10 The Relationship Between Motor Processes and Cognition in Tactile Vision Substitution

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Studies with tactile vision substitution for congenitally blind persons provide an unusual opportunity to observe the acquisition of "visual" spatial concepts in adolescents and adults. Since all aspects of the training are under the experimenter's control, the effects of each component of the process can be studied. In this paper the relationship between motor processes and cognition will be examined; specifically, the effect of placing the "eye" (television camera) under the control of the blind subject. We have noted that as long as the subject can control the movement of the camera, he can perceive in terms of the three-dimensional visual spatial world of which he is a part. It is possible to change the location and even the orientation of the tactile array (e.g., from the skin of the back to the abdomen), or the motor system controlling camera movement (either hand held, or located on spectacle frames and thus controlled by neck muscles), without compromising accurate spatial orientation.

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1 Tactile Vision Substitution System

In our sensory substitution studies, a substitute "eye" (a television camera) is placed under the motor control of a blind person. The optical signals received by the camera are transduced into stimuli that can be presented to skin receptors. A matrix of stimulators delivers images to the skin for relay to the brain. The blind person can be trained to use the information as "visual".

The instrumentation developed for the tactile sensory substitution system (TVSS) has been described (Collins & Bach-y-Rita, 1973) and our studies have been reported elsewhere (e.g., Bach-y-Rita, Collins, Saunders, White, & Scadden, 1969; Bach-y-Rita, 1972, 1982, 1983; White, Saunders, Scadden, Bach-y-Rita, & Collins, 1970).

Most of the subjects were congenitally blind college students who were paid to participate in the studies. Two of the research subjects were later included in the research team; one completed an engineering degree and became a research engineer on the project and the other became a graduate student and completed a Ph.D. while collaborating as a Research Psychologist.

Blind subjects were initially trained to control the camera, including manual control of the operation and focus and zoom. Each subject learned to direct the camera towards part of the field. Having achieved familiarity with manipulation of the camera, the person was taught to discriminate individual lines (vertical, horizontal, diagonal, or curved), subsequently shapes (circles, squares, or triangles), and solid geometric forms. When these were identified readily, a number of common objects (cup, chair, telephone) were presented, in varying positions and at different distances from the camera. As the appearance of these objects became familiar, the blind person discovered optical effects and developed visual concepts, such as shape distortion as a function of viewpoint and apparent change in size as a function of distance.

When two or more objects were presented simultaneously, the blind person learned to recognize each from minimal or partial cues. The subjects were able to describe the layout of three or four objects on a table in correct relationship even though they overlapped or were only partly visible. As training continued, techniques of visual analysis were developed. Studies with the TVSS have revealed rapid perceptual learning in spite of the poor resolution of the stimulus display. New perceptual concepts, such as the perceptual use of parallax, shadows, looming, and monocular cues of depth, were learned within surprisingly few trials, even though they had not been previously experienced by the congenitally blind persons.

Facility in directing the camera was accompanied by a change in the sensation derived from the patterned punctate stimulation of the skin. In the early stages of training (or when the camera was either immobile or under the control of another person), subjects reported experiences in terms of the sensations on the area of skin receiving the stimuli. However, when they could easily direct the camera at will, their reports were in terms of objects localized externally in space in front of them.

The provision of a motor linkage (camera movement) for the sensory receptor sur-
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face on the skin produced a surrogate “perceptual organ.” The receptor surface thus became part of a perceptual organ that could substitute for the normal visual perceptual organ, consisting of the eye with its receptor surface (the retina) and its motor apparatus (eye and neck muscles) (Bach-y-Rita, 1972).

We determined that the TVSS had practical educational and vocational applications; for example, we explored the presentation and recognition of forms, objects, letters, and graphic material (e.g., bar graphs), the identification of geometric projections and the ability to view objects under a microscope, such as a red blood cell or the wing of a fly. Further, instruction on spatial perception, as in the appearance of a table or a coin seen from a different angle, or the localization in depth of several objects in the field of view, or the flickering movements of a candle flame when moved by an air current, provided our blind subjects with concepts not available by any other means. A highly personal account has been published by a congenitally blind Ph.D. candidate in Philosophy (Guarniero, 1974, 1977). He later wrote his doctoral dissertation on space perception (Guarniero, Note 1).

