Acta Neurol. Scandinav. 43, 417–426, 1967.

Smith-Kettlewell Institute of Visual Sciences, Presbyterian Medical Center,
San Francisco, California.

SENSORY PLASTICITY

Applications to a Vision Substitution System

PAUL BACH-Y-RITA

INTRODUCTION

A prosthetic challenge is offered by the possibility of using the tactile sensory system to carry optical information from an artificial receptor to the brain. After a training period, sensory plasticity may enable such information to be perceived as three-dimensional "visual" information. Sensory plasticity is defined here as the ability of one sensory system (receptors, afferent pathways, and the central nervous system representation) to assume the functions of another system.

Sensory information reaches the brain in the form of nerve impulses (*Rushton* 1961). There is no doubt that the temporal and spatial patterns of nerve impulses provide the basis of our sensory perception; the coding of information in the form of nerve impulse patterns is a fundamental concept in neurophysiology and psychology (*Melzack & Wall* 1962). For example, visual information is sent along the optic nerves in the form of patterns of nerve action potentials. The optical *images,* per se, reach no farther than the retinal receptors. The brain must interpret the nerve impulses as a visual image, after decoding the patterns of afferent impulses.

A large body of evidence indicates that the brain demonstrates both motor and sensory plasticity. The aim of this paper is to examine the evidence for plasticity as a fundamental basis for the development of a high resolution vision substitution system.

MOTOR PLASTICITY

Leyton & Sherrington (1917) noted that in monkeys extirpation of cortical motor areas produced marked paresis, but that over a period of time recovery occurred. Foerster (1930a) showed that training may

This work was supported by NIH Career Program Award No. 5 K3 NB 14,094, and NIH General Research Support Grant No. 5 S01 FR-005566-03.

lead to a restitution of arm and hand movements in adult humans, in spite of anatomically verified complete degeneration of the pyramidal tract. In these cases new motor functions may appear through learning processes involving the highest level of integration (*Gellhorn* 1953).

In a series of patients with motor disabilities as the result of poliomyelitis, *Weiss & Brown* (1941) transposed the biceps femoris muscle (a flexor) to the extensor side of a knee joint to substitute for the weakened or lost action of a paralized quadriceps muscle. Initially, the muscle contracted only in the flexor phase, but "... surprisingly few trials were required to make the transplant suddenly contract in the extensor phase, too." After further trials, the muscle operated only in the extensor phase. *Weiss* and *Brown* (1941) supported the view that the adjusted use of the transplant was due to the development in higher centers of a new type of action which could override the innate coordinative associations without abolishing them.

RECOVERY OF SENSORY FUNCTIONS

Sensory functions often recover after extensive lesions. *Foerster* (1930b) suggested that the recovery of cortical sensory functions is due to a "reorganization" of the remaining parts of the nervous system. *Fessard* (1961) proposed that a network of nerves may offer several alternative routes to the same point, and that this may be the main reason for the maintenance of function after severe mutilation.

After bilateral occipital lobe ablation in monkeys which included the entire striate cortex, all visual responses were lost, but within several months most of the monkeys had regained visual responses (*Pasik & Pasik* 1964). *Smith & Burklund* (1966) have reported a case of left-sided, total hemispherectomy in a 47-year old man with marked recovery of functions.

These data indicate that plasticity can and does occur in both motor and sensory systems. The possible mechanisms will be discussed below.

AFFERENT INFORMATION TRANSMISSION

Behavioral and neurophysiological experiments suggest that the sensory pathways are plastic, rather than fixed, in the transmission of impulses generated by a particular stimulus (*Livingston* 1959). Also, even such a highly specialized cortex as the visual cortex receives afferent impulses from sensory receptors other than the visual receptors (*Murata, Cramer & Bach-y-Rita* 1965). In addition to specific pathways, afferent impulses from many sources converge on cells of the reticular formation (*Bach-y-Rita* 1964), and the role of this input on subjective sensory experience has yet to be fully understood. The brain stem evidently plays an important role in the government of neuronal plasticity (*Livingston* 1959). The extensive multisensory invasion of many cortical and subcortical regions produces neuronal fields of intercommunications which should be ideal places for new associative links (*Fessard* 1961).

