serves to inhibit stimulation from adjacent regions thus producing enhancement of the response in a limited area. In the retina with its tightly packed receptors, inhibition may extend over a relatively large arc. In the skin, a comparable spread of inhibition would cover a much larger surface area in order to encompass a similar number of receptors. Neurophysiological investigation will be needed to determine whether lateral inhibition actually tends to inhibit stimulation over a large area of the skin. The problem of internal detail detection and identification may also be caused by lateral inhibition. It is known that funneling of stimulation into common channels occurs on the skin (von Békésy, 1959, 1967). Such funneling might possibly limit the detection or detailed inspection of regions lying within the boundaries of a large pattern of stimulation. This difficulty seems to be the largest problem confronting the Ss using the 400 point T.V.S.S. In four experiments--those dealing with external and internal form recognition, checkerboard slant detection, four alternating lights, and the Embedded Figures Test--the limitations with internal detail impaired performance accuracy. The fact that visual performance was not affected by this feature suggests that the visual system has neurophysiological means of processing such information. This process seems to be the major difference (excluding eye movements for the moment) between the visual and tactile form recognition noted in these studies.

The final prediction concerned the expected longer latencies with complex patterns. As has already been discussed, camera manipulation was significantly slower than eye movements and the resulting latencies on all pattern discrimination tasks requiring scanning was much longer tactilely than visually.

In general, the findings reported in the previous chapters lend strong support to the theory that similarities exist between the visual and tactile modalities. In turn, the similarities demonstrated in these investigations support a theory of perception based on amodal qualities of sensation and on the importance of observer-controlled sensor movement. The response characteristics of the visual and tactile modalities to comparable displays is often similar. Cross-modality transfer seemed to be demonstrated in the peg rotation and checkerboard slant studies. Camera movements, like eye movements, are necessary and seem to become ideosyncratic with learning. Distinctive features of familiar patterns elicit valid and complete percepts. These four observations together lend support to this theory of perception. It is proposed that form and space perception are amodal, based on higher order processes which are not modality specific. The individual sense modalities serve to provide the dimensions, qualities, and aspects of proximal stimulation which provide the basis of the percept. At the outset of learning, as in the case of depth perception by the congenitally blind, some intermediate steps in the perceptual process may exist, (e.g., a verbal intermediary or intellectual rule may be attached to some specific display). But with time, as with distinctive features of familiar objects, the display features themselves will trigger engrams or the entire display——motor responses, verbal mediaries, intellectual rules and the like——permitting immediate perception. The results reported for investigations with the T.V.S.S., especially the performance of the congenitally blind Ss, lends support to such a theory of form and space perception.

The results with the T.V.S.S. suggest that the system can be used to provide information for the blind concerning two- and three-dimensional displays. The necessity to devote much of the training time to camera manipulation should be lessened by the development of a light-weight television camera which can be worn on the head. Continued practice with the system should increase accuracy and shorten latencies for the performance of most tasks.

The interpretation of displays containing more details than the displays used in the reported studies will probably require a higher resolution display matrix than that used in the prototype systems. Research will be needed to determine the optimal number of stimulators, the number which continues to provide an increment of useable information without unnecessarily burdening the user with bulky hardware. Research will also be needed to determine whether the problem with internal display regions will be alleviated by increasing the resolution of the matrix or whether electronic enhancement of contours and edges will be needed.

Sensory substitution then seems to be possible. The tactile system was substituted for the visual system for the input of patterned displays, both two- and three-dimensional. It remains to be determined whether it will be necessary to artificially duplicate the coding of stimulation which occurs within some modalities or whether neural reorganization will, with learning, develop to facilitate the transmission and processing of sensory information. The combination of these two processes--neural reorganization, and electronic duplication of neural processing activity--should ensure success of sensory substitution.

VII

The Role of Sensor Movement

The important role of eye movements and camera-manipulation in the perceptual process with either visual or patterned tactile stimulation has been alluded to throughout this paper. Festinger (1971), proposed a theory of visual perception which stresses the role of memory traces of learned efferent programs as the central component in the perceptual process. According to this theory, an observer learns a particular, idiosyncratic pattern of eye movements when viewing an unfamiliar display. Subsequently, a distinctive feature of the display will elicit memory traces of the scanning movements of the entire display. Readiness to make the movements, even when they are not completed, is considered sufficient for the eliciting of the percept. Festinger's theory places primary emphasis on long-term memory storage of efferent programs for the perceptual process, and little importance is given to the detected features of the display. These features serve as end-points in a system of coordinants for directing and matching saccaddic eye movements. The observer attempts to scan the present display from feature to feature by initiating the efferent program elicited from long-term memory storage. If this program is sufficient to permit scanning the entire display, a veridical percept is produced. Eye movements for scanning familiar displays, according to Festinger's theory, are controlled more by memory traces than by proximal stimulation.