2 The Somatosensory System: Its Relevance to Tactile Sensory Substitution Studies

2.1 Tactile Pattern Stimulation

An apparently logical way to design a tactile sensory substitution system is to measure the static two-point discrimination of the target skin area and limit the display to an array of stimulators separated by at least the two-point discrimination distance. However, the central nervous system extracts information from patterns in a dynamic display. Thus, although two-point discrimination is 56 mm on the skin of the back, in our TVSS displays we were able to use vibrator separation of less than half that distance. Patterns were also successfully presented through closely spaced electrical stimulators. With both types of stimulation, the array could be moved from one part of the body to another.

It is thus apparent that the brain can adjust to considerable variation in the tactile array and its body interface. It is not necessary to use the same cutaneous receptors or even the same locus during each experimental session. Critical factors for stable perception are a reliable tactile display and motor control of the information acquisition (with the TV camera).

2.2 Information Transfer

The results obtained with tactile substitution systems reveal that the somesthetic system is capable of mediating information from an artificial “eye.” The receptor matrix on the skin becomes, in essence, a relay to the brain of the information from the artificial “eye” (TV camera). In this sense its role is comparable to the dorsal
column nuclei or the ventrobasal thalamus, which normally function as relay stages in the somesthetic system. This system conveys information from the cutaneous receptors centrally, whether the information is received through "normal" tactile stimulation or through the mosaic of mechanical or electrical stimulators that transmit the output of the TV camera. Undoubtedly, the information is partially processed at subcortical levels, with descending centrifugal influences and "filtering" and "funneling". The information is then relayed to perceptual regions of the brain, probably via the somesthetic cortex.

The characteristics of the cutaneous receptors allow a rapid transfer of information, with possibilities for increasing the rate of transfer. In comparison with the retina, there is a faster transmission from the skin to the brain owing to the absence of retinal delay in the somesthetic system. This is especially evident if the display is delivered to a skin region close to the brain such as the forehead to scalp. Tactile acuity is best when brief mechanical stimuli are applied repetitively and inhibition is stronger for stimuli with rapid onset, which produce a greater amount of "funneling". Indeed, a decrease in lateral spread with an increase in frequency is a universal phenomenon (von Bekesy, 1967). These factors should be reflected in the performance of a mechanical tactile sensory system. Although the only frequency of mechanical vibration we have employed has been 60 Hz (for simplicity and economy, we used the line current frequency), a higher stimulus frequency should produce increased resolution. In fact, the Linvill-Bliss Optacon studies have demonstrated that 250 Hz is the most appropriate stimulus frequency on the fingertips (Rogers, 1970). The optimum frequency may also reflect the type of cutaneous receptors activated by the skin stimulation. Future studies may employ a stimulus frequency chosen in accordance with a desired "decay rate."

2.3 Central Nervous System Factors

Electrical stimulation undoubtedly activates different receptors and different patterns of receptors than do mechanical vibrators. The short path of the electrical current between the inner and outer rings of the concentric electrodes may maximally stimulate only the superfluous free nerve endings, although the reaction times noted suggest that fast pathways are used. On the other hand, mechanical vibrators produce waves which stimulate receptors in sequence and probably also stimulate deeper receptors. The absence of subject confusion (noted in our tactile vision substitution studies) when the locus and even the type of stimulus is changed suggests strongly that the plastic changes to enable the subject to receive in the new way have occurred at a high level: certainly it is not the peripheral receptors that have changed. It is also unlikely that spinal cord mechanisms are critical, since mechanical stimulation on the back and electrical stimulation on the abdomen obviously involve different spinal cord structures at different cord levels. Our results thus lend support to the pattern theory of cutaneous innervation, but also suggest that it is the higher supracord structures that are primarily involved in sub-
normally function as relay stages in the nervous system. Information from the cutaneous receptors is transmitted through "normal" tactile or electrical stimulators that allow a rapid transfer of information to the brain. In comparison with the information from the scalp, tactile stimuli are more vividly experienced.

