SENSORY SUBSTITUTION AND LIMB PROSTHESIS

P. Bach-y-Rita and C. C. Collins

Summary

Recent work in our laboratory has demonstrated that the skin can be used as a high resolution substitute sensory channel to mediate transmission of information from an artificial receptor to the brain. After several hours of training, blind persons can learn to locate subjectively the sensation as if it were originating from the stimulus object rather than from the skin. We have developed a visual substitution system utilizing a television camera and a commutator to transfer the TV signal to a 20×20 array of vibrotactile stimulators placed against the skin of the back. Even the congenitally blind subjects learn to interpret the tactile display as a "visual" image, and can identify complex arrangements of objects, people, words, etc. Complex visual phenomena such as depth perception, the two dimensional representation of three dimensions, and size constancy can be used by the blind subjects. A project is under way to apply these tactile sensory substitution principles to the development of sensation substitution (touch, position, and pressure sense) in limb prostheses.

Introduction

Several years ago we initiated a project to explore the possibility of using the cutaneous sensory system to carry optical information from an artificial receptor to the brain. It was conceivable that, after a training period, sensory plasticity might 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 [3].

Recent studies in our laboratory have demonstrated that the skin can indeed be used as substitute sensory channel to mediate transmission of information from an artificial receptor to the brain. We have developed a tactile vision substitution system (TVSS) which, even in its present primitive state, has enabled blind subjects to perceive "visual" details of their environment. Practically, the

---

This investigation was supported by Health, Education and Welfare, Social and Rehabilitation Service Grant No. RD-2444-S; United States Public Health Service Research Career Award No. 5 K3-14-094.

system utilizes a television camera, a commutator, and an array of 400 vibrotactile stimulators in contact with the skin of the back [3, 4, 5, 6, 8, 9, 12, 22, 23].

Blind individuals and amputees suffer a sensory deprivation which we believe can be substituted for, at least in part, by the use of artificial receptors. Such receptors, in practice represented by a television camera in the case of visual defects, and in theory represented by transducers attached to the prosthesis itself in the case of limb loss, would transmit information to the skin, whence it would be relayed along neurons to the brain. Thus artificial "sensory" inputs could substitute for natural stimuli.

We have already demonstrated the feasibility of using skin receptors to substitute for visual stimuli. The primary purpose of the present paper is to propose that it may be equally possible to supply the amputee with a sensory substitution system of significant value in helping him overcome his defect.

Basic concepts underlying the development of the TVSS, as well as the actual results obtained by blind subjects with this apparatus, would seem at least in theory to be applicable for use in limb prostheses. Therefore it appears appropriate here to summarize our results to date with the TVSS, and to discuss the neurophysiological concepts upon which this type of sensory substitution system is based. Upon that foundation, the theoretical application of such a sensory substitution system for use in limb prostheses will be discussed.

Methods

The TVSS in operation at present includes 400 solenoid stimulators arranged in a 20×20 array built into the back of a dental chair. The stimulators, spaced 12 mm apart, have 1 mm diameter Teflon tips which vibrate against the skin of the back. Their on-off activity is triggered by the patterns of light viewed by a television camera, and can be monitored visually on an oscilloscope as a two-dimensional pictorial display. In most of our experiments to date the subject has manipulated the TV camera mounted on a tripod (Fig. 1).

More than thirty blind subjects have been trained to use the TVSS. Of these, eight (six congenitally blind) have received 40 or more hours (40—200) of training.

After being introduced to the mechanics of operating the apparatus, subjects are trained to discriminate vertical, horizontal, diagonal and curved lines. They then learn to recognize combinations of lines (circles, squares and triangles) and solid geometric forms. After approximately one hour of such training, they are introduced to a "vocabulary" of twenty-five common objects: a telephone, chair, cup, toy horse and others. With repeated presentations, the latency or time-to-recognition of these objects falls markedly; in the process, the students discover visual concepts such as perspective, shadows, shape distortion as a function of viewpoint, and apparent change in size as a function of distance. When more than one object is presented at a time, the subjects learn to discriminate overlapping objects, and to describe the positional relationship of three and four objects in one field. The visual analysis technique and concepts thus developed are then used in letter recognition, in the perception of moving stimuli and in the exploration of other persons standing before the camera. Our subjects learn to discriminate between individuals, to decide where they are in the room, to describe their posture, movements, and individual characteristics such as height, hair length, presence or absence of glasses and so on.