Another theory concerning the role of eye movements in visual recognition has been proposed by Noton and Stark (1971). This theory again emphasizes the role of memory traces in the control of eye movements. According to this theory, an observer viewing an unfamiliar display makes saccaddic eye movements between distinctive display features, usually angles and the like, and briefly fixates each feature. On subsequent presentations of the display, the same pattern of eye movements and fixations are elicited. This characteristic and idiosyncratic pattern of movements and fixations, called a "feature ring", is considered to have been built up during the original scanning of the display and later serves as a model for matching purposes. Matching the memory trace with the current scanning and features fixated leads to recognition. The movements employed in scanning a familiar display again are considered to be controlled by memory traces.

The major weakness of both theories which emphasize the role of memory traces in the control of eye movements within the perceptual process is the infinite number of such traces for efferent programs or feature rings that would be necessary considering the equally infinite number of transformations that can occur from altering display distance and orientation. Memory traces for eye movements could be the central component in the perceptual process only for familiar displays appearing at identical distances and orientations. With any other transformation, the display could not be correctly scanned with the elicited movement program.

Investigation is needed to determine the mechanisms which control the formation of eye movement programs. The results should indicate whether the scanning of familiar displays is controlled by memory traces or by properties detected in the proximal stimulation. A four part experiment is proposed. 1) Observers are to be presented ten unfamiliar visual displays--such as photographs of unfamiliar landscapes. Each display will be assigned a name to be learned. Eye movements will be recorded by electro-oculographic methods to provide records of eye movement sequence. 2) After the observers have learned to identify each of the ten displays, the displays will again be presented, and the observers will be asked to identify each. Eye movements, accuracy, and latency to correct identification will be recorded. 3) Subsequently, the displays will be presented in various transformations, either size or orientation will be altered. Eye movements, accuracy, and latency to correct identification will be recorded. 4) A single feature of each display--such as a distinctive angle or characteristic protrusion which subtends less than one- to two-degrees of the visual field--will subsequently be presented to the observers under a stabilized retinal image condition. The observers will be asked to identify the original display. Accuracy and latency will be recorded.

The theories proposed by Festinger and by Noton and Stark lead to several predictions as to what should result from the proposed experiment. The Noton and Stark theory would predict that initial presentation of the displays should be characterized by a regular and cyclical pattern of eye movements from each display feature to the next. Subsequent presentations of the displays should be characterized by idiosyncratic scan patterns with rapid and accurate display identification. However, new scanning patterns will be needed when the displays appear in transformed size or orientation. These theories suggest that a new pattern of eye movements will develop, which will be regular and cyclical again as the Ss scan from feature to feature. The latencies to correct identification will be increased under this condition.

Under the stabilized retinal image condition, the presentation of distinctive features from the original displays should still produce immediate identification according to the theories which emphasize the importance of memory traces of efferent programs in the perceptual process. It is assumed that the observer will be ready to initiate the learned program even if the stabilized image does not permit scanning the entire display. But the presentation of distinctive features from the transformed displays to observers under the stabilized retinal image condition may not produce accurate identification. The major question to be answered here is whether an observer can recognize a familiar feature being fixated in either size or orientation transformation.

In the event that display identification occurs with display transformation (either with stabilized retinal images or free scanning conditions), theories that emphasize the primary role cannot be supported. Elements other than these memory traces must be considered primary. Similarly, if the saccaddes used to scan transformations of the original displays are not entirely new but rather are corrected versions of the learned scan sequences, it must be concluded that other information enters into the process of programming saccaddic eye movements rather than solely memory traces. For instance, according to the theories, if a familiar display is presented at an increased distance from an observer, each saccadde from the learned scan pattern will be characterized by over-shoots. But if, under these conditions in the proposed experiment, the results indicate accurate saccaddes within the previously employed scan sequence, it must be concluded that information from the proximal stimulation has been used to determine the size or angle subtended by the display features. Such findings would suggest that saccaddes are programmed not only by memory traces of past experiences but also by characteristics detected within the proximal stimulation. In such a case, it will be reasonable to conclude that efferent programs are learned for familiar displays, but such programs are flexible, subject to change in the presence of other existing information. Characteristics detected in the proximal stimulation and memory traces associated with these characteristics must then be considered to be the primary components of the perceptual process in vision.