2.4 "Visual" Quality of the Tactile Image

When a blind subject moves the camera across a field or an object, he obtains an image that moves across the receptors in his skin. Mechanisms similar to those in the retina (such as lateral inhibition) are available for edge enhancement. Our data suggest that, at least initially, the blind subjects obtain the "visual" information primarily by an analysis of contours (although simultaneous analysis of the information is also used), and thus artificial edge enhancement should produce improved performance.

Subjects using the TVSS learn to treat the information arriving at the skin in its proper context. Thus, at one moment the information arriving at the skin has been gathered by the TV camera, but at another it relates to the usual cutaneous information (pressure, tickle, wetness, etc.). The subject is not confused; when he scratches his back under the matrix he does not "see" anything. Even during task performance with the sensory system, the subject can perceive purely tactile sensations when he is asked to concentrate on these sensations. Further, as noted above, no relearning is necessary when the matrix is moved from one skin locus to another, provided that the camera is controlled by the blind subject. Experienced blind subjects trained with the mechanovibratory matrix on the back immediately adapted to the electrical stimulus matrix on the abdomen. The vibrators produce waves of skin movement, which travel across the skin. (Von Bekesy, 1967, has reported skin waves on the arm of the order of 2 cm for vibrations of 50 Hz. An increase in vibrator frequency up to 150 Hz reduces the wavelength to 0.6 cm.) In contrast, the effect of electrical stimulation is limited to a small region between the inner and outer rings of the concentric electrodes.

Blind subjects apparently learn how to interpret the information relayed through the skin stimulators in terms of "visual" images. The learning process may be similar to that which takes place in children with normal sensory and motor systems, or in adults learning a foreign language or Morse code, or in deaf persons learning manual communication. Blind subjects who have trained with the TVSS demonstrate perceptual equivalence between and across modalities. However, this is also frequently noted under other circumstances: Gibson (1966) noted that "fire" is the same whether the information has been obtained by hearing, feeling,
looking, or smelling. There is a common aspect of perceptual activity that permits one to utilize information from several channels in such a way that invariant properties of objects are extracted.

As learning progresses, the information extraction processes become more and more automatic and unconscious, and the "chunking" phenomena discussed by Miller (1956) allow the number of bits per chunk to increase. For example, a blind subject "looking" at a display of objects must initially consciously perceive each of the relative factors such as the perspective of the table, the precise contour of each object, the size and orientation of each object, and the relative position of parts of each object to others nearby. With experience, information regarding several of these factors is simultaneously gathered and evaluated. Thus concepts of "chunking" appear to apply to the development of increased information transfer through a sensory substitution system. This highly complex "visual" work can thus be reduced, by selective processes, to manageable proportions, allowing the input to be mediated by the somesthetic system or, in Gibsonian (1966) terms, the subject learns to extract the relevant information. Since the channel capacity of the somesthetic system does not differ markedly from that of the visual system (Miller, 1956), it is possible that with a high-resolution sensory substitution system, the information transfer rate may be comparable to that in a normal visual system, if the chunking processes can be developed.