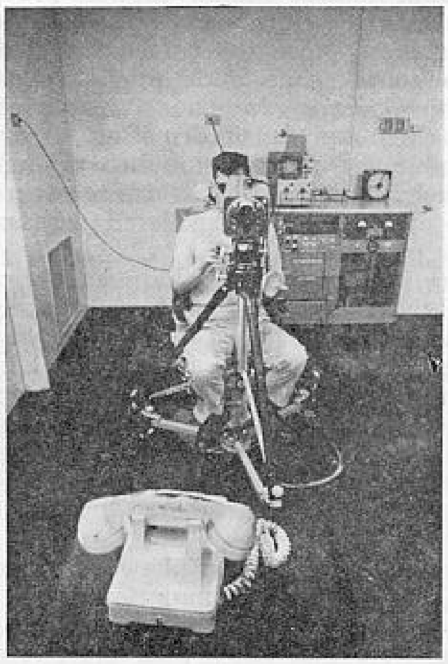

Fig. 1. Photograph of the tactile television system.

The subject directs the TV camera to an object of regard which is converted to a pulse-sampled video image by the commutation in the rear of the picture. The commutator, in turn, electronically switches each of the vibrating stimulators in the tactile array to present a 20-line (400-point) mechanical image on the skin of the subject's back.

Our subjects spontaneously report the external localization of stimuli, in that sensory information seems to come from in front of the camera, rather than from the vibrotactors on their back.

Thus, after sufficient experience, the vision substitution system seems to become an extension of their sensory apparatus. Specific tests and quantified results have been reported previously [5, 6, 22, 23] and will not be repeated here.

We have recently completed a prototype of a new model of the TVSS which utilizes a movable hand-directed camera. The entire apparatus is mounted on a wheelchair. This model consists of a 400-point stimulator matrix similar to that previously described. The lightweight camera is suspended from a beam over the chair. The subject is able to move the camera freely in all directions, including the horizontal plane. Such lateral movement permits the subject to obtain images of the same target from varying angles. Motion parallax then provides information on depth and identity not readily available with a tripod-mounted camera. With a system mounted on wheels, it is possible to explore extralaboratory environments. Such evaluation is considered necessary prior to the construction of a portable unit.

The primary improvement of the newest system is the direct manipulation of the camera. In most cases, experienced subjects have required two to three hours of practice with this system in order to become efficient with the free-moving camera. When optimal camera manipulation has been learned, subjects have reported that detailed inspection of familiar objects is enhanced with the new system. The subject is able to move the camera rapidly back and forth across troublesome or confusing areas of a target with this system, rather than slowly reversing the direction by cranking, as in the earlier model.

Recently we have also been exploring the possibility of using electrical rather than vibratory stimulation of the skin. This would allow construction of a much lighter and simpler system. We have determined parameters that allow pain-free electrical stimulation, and are proceeding with the development of a stimulus array to be strapped on the trunk like a vest [9].

Neurophysiological Considerations

Our studies indicate that cutaneous receptors and pathways are capable of carrying pictorial information to the brain. Such information is displayed on the skin of the back by means of an array of vibrotactile stimulators activated by a television camera. Further, inasmuch as blind subjects interpret such patterned stimuli as "visual" (external localization of a pictorial display), rather than "cutaneous", it would appear that the central nervous system is capable either of utilizing existing mechanism or of developing new mechanisms to process this information. This processing includes the ability to use such complex visual concepts as depth perception and size constancy.

Sensory information reaches the brain in the form of nerve impulses [20], at which point the brain must interpret the nerve impulses as a specific image. Behavioral and neurophysiological experiments suggest that the sensory pathways are plastic rather than fixed in the transmission of impulses generated by a particular stimulus [17]. Even a cortical area as highly specialized as the visual cortex receives afferent impulses from sensory receptors other than the visual receptors [18]. And in addition to specific pathways, afferent impulses from many sources converge on cells of the reticular formation [2]. The role of this input on subjective sensory experience has yet to be fully understood. However, the brainstem evidently plays an important role in the governing of neuronal plasticity [17]. The extensive multisensory invasion of many cortical and subcortical regions produces neuronal fields of intercommunication which should be ideal places for new associative links [13].