Similar experimentation is proposed to be conducted with the T.V.S.S. One major difference between the presently used camera manipulation and saccaddic eye movements must be stressed. Visual scanning of visual displays typically consists of three or four fixations per second linked by saccaddic eye movements with velocity of approximately 700-degrees a second. Saccaddes are ballistic, voluntary eye movements which terminate in a predetermined fixation point. In contrast, the speed of hand movements employed for positioning the T.V.S.S. camera has been measured with a resulting velocity of approximately 0.8-degrees a second. Such a velocity is more in line with that of the pursuit movements of the eyes which do not result from a predetermined program and do not result in knowledge of fixation direction. For this reason, comparison of hand positioning the camera and saccaddic eye movements may not be sound. However, the fact that the proprioceptive feedback received from the hands and arms does lead to accurate knowledge of direction after a scanning movement, such a comparison seems to be warranted.

Recording camera movement with an x-y pen recorder will permit determining whether repeated scanning of a display with the T.V.S.S. results in a fully predictable scan pattern. The T.V.S.S. camera and suspension bar are fixed with position-potentiometers to permit recording of camera movements in both the vertical and horizontal planes. It is also possible to use the output of the position-potentiometers to control the movement of a spot of light on an oscilloscope screen. A dynamic recording of the scanning with the T.V.S.S. can be obtained by properly positioning a mirror in front of the oscilloscope and between a video-tape recorder camera and the display. In this way, a moving spot of light is superimposed on the display features being scanned. Such dynamic recordings will indicate the scan sequence as well as the features selected for greater examination by the observer.

The proposed experiment is designed to determine if idiosyncratic patterns for scanning familiar displays develop as proposed in the introductory chapter of this paper and, if so, whether these scan programs are central in the perceptual process. Ten familiar objects will be presented to experienced T.V.S.S. Ss at normal distance and in frontoparallel positions. Camera movements will be recorded, and accuracy and latency of identification will be recorded. Three randomized sequences of these objects will be presented to each S. Comparison of the traces produced by the x-y pen recorder should suggest whether the scan patterns are repeated on subsequent display presentations. Analysis of the dynamic recording should indicate whether specific object features must be fixated before eliciting the proposed learned scan patterns. Subsequently, the objects will be presented to these Ss with variations in distance and orientation. The proposed learned scan patterns will not serve as efficient methods of scanning these displays. If the scan pattern is altered, it should be possible with the use of the dynamic recording to determine which features in the displays elicited the correct identification by observing which features are fixated just prior to the correct report.

The role of proprioception produced by self-controlled camera manipulation in the identification process can be partially investigated by presenting to a stationary camera the dynamic recording of the observers' own scan patterns from the analog visual display. As a control, the investigator can move the camera through an identical scan pattern as the S passively holds the camera. If identification does not occur, it can be assumed that the role of self-controlled camera-manipulation is significant in the identification process. If identification of the displays occurs in this passive situation, it may be hypothesized that the readiness to initiate a learned scan program plays an important role in the perceptual process.

These T.V.S.S. experiments will later be repeated with a lightweight television camera which will be mounted on spectacle frames. Head movements, with the observer wearing a simulated camera of this type, have been measured with a resulting velocity of approximately 400-degrees a second. Such a velocity is more in line with that of saccaddes than that of hand movements; therefore, it should be expected that scan programs are more likely to develop under this condition than with hand movements. Even if the proposed investigation with the hand positioned camera does not indicate the existence of idiosyncratic scan patterns, the later research should. The more rapid sensor movement should produce more similarities in performance and in the perceptual process between sighted observers using vision and blind observers using a head-mounted camera.