2.5 Overload

Normal sensory systems do not usually overload, since the central nervous system is able selectively to inhibit information not needed for any particular perceptual task. We have discussed this elsewhere: "Many efforts at creating sensory aids set out to provide a set of maximally discriminable sensations. With this approach, one almost immediately encounters the problem of overload — a sharp limitation in the rate at which the person can cope with the incoming information. It is the difference between landing an aircraft on the basis of a number of dials and pointers that provide readings on such things as airspeed, pitch, yaw, and roll, and landing a plane with a contact analog display... Visual perception thrives when it is flooded with information, when there is a whole page of prose before the eye, or a whole image of the environment; it falters when the input is diminished, when it is forced to read one word at a time, or when it must look at the world through a mailing tube. It would be rash to predict that the skin will be able to see all the things the eye can behold, but we would never have been able to say that it was possible to determine the identity and layout in three dimensions of a group of familiar objects if this system had been designed to deliver 400 maximally discriminable sensations to the skin. The perceptual systems of living organisms are the most remarkable information-reduction machines known. They are not seriously embarrassed in situations where an enormous proportion of the input must be filtered out or ignored, but they are invariably handicapped when the input is drastically curtailed or artificially encoded."
perceptual activity that permits such a way that invariant properties become more and more noticeable phenomena discussed by to increase. For example, a blind person can consciously perceive each of the precise contour of each object, and the relative position of experience, information regarding and evaluated. Thus, concepts of increased information transfer are highly complex “visual” work can exhibit proportions, allowing the r, in Gibsonian (1966) terms, the Since the channel capacity of the that of the visual system (Miller, 1951) substitution system, the input in a normal visual system, if the central nervous system is for any particular perceptual task, at creating sensory aids is put to use. With this approach, one almost — a sharp limitation in the rate at formation. It is the difference between dials and pointers that provide a roll, and landing a plane with a roll when it is flooded with information the eye, or a whole image of the idea, when it is forced to read one through a mailing tube. It would all the things the eye can behold, it was possible to determine the sense of familiar objects if this system discriminates sensations to the skin. The most remarkable information-embarassed in situations where it is not allowed or ignored, but they are curtailed or artificially encoded.

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Some of the controversy about the necessity of preprocessing sensory information stems from disappointment in the rates at which human beings can cope with discrete sensory events. It is possible that such evidence of overload reflects more an inappropriate display than a limitation of the perceiver. Certainly the limitations of this system are as yet more attributable to the poverty of the display than to taxing the information-handling capacities of the epidermis” (White et al., 1970).

2.6 Transduction into the Mode of Information Handling of the Substitute Sensory System

In one of the most successful sensory substitution systems, American Sign Language (ASL) for the deaf, information usually presented to the auditory system (which is capable of high frequency analysis, but receives relatively little information simultaneously) is presented to the visual system (which has a poor frequency response, but can receive a large amount of information simultaneously). Although the hand movements of the deaf ASL communicators are slow in relation to the auditory system frequency capacities, the hand movements and associated facial and body movements transmit a great amount of information simultaneously and allow the deaf persons to “speak” in real-time. Similarly, to transmit visual information to the somatosensory system (which is capable of a frequency resolution on an order of magnitude greater than the eye but much less than the auditory system, but handles more simultaneous information than the ear although less than the visual system), the visual information must be transduced to allow the somatosensory system to operate most efficiently. This is discussed elsewhere (Bach-y-Rita, 1983).

2.7 Somatosensory Cortical Evoked Potentials in Blind and Sighted Subjects

To evaluate and identify further brain plasticity mechanisms demonstrated by the sensory substitution studies, we have evaluated differences in the cortical potentials evoked by patterned fingertip stimulation between sighted subjects and blind persons with extensive tactile training. The early components of the evoked potential are the same, but later components reveal shorter latencies in the blind subjects, with the N3 latency being 13% shorter (Feinsod, Bach-y-Rita, & Madey, 1973). These data may reflect plastic changes due to training.
3 Motor Control and Cognition

3.1 TVSS Motor Control and Cognition Studies

Systematic studies of the motor control aspects of tactile vision substitution have not been undertaken. However, some of the anecdotal reports relating to motor control will be discussed briefly.

To differentiate between camera movement and object movement, both proprioceptive input and motor command [or in terms discussed by von Holst and Mittelstaedt (1950), the distinction between afferent stimulation (environment) and reafferent stimulation (active motion of the perceiver)] may play a role. This is comparable to the adaptation to prism and reversal lenses in vision studies, which requires some orderly relation between sensation and the sensory consequences of self-produced motion (Teuber, 1960). After training with the TVSS, Guarniero (1977) noted that “watching an image move in the direction opposite to the one in which the camera was moving was at first a most unsettling phenomenon, but eventually I learned to make the necessary adaptation so that objects appeared stationary as I scanned them. This was especially difficult for me to become accustomed to, because nothing in my tactile experience had prepared me for it.” A further adaptation had to be made when he was given motor control of zoom and lens aperture: “After an hour or so of using the new camera, objects started to regain their familiar sizes.” Guarniero (Note 1, p. 137) points out that only touch, vision, and the TVSS require movements of the receptors to explore the environment.