Experimental evidence suggests that point-to-point peripheral to central sensory representation does not occur. The nerve impulses from each sensory receptor or group of receptors are apparently not kept isolated from other sensory nerve impulses. In this regard, *Mountcastle* (1961) suggested that the connections of primary afferent fibers to central cells are not sufficiently specific to explain the discriminations of which we are capable on any theory of insulated parallel lines (separate nerve fibers). The central nervous system appears to work with complex patterns of events which occur in large populations of cells. He stated that such a mechanism may be located in a sensory receiving area of the cerebral cortex which is responsive to the spatial and temporal patterns of neural events reaching it, and which extracts from that pattern information concerning the peripheral event provoking it.

Thus, the reception of information depends on the excitation of a population of receptors in such a way as to produce coded nerve impulses which are delivered to the brain. The skin may have possibilities for coding even superior to those of other channels (*Gilmer* 1966) since it combines temporal and spatial qualities, and it is rarely ever "busy". *Bliss* (1962) has suggested that the key to a high information transmission rate from the skin is the development of a complex tactile display in which many stimulators and many sensation dimensions are used. *Howell* (1960) noted that the reaction time for touch is lower than for vision, and probably also than for audition. He suggested a potential superiority over other channels may exist in the skin with respect to information processing.

CUTANEOUS RECEPTORS

The potential for coding would also seem to exist in skin to the requisite degree. Studies by *Weddell* and his associates (summarized by *Weddell* 1961) have shown that encapsulated skin receptors are absent over most of the body surface. Thus, although only naked nerve endings and hair basket receptors are found in the skin of the forearm and other hairy areas (over 90 per cent of the body), all of the usual cutaneous sensations are present. *Weddell* demonstrated that the human cornea contains only naked nerve endings, yet all the primary modalities of common sensibility can be evoked from it. The density of nerve endings is so great that over the entire body a discrete pinprick will always activate more than one ending (*Melzak & Wall* 1962, *Weddell* 1961).

CODING OF AFFERENT INFORMATION

If an adequate artificial receptor were available, and the machine-man interface and training problems were overcome, would the information transmission capacity of a circumscribed cutaneous area be sufficient to project high-resolution optical images from the skin to the brain? *Adrian* (1949) noted that 100 nerve fibers can send more than 10,000 impulses per second to the brain. *Rushton* (1961) has pointed out that a single nerve can carry 30 bits of information in 0.1 second. He stated, "Clearly the flow of information is limited not by the transmission lines but by the coding or decoding of the messages transmitted." *Mountcastle* (1961), however, considers that the limiting factor in transmission frequency is the peripheral receptor.

Thus, an evaluation of the data on cutaneous receptors and on the coding and transmission of afferent impulses suggests that the information transmission capabilities of a circumscribed cutaneous area should be sufficient to allow high resolution images presented to that area from an artificial receptor to be projected to the brain.

DECODING OF AFFERENT IMPULSES

The sensory information reaching the brain must be decoded. *Head* (1918) pointed out that the mass of afferent impulses must undergo integration before they can exercise any useful function, and that this is true not only for their qualitative but also for their projectional characters; the projectional aspects of sensation are not related to ourselves, but to external objects and, in fact, he defined "object" as a complex of projected responses.

Melzack & Wall (1962) suggest "... central cells can detect some characteristics of stimuli from the impulse patterns arriving from the skin by means of the properties of differential threshold, temporal summation and adaptation ... The central cells will be bombarded not only by the sequence of impulses in a single fiber, but also because there is a convergence of many fibers onto each cell, by the spatial summation of the time sequence of impulses in many fibers ..."

How is the coded sensory information decoded? Data cited above suggest that sensory messages from a peripheral area may reach the brain by several alternate pathways. The clinical and the research data on motor and sensory plasticity support the concept that central representation is not rigidly localized. Thus, although the mechanisms are not known, it is apparent that the decoding of sensory messages must be a changeable, or plastic process. In *Adrian*'s (1949) view, the brain "... is no longer thought of as a diagram with fixed centers for this and that function, but rather as a sheet of nerve cells beating in groups, large or small, which combine and split up again ..."

CENTRAL PLASTICITY

Histological data demonstrate a neural substrate for central plasticity. Each afferent nerve fiber entering the brain is potentially capable of influencing a large population of central cells.