Experimental evidence suggests that there is no central sensory representation of the periphery on a point-to-point basis. Rather it would appear that 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 which are even superior to those of other channels [15] since it combines temporal and spatial qualities, and it is rarely "busy." Bliss [7] 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 dimensions of sensation are used. Howell [16] noted that the reaction time for touch is shorter than for vision and probably also shorter than for audition. He suggested that the skin may possess a potential superiority over other receptor channels with respect to information processing.

In the present studies, we have utilized the receptors of the skin of the back despite the insensitivity of this cutaneous area relative to other areas of the body. This site was most amenable to the contingencies of instrumentation design [8], and suited our wish to utilize a receptor surface least likely to interfere with other tasks. The highly sensitive skin of the hand was eliminated as a possible receptor surface on the basis of these guidelines.

The cutaneous receptors, activated by the 20×20 array of vibrotactile stimulators, produce a pattern of neuronal impulses which is carried to the brain via the afferent nerves from one or both of the receptor types present: hair follicle receptors and free nerve endings. The morphology and distribution of these cutaneous receptors has been discussed by Sinclair [21]. If the concept of receptor specificity were interpreted strictly, it would be expected that stimulation from the tactors would produce cutaneous sensations such as touch. However, after several hours of training, the sensation produced during a perceptual task is not cutaneous; the cutaneous receptors are mediating tele-receptor pattern information and in that sense the sensation is comparable to a visual sensation. The blind subject, using the TVSS to explore such objects as a telephone or a toy animal, perceives what a sighted subject sees when looking at the same objects on the oscilloscope monitor. This perception includes depth information, obtained by "monocular" cues such as linear perspective, motion parallax, occlusion, and elevation in the visual field, when exploring spatially distributed arrangements of objects. Thus pictorial information from the TV camera (functioning as an artificial retinal receptor surface) reaches the tactile receptors, which relay this information along neural pathways to the brain.

The evidence that vision substitution can be provided by cutaneous stimulation raises questions of theoretical interest to neurophysiologists. For instance, what mechanisms allow information arriving by cutaneous channels to be subjectively interpreted "visual"? How are visual concepts, such as the two-dimensional representation of three dimensions, size-constancy, and linear perspective, mediated by central nervous system regions normally used for surface-contact information? Which central nervous system areas participate in information processing?

Some insight into these questions may be found in the theory of phase interference. Thus, if sensory information is holographically distributed throughout much of the brain, as has been discussed by various authors (including Pribram [19]), incoming sensory information should interact with other afferent inputs arriving via the same or other modalities. In this way, both percepts and motor responses to them can be the products of instantaneous afferent input modulated by memory and previous experience. These could integrate newly arriving information and produce centrifugal impulses which modify afferent information arriving at the receptor and at the relay nuclei. It would also be of great interest to know if centrifugal afferent receptor mechanism can be developed for efficient handling of the information arriving at the cutaneous receptors as "visual" information.

Pribram [19] has discussed the influences exerted by areas of the association cortex on the content of the sensory information that reaches the brain. He suggests that somewhere between the receptor and the cortex the inflowing signals are modified to provide information already linked to a learned response. Desmedt [10] has demonstrated that central structures can modify incoming information at the receptor level. We have considered these factors, as well as the descending influences involved with motor performance related to perception, in developing methods of training blind subjects to use the TVSS. There is a great difference in the speed of learning when the movement of objects is by a passive videotape presentation as compared to the subject's control of camera movement and zoom and aperture settings. However, in the latter conditions, not only are the descending regulatory influences related to experience and to motor movements involved, but valuable proprioceptive information is also gained by controlling all camera movement.

Alternatively, if the primary sensory cortex is the principal receiving area for "visual" information carried by the cutaneous sensory system, is the portion of the sensory homunculus representing the skin of the back sufficiently extensive to mediate complex "visual" tasks, or will the representation of this region on the sensory homunculus be modified? Desmedt, Debecker and Manil [11] have shown that the late components of the cortical evoked potential recorded over the somesthetic sensory cortex change when the subject concentrates on a tactile stimulus. It is possible that changes will occur in the somesthetic cortex of a blind subject undergoing training with the TVSS as the pattern stimulus becomes more meaningful.