It is predicted here that the results of the proposed experiments will indicate that sensor movement (either eye or camera) in all three experimental conditions becomes stereotypic with familiar displays and that long-term memory traces are involved in determining scan patterns. But it is also predicted that the results will indicate that characteristics detected in the proximal stimulation are equally important in scanning familiar displays and primary in scanning unfamiliar displays. The common denominator in determining the scanning of both familiar and unfamiliar displays is the role of characteristics detected in the proximal stimulation. For this reason, if the experimental results support these predictions, it must be concluded that these characteristics detected in the stimulation serve as the primary component in the perceptual process, both with visual and patterned tactile stimulation. In this case, efferent programs for sensor movement elicited from long-term memory storage serve to make the recognition process with familiar displays more rapid and more efficient.

VIII

Final Considerations and Recommendations

A brief review of the literature pertaining to patients who have had congenital cataracts removed should be pertinent to the understanding of the difficulties faced by some of the congenitally blind subjects learning to use the T.V.S.S. as well as to the formulation of predictions as to what might be anticipated in future research and development of such a device.

Hebb (1949) reviewed the writings of von Senden regarding a number of such congenitally blind patients, and later Gregory and Wallace (1963) reported their observations of one patient. In general, form discrimination at the outset of newly acquired sight was difficult, but some patients were immediately able to identify geometric forms and upper-case letters by painstakingly tracing contours and counting corners. The patient with the best reported performance was able, after one month of practice, to identify a number of objects with apparent normal accuracy and visual behavior (Teuber, 1960). Most of these patients never achieved normal visual ability even after several years with sight. Detailed pattern discrimination, as that necessary in interpreting human facial expressions, was never achieved. In all cases, continued experience improved performance in most identification and localization tasks. For instance, no patient was able to distinguish cubes from squares at the outset of newly acquired sight, but repeated practice with these forms made the task possible.

The parallels between the experience of these patients and that of the subjects learning to use the T.V.S.S. are striking. Some congenitally blind subjects have been able to identify some geometric forms and upper-case letters at the outset of training by tracing contours and counting corners. Much practice is needed before cubes and squares can be discriminated, but continued practice permits this discrimination to develop.

Hebb stated that the studies with the congenitally blind patients suggested that visual discrimination requires a long learning period and that eye movements are an important feature in vision which also require practice. Teuber (1960) proposed three additional explanations for the relatively poor visual performance by these patients. First, other structural damage—such as lesions and atrophy by disuse—may occur and continue to exist in patients with congenital cataracts. Second, suppression of function (failure to attend to information provided by newly acquired input) may occur in such patients. And third, a general, non-specific retardation of behavior may occur in patients subjected to a prolonged deprevation of sensory input.

All of the explanations proposed by Hebb and Teuber most likely account for some of the deficit in visual performance manifested by these patients. Medical observations of both congenitally and adventitiously blind patients indicate that the extraocular muscles atrophy with disuse. Saccaddic eye movements for scanning displays then would be impossible at the outset of newly acquired sight. The patients were restricted to head movements for the scanning and fixating of features in the visually unfamiliar displays. Of course, even these head movements were not customarily used and needed practice. Also, the role of selective attention must have been important in many situations. These patients were unaccustomed to attending to visual stimulation while suppressing other sensory inputs. Other inputs, such as tactile and auditory stimulation, remained dominant. An example of this sensory dominance can be seen in one incident reported by Gregory and Wallace (1963). Their patient, accustomed to identifying objects by touch, was shown a machine. He remarked that he would need to feel it before he would know what it looked like.

Teuber (1960) proposed a general, nonspecific retardation of behavior as an explanation for the visual deficiency in the performance of some of the formerly blind patients. Axelrod (1959) stated that blind children as a group generally score lower on performance tasks requiring either tactile or auditory discrimination than do their sighted counterparts. The deprivation of these children seems to be more experiential than visual. Many such congenitally blind children do not receive the same motor and sensory experiences as do sighted children because the sheltering by parents is too severe. For this reason, congenitally blind people as a group cannot be expected to score as high as sighted people on many tasks. Such an expectation should hold for congenitally blind subjects learning to use the T.V.S.S. To this point in research, only congenitally blind who manifest good behavioral adjustment have received extensive training with the system. In the future, those teaching the blind to use the T.V.S.S. should expect to find that less well adjusted congenitally blind subjects will have more difficulty performing the assigned tasks than the well adjusted. In all cases, time will be needed for the blind to learn the necessary hand or head movements for efficient pattern scanning, and time will be needed for memory traces of scan patterns and distinctive features to build-up into a rich store of past experiences. Time will be needed to learn to place the new sensory input into a relatively dominant position in the perceptual process. To this point in work with the T.V.S.S., the most experienced subjects have received approximately 500 hours of practice with the system, approximately the same amount of time spent by the best performing patient reported by Teuber (1960). However, these blind subjects have spread their practice over a three year period, a time period which cannot be fairly compared to the one month of wakeful and continuous practice spent by the one patient. This patient received continual reinforcement for visual judgments which should be very effective in the learning of visual skills.