One corticipetal axon may influence up to 5000 neurons, each of which may embrace as many as 4000 neuronal perikarya within its own dendritic field (*Sholl* 1956). In the cortex, only 10 per cent of the total neuronal surface is perikarya: most of it is made up of dendritic arborizations. Several investigators, including *Leyton & Sherrington* (1917), noted that cortical representation of a specific movement may vary from minute to minute. The effect of cortical stimulation is dependent on the impulses at the cortex from other sources (*Sholl* 1956). *Sholl* (1956) concluded that there is a lability, or plasticity, inherent in this tissue that forbids the attempt to "localize function" at specific points.

Following an extensive study on rats with selective cortical ablations, *Lashley* (1952) noted that, with certain exceptions, the cortex had the property of "equipotentiality", the apparent capacity of an intact part to carry out, with or without a reduction in efficiency, the functions that had been lost by the lesion.

In view of the foregoing evidence, it is conceivable that not only is the central nervous system plastic in regard to naturally occurring stimuli and to anatomical lesions, but that it may also be capable of adapting to novel stimuli. The novel pattern of afferent impulses from an artificial receptor may be capable of delivering to the brain a complex "image". With suitable training, new decoding mechanisms may be developed to process the resulting patterns of nerve impulses.

Fessard (1961) noted that any repetitive activity, when made more or less intense, induces plastic changes, and that the persistence of the effects due to plastic changes endows the system with new functional properties. Similarly, the patterns of nerve impulses from an artificial receptor may produce plastic changes and new functional properties.

POSSIBLE EFFECTS OF SENSORY SUBSTITUTION

Is it possible to alter the central effects of afferent impulses from a circumscribed region? Central sensory representation, although to a degree phylogenetically determined, may possibly be modified if the functional roles of the particular "sensations" are modified. This concept can be submitted to test by increasing the functional demands from a cutaneous area which normally has a limited sensory role. This can be accomplished by presenting suitable coded "visual" information from an artificial receptor to the cutaneous area. A successful vision substitution system, producing high-resolution "visual" (rather than the normal tactile) experiences on presentation of the optical images to the skin of the back, may produce measurable central effects. In normal subjects the cutaneous sensations of the back have a small central representation (*Penfield & Jasper* 1954). It may be possible to measure the change in the response evoked from the cutaneous area. The methods of *Uttal & Cook* (1964) for studying cortical potentials evoked by somatosensory stimuli may possibly be utilized to compare the evoked potentials before and after training with the vision substitution system.

PILOT STUDIES

Many attempts have been made to develop artificial cutaneous communication systems. The equipment and the psychophysical aspects of the principal research approaches have been reviewed (*Bliss* 1967, *Geldard* 1960, *Gilmer* 1966, *Hawkes* 1960). At present several research groups are studying the means of presenting optical data to cutaneous areas. Some of these will be discussed in relation to a tactile television system concept (*Collins*, in press).

Gardener (in press) has developed a system including an array of photosensors, a computer, and a 12×8 array of piezoelectric vibrating stimulators which are in contact with the fingers. Subjects have learned to differentiate simple geometric forms (squares, triangles), as well as horizontal and vertical bars. *Kotovsky & Bliss* (1963), working with an array of air-jet stimulators on the fingers, noted that subjects could identify any three stimulators actuated, and sensations of apparent motion could be induced. They noted that adaptation to the stimuli did not occur.

In Poland, *Starkiewicz & Kuliszewski* (1965) have developed an array of 120 photoelectric elements which transforms an optical image into tactile stimuli on the forehead of the blind subject by means of electromagnetic transducers.

In our laboratories, a vision substitution system is under development to transform optical images from a TV camera into cutaneous vibratory stimuli delivered to the skin of the back (*Collins, Acker, Holmlund & Bach-y-Rita*, in preparation). The skin receptors become the first station relaying information to the brain from the artificial receptor (TV camera). A commutator has been constructed to drive an array of 400 vibrotactile stimulators placed on half-inch centers. An array of nine stimulators (3×3) on 2-centimeter centers has been constructed in order to test the system before proceeding with construction of the larger array.

Preliminary testing is in progress using the nine-point stimulator model. The array, fixed in the back cushion of a dental chair, contacts the skin in a 4 × 4 centimeter area of the back just below the subject's right scapula. Stimuli of fixed, suprathreshold amplitude, vibrating at 60 cps, are delivered through styli with rounded tips of approximately 1 mm radius. Data on a blindfolded subject is presented here. In the first two test series described below, a manual control panel with nine push switches corresponding to the stimulus points in the array was used to deliver the stimulus pattern. In the later test series, the stimulus array was activated by the TV camera and commutator designed for the system.