A final point to consider is the mode in which information is presented to the receptor. Is it necessary, or even desirable, to encode the output from an artificial receptor in order to reduce the amount of data delivered to the skin? The view of White et al [23] is pertinent to this point:

"In the past many efforts at providing information to the blind have been based upon somewhat old-fashioned ideas about the way the perceptual systems work. In early psychology, there was a distinction between sensation and perception. The former had to do with stimulation of end organs, which sent their messages to the brain where they were synthesized and correlated through long experience until a percept emerged. Many efforts at creating sensory aids are still restricted by this evaluation, and 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 which 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 skin will be able to see all the things the eye can behold. However, we might never have been able to say it was possible to determine the identity and three-dimensional layout 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. 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."

Tactile Display Systems for "Sensory" Information from Limb Prostheses

Thus far we have been discussing tactile sensory substitution for loss of vision. We would like now to consider tactile sensory substitution as an aid to limb prosthesis control.

With most upper-extremity prostheses, the position of the shoulders provides some kinesthetic feedback, but the eyes must provide most of the information on forearm position. Thus an amputee rarely uses his prosthesis outside his field of view. Normally he cannot carry on a conversation while he uses the prosthesis to eat, since controlling the prosthesis requires his full attention. Indeed, Alles [1] has pointed out that if the amputee who wears a prosthesis with multiple degrees of freedom "is to feel that it is an extension of his body and not that he is just the operator of a remote manipulator, he must receive kinesthetic information through a sensory channel in addition to his eyes. Otherwise he will operate it like a steam shovel, one joint at a time" [1].

Kinesthetic feedback systems for amputees have been designed by several groups of investigators. Among these Alles [1] (who has reviewed the previous literature), has designed a feedback system for an artificial elbow joint utilizing two stimulators located approximately four inches apart on the upper arm. His system is based on the von Békésy phantom sensation principle: the relative amplitude of stimulation at each stimulator is altered as the amputee flexes his elbow, and the sensation travels up his arm between the two stimulators.

We feel that there are a number of possible formats for a tactile display system which could substitute for the kinesthetic feedback of angle and position of an artificial elbow joint. One of these is illustrated in Figure 2, which shows a direct pictorial display of two isometric views of the forearm prosthesis. Such a display might be generated by the use of a small computer which receives its input from goniometers mounted at each joint, and which controls a pictographic display on an array of tactile stimulators. An alternative input for such a display corresponding to visual position feedback might be more simply derived from small shoulder-mounted television cameras with wide-angle lenses, constantly monitoring the position and relative angulations of the different joints of the arm prosthesis.

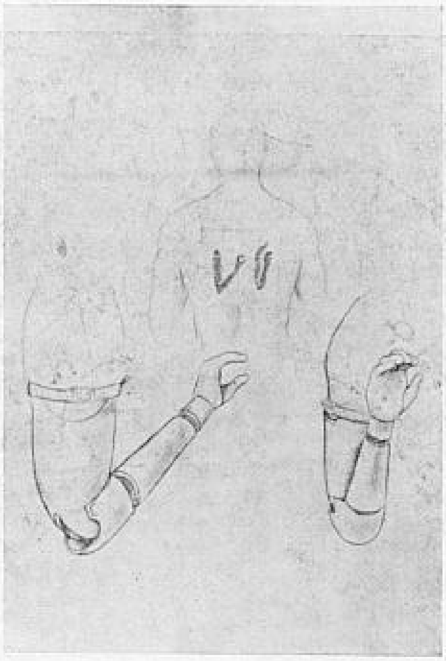

Fig. 2. Pictographic display of limb prosthesis position in two isometric views applied to the skin by means of a tactile stimulator matrix identical with that of the existing vision substitution system.

Such a display may be generated by a small computer taking its input from goniometric transducers at each prosthesis joint and would represent the direct analog of visual position feedback for prosthesis control.