In vision, the muscles (oculorotary) and the receptor matrix (retina) controlled by them are in close proximity. In the TVSS studies muscles could be distant from the sensory input, and muscle control mechanisms could be interchanged. Thus, with the skin stimulation matrix kept in one area (e.g., the skin of the abdomen), the camera could be head mounted (controlled by neck muscles) or changed to hand held, with no noticeable effect on perception. Furthermore, the motor control can be complex: at the earliest stage of the TVSS project the TV camera was mounted on a tripod; vertical and horizontal movements were controlled by separate hand cranks, yet the blind subjects easily adapted to the awkward movement control system.

The change from the perception of a tactile stimulation to a spatial three-dimensional perception occurred in most TVSS subjects after 5–10 h of training. Subjects would begin to report perceptions in terms of space and distance (“out there”) instead of merely describing the shape of the object. This important change was not easily recognized by the subjects; in fact Guarniero (1977), a highly analytical subject, was not convinced that he perceived spatially. However, in addition to reports of spatial percepts, incidents occurred that re-inforced this observation. For example, one subject was observing changes in perspective by viewing a large cardboard checkerboard; the cardboard was tilted in different directions and the subject was asked to judge the directions of the tilt. At one point, the cardboard slipped out of the hands of the instructor and fell against the subject. A few days
Tactile vision substitution have led to the study of motor object movement, both processes discussed by von Holst and ent stimulation (environmental conditions) may play a role. This is lenses in vision studies, which and the sensory consequences of the TVSS. Guarniero direction opposite to the one in a unsettling phenomenon, but sion so that objects appeared difficult for me to become accus- had prepared me for it." A fur- in motor control of zoom and w camera, objects started to re-17) points out that only touch, ceptors to explore the environ- receptor matrix (retina) controlled s muscles could be distant from s could be interchanged. Thus, e.g., the skin of the abdomen), y neck muscles) or changed to s. Furthermore, the motor con-SS project the TV camera was ents were controlled by separate d to the awkward movement stimulation to a spatial three-objects after 5—10 h of training, ms of space and distance ("out e object. This important change Guarniero (1977), a highly anal- spatially. However, in addition sat re-inforced this observation. n perspective by viewing a large in different directions and the it. At one point, the cardboard against the subject. A few days later, the instructor moved the zoom control of the camera as the subject viewed the checkerboard. He had a clear defensive reaction, moving backward to avoid what he perceived to be the cardboard checkerboard falling on him. Thus, the increase in size of the checkerboard was perceived by him to be a looming object and the movement was perceived to be toward his face, even though the tactile array was placed against the skin of his back. The subject was controlling the camera movement, and thus perceived the spatial characteristics of the stimulus.

A number of the tasks performed by blind TVSS subjects can be interpreted as demonstrating hand("eye") coordination, and thus requiring three-dimensional spatial (cognitive) and motor interaction. Among these tasks are the following:

(a) Assembly and Inspection of Miniatuur Electronic Components. In cooperation with an electronics manufacturing firm, a highly trained TVSS subject (who was totally blind from the age of 2 months) learned to perform complex miniature diode assembly and inspection tasks requiring a considerable degree of hand("eye") coordination while working on the assembly line. A small television camera was placed in the ocular of a dissecting microscope, and the subject received the image on the skin of the abdomen through a vibratotactile array fixed to the workbench. He attained a high level of performance in both the inspection and the assembly components of the job (described elsewhere; e.g., Bach-y-Rita, 1982).

(b) Tactually Guided Batting. The aim of this investigation was to study to what extent it is possible to perform a predictive task such as catching a ball guided only by information presented tactually. The tactile display was a 20 × 20 matrix of vibrators presented to the back of two well-trained blind subjects. The perceptual-motor task consisted of "batting" a ball which was rolled towards the subject with tactual information about its path. The results demonstrated that it is possible to pick up tactual information in this form, organize the response and perform appropriate movements within the time available (Jansson & Braby, Note 2).