Future research related to the T.V.S.S. should provide the information regarding the perception of patterned tactile displays by the blind necessary to permit development of optimal visual aid. Five recommended areas for research follow.

1. Further investigation is needed concerning the role of camera manipulation, both with hand and head movements, as indicated in Chapter VII of this paper. The repeated recording of the scan paths used by individual subjects will permit the determination of whether certain scanning techniques are fully idiosyncratic or common to more than one person and whether efferent programs are learned and used on subsequent presentations of the same display.

2. The optimal camera lens angle must be determined. In vision, the foveal region, encompassing between one- and two-degrees of the visual field, is used for detailed inspection of displays. Peripheral vision permits detection of features to permit saccaddic movement for

foveal fixation. A wide-angle presentation of the periphery of displays surrounding a narrow-angle, detailed central display may also be optimal with the T.V.S.S. But the difficulty observed with internal display detail makes it likely that an alternative method of display will be needed. For instance, a preliminary wide-angle lens setting may be needed to locate distinctive features which will receive subsequent detailed inspection with a one- to two-degree lens angle setting. The latter alternative—assuming an easy-to-operate zoom mechanism can be developed to be used with a head-mounted camera—seems to be the most suitable means of overcoming the difficulty with internal display detail, with a relatively low resolution tactile display.

3. Information is needed concerning the neurophysiological and psychological organization of stimulation which may occur with patterned tactile stimulation. Single-unit recordings should provide the needed information concerning whether specialized feature detectors and on-off fibers exist in the somatic system. The gestaltists' experiments which demonstrated the existence of laws of visual organization should be replicated with the T.V.S.S. to determine if similar or identical laws apply to tactile stimulation. Although Revesz (1934) did not find the existence of closure when pressing cardboard cutouts against the skin, investigators with the T.V.S.S. have obtained evidence which suggests that laws regarding figure-ground relationships, contours, and grouping, may apply to patterned tactile stimulation.

4. Research is needed to determine the role of selective attention in large tactile displays. In vision, observers can fixate a small display and sequentially select features on which to attend (Averbach and Sperling, 1961). If such ability exists or can be learned with tactile

displays, large, high resolution tactile matrices can be considered for the T.V.S.S. Such research can be conducted with lower resolution matrices (perhaps 1000 points) by restricting camera movement to a given arc so that several forms appear in the field at all times. The observer can be asked to attend to a particular region of the field and to identify the form appearing there. With brief presentations, this method can also be used to replicate many of the studies conducted to investigate the extent of short-term visual memory (Averback and Sperling, 1951). The fact that the casual observer is able to shift attention from one area of tactile stimulation, such as the pressure of a shoe, to another, such as the feeling of a shirt collar, a prediction can be made that the needed selective attention can be learned with large tactile displays.

5. Investigations with different populations of blind subjects—adventitiously blind subjects and congenitally blind subjects with various levels of behavioral adjustment—should provide information concerning the role of past visual experience, behavioral retardation, and a variety of other factors which may influence performance with the T.V.S.S. such as age, intelligence, spatial ability, and personal motivation. Based on the research reported earlier, it can be predicted that the adventitiously blind subjects will perform many tasks better than the congenitally blind subjects because they can rely upon transfer from past visual experience and have suffered less from possible early developmental deprivation. Rapid learning should be observed in subjects who receive the opportunity to wear a portable system on a regular basis. This rapid learning should be most pronounced in the situations where young congenitally blind and newly blinded subjects have the opportunity of regular usage of such a device. These two groups of subjects may be expected to

develop skills which advance behond those developed by congenitally blind subjects who begin training later in life.

The results from the recommended research should provide useful information concerning the development of and the process of perception as well as permit further evaluation of sensory substitution.

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