Again, a more economical format might be engineered to the specific needs of the amputee. One such possible tactile display is illustrated in Figure 3. Here the angles alpha, beta, gamma, and delta, respectively, represent elbow angle, axial wrist rotation, wrist angulation, and centimeters of "finger" clamp opening. Each of these angles might be simply converted to the position of a tactile stimulus on the arm stump by means of the inputs from an appropriate set of goniometers. The latter could take the form of direct digital angle converters, i.e., segmented switches, each switch controlling a separate tactile stimulator. For example, in Figure, the elbow angle, alpha, is indicated to the amputee by a vertical array of tactile stimulators running up most of the length of the stump. One of these stimulators would be activated at a time. Thus activation of the lowest stimulator would indicate a full extension of the elbow, while progressively higher activation would signal increasing degrees of flexure of the prosthetic elbow.

The three remaining angles of the prosthesis might each be represented by a band of tactile stimulators running circumferentially around the stump. Thus the top band could indicate axial wrist rotation by means of actuating the appropriate tactile stimulator located at an angle around the stump corresponding to the degree of rotation of the wrist. Similarly, wrist angulation (flexure) might be displayed on a band of tactile stimulators located circumferentially about the middle of the stump. In the same way, "finger" clamp spacing could be indicated by a C-shaped band of tactile stimulators around the lower part of the stump. Activation of the two outer stimulators would signal the greatest clamp opening. The spacing between the activated stimulators would decrease progres-

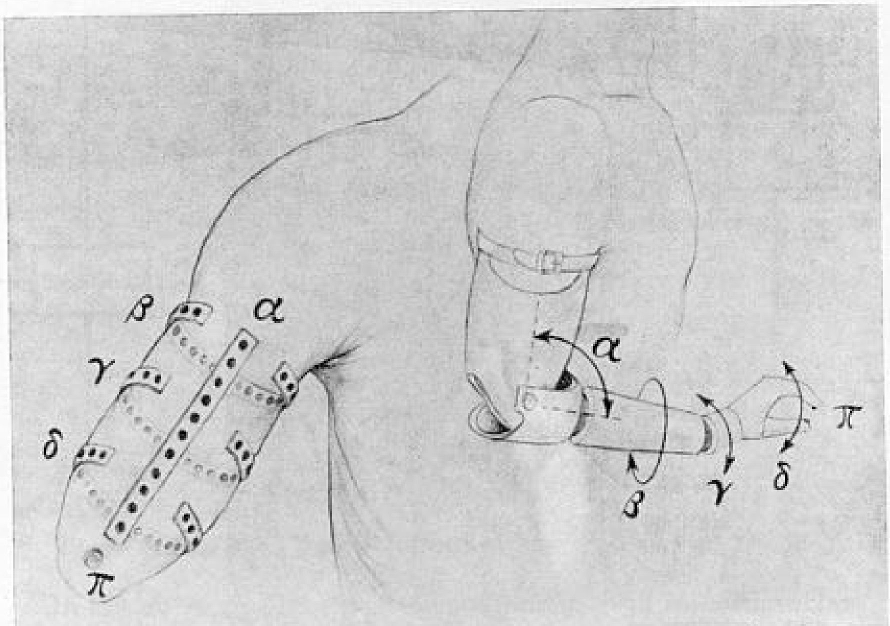

Fig. 3. A simple and economical tactile display method serving as a substitute for kinesthetic feedback of relative forearm angles.

Segmented switches on each prosthesis' rotary axis serve as direct digital angle converters to actuate point-for-point the corresponding tactile stimulator in contact with the upper arm. Pressure acting on "finger" clamp force transducers may be relayed by means of tactile stimulators having their frequency modulated upward with increasing pressure.

sively as the " finger" clamp spacing was reduced, until complete closure of the "finger" clamp would activate only the two adjacent tactile stimulators in the center of the band.

In addition to positions and angles, the pressure under the "finger" clamp might be measured and relayed to a frequency modulated tactile stimulator on the upper arm stump. For example, a ceramic or spring-force transducer could directly control the frequency of the tactile stimulus and might thus allow sensitive control of pressure exerted by the prosthetic "finger" clamp.

This proposed tactile kinesthetic substitution system (TKSS) is designed to provide information on five different modalities of joint position and pressure. Such a wealth of data from a prosthesis, applied to the skin of the upper-arm stump, must then be