(c) Handshaking. Congenitally blind TVSS subjects learned to perceive an outstretched hand and reach out to clasp it accurately with their own hand, monitoring the relative movement of the two hands (e.g., Guarniero, 1977).

TVSS subjects interviewed 10 years after completing their participation in the project emphasize the importance the training has had in developing visual concepts. As one subject stated, "I know what sighted people are seeing as they walk around a desk." The changes in perspective with self-generated motion while maintaining a unitary percept (the desk did not change shape) was thus particularly noteworthy to him.

3.2 Some Theoretical Questions

The theoretical questions that may be studied with tactile vision substitution are intriguing: Is the visual cortex necessary for tactile vision substitution? To date we have not trained cortically blind persons. In any case, it is by no means certain
that the visual cortex serves only visual functions. We showed many years ago that
cat primary visual cortex cells received inputs from skin and auditory (we did not
test for other modalities) receptors (Murata, Cramer, & Bach-y-Rita, 1965), and
Rosenzweig, Krech, Bennett, and Diamond (1962) have shown that in rats blinded
at birth, the principal cortical changes produced by an enriched environment were
in the occipital cortex, even though the rats had developed without any visual
input. There is considerable interest in the possibility that the occipital cortex is
an area of spatial function (e.g., Thompson, 1982; Doty, 1982). However, non-
visual functions of the visual cortex had earlier been demonstrated by Lashley
(1943). Tactile vision substitution studies may help to clarify the spatial orientation
role of the occipital cortex.

Among questions that may be answered by further study are the following:

(a) How is the experience of a continuous visual world developed? A puzzle in the
psychology of perception has been the appearance of the visual world as a coherent
whole despite our viewing it through a temporally discontinuous series of eye fixa-
tions. Jonides, Irwin, and Yantes (1982) discuss the importance of a briefly lasting
memory in which temporally separate glimpses of a display are stored simultane-
ously and are spatially reconciled with one another, thus allowing a coherent view
of a display that is constructed from the individual glimpses of which it is made.
They further discuss the effect of saccades and saccadic suppression, and they
hypothesize that the integration of information indicated by the saccade condition
requires the use of a special memory.

Blind TVSS subjects have also experienced a continuous stable "visual" world.
It apparently must be learned: for example, Guarniero (1977) described his initial
impression, while sweeping across a field with the TV camera, that the field was
moving in the opposite direction. Tactile vision substitution studies, in which all
factors can be controlled (including the ability to provide discontinuous input and
possibly to create "saccades") may help to clarify these questions.

(b) Visual illusions. The fact that we have demonstrated "visual" illusions (e.g., the
waterfall effect) with blind TVSS subjects strongly suggests that central, rather than
retinal receptor mechanisms, underlie these phenomena.

A number of other theoretical questions, such as the cortical representation
of functions including motor localization, may be appropriately studied with sen-
sory substitution models. In particular, the development of a primate tactile vision
substitution model would allow neuronal mechanisms to be evaluated. However,
a discussion of these topics is beyond the scope of this chapter. Results to date with
the TVSS have demonstrated, however, that sensory substitution models are of
considerable value in the study of perception, cognition, and motor control.
showed many years ago that in and auditory (we did not, & Bach-y-Rita, 1965), and we shown that in rats blinded a enriched environment were developed without any visual that the occipital cortex is Doty, 1982). However, non-

study are the following:


References


Miller, G.A. The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, 1956, 63, 81-97.


Summary. A vision substitution system, in which "visual" information is acquired by congenitally blind persons by means of a tactile display of the image captured by a television camera, offers an opportunity to study the relationship between motor processes and cognition. As the blind subjects learn to use the system, spatial perception is related to the camera if its movement is under the subject's control. This occurs whether he is controlling camera movement with head or hand movements; the two control modes can be interchanged at will. To differentiate between camera movement and object movement, both proprioceptive input and motor command may play a role. A number of other practical and theoretical questions can be answered by using the tactile vision substitution system, and the development of an animal model would allow the study of underlying neural mechanisms.