1. *Relative Area Discrimination*

a) One, two, three, or four adjacent points were simultaneously activated. As the number of points increased, the skin area stimulated was perceptibly larger. After four minutes of orientation practice, the number of points activated in random combinations were correctly identified in 75 out of 100 trials.

b) Activation of one, two, four, or eight adjacent stimulators resulted in correct identification of the number in 84 out of 100 random presentations.

2. *Simple Form Recognition*

Four simple forms, "L", "T", "X", or "+" were chosen because they could be produced easily in the 3×3 array with an equal number of stimulators. When presented as static figures; *i.e.*, appropriate points simultaneously activated, the recognition of the form was extremely difficult and may have required extensive practice for identification. By sequential activation of the stimulator points (via push buttons), dynamical "written" forms were easily identified. After five minutes of practice, correct recognition was recorded in 78 out of 100 random presentations.

3. *Movement Perception*

a) Identification of the orientation and direction of movement of horizontal and vertical bars were easily achieved. A white horizontal bar was passed across the field of the TV camera both from above and from below. Also, a vertical bar was passed from left to right and from right to left. Frequencies of movement up to one cycle per second were employed. After a few trials, 100 per cent correct identification of the orientation and direction of movement were obtained in both cases.

b) A horizontal bar was passed across the field of the TV camera in a vertical direction sinusoidally through an arc of five degrees across the array at a rate of one cycle per second. The blindfolded subject was easily able to follow the movement with his finger.

4. *Scanning with the TV Camera*

By manipulating the TV camera, the blindfolded subject was able to: one, follow the controur outline of large objects, two, distinguish between squares of one and three degrees in angular size to the camera, and three, correctly identify and differentiate between 10-degree squares and rectangles of 10 degrees.

Further testing is proceeding; all nine stimulators now contact the skin of the back within a one-inch square, and the resolution is approximately equal, after a short period of training, to that described above. The results will be reported elsewhere (*Morris, Collins & Bach-y-Rita*, in preparation).

The larger array of 400 stimulators will allow dynamic optical images of greater detail to be delivered to the skin. It should be possible to evaluate the ability of the subject to learn to interpret the resulting patterns of afferent impulses as projected "visual" images. With a successful vision substitution system, the images may be subjectively projected outward in space, an experience comparable to a normal visual experience.

DISCUSSION

The theoretical basis for the design of the vision substitution system described above implies a concept of a brain so malleable that the subjective experience of "vision" (as well as the quantitative and qualitative afferent information necessary for useful "vision") could be obtained through an artificial receptor projecting to the cutaneous receptors.

Subjective experiences may be products of a learning process in which afferent inputs from multiple sources are utilized. It is consistent with this premise that the afferent information from a single receptor might take part in the production of several different sensations, depending on the accompanying temporal and spatial patterns of afferent activity. The subjective categorization may be largely due to a learning process which would include the development of decoding mechanisms which produce the subjective categories (*e.g.*, touch, tickle, wetness). The identification would be based on analysis of the patterns of afferent nerve impulses reaching the brain.

In the case of information originating from an artificial receptor, the ability of the brain to extract the data and recreate subjectively the image captured by the artificial receptor would depend on the adaptability, or plasticity, of the brain. There is ample evidence, discussed above, that the brain is capable of adapting to a variety of extreme conditions. That a successful sensory substitution system is not presently in use may not be due to limited functional capabilities of the brain; it may be due to the fact that an artificial receptor system has not yet been constructed to challenge the adaptive capacities of the human brain.

SUMMARY

Evidence for sensory plasticity is evaluated in relation to the substitution of one sensory system for another. A vision substitution system composed of a TV camera, a commutator, and a large array of stimulators in contact with the skin of the back is under development. Preliminary data is presented showing successful form discrimination and object tracking utilizing the system with stimulator matrix leaving a 2-centimeter interstimulator distance.

I thank Dr. *Arthur Jampolsky* and Dr. *Forbes Norris* for their valuable comments.

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Received February 2, 1967.

Paul Bach-y-Rita, M.D.,
Smith-Kettlewell Institute of Visual Sciences,
Presbyterian Medical Center,
San Francisco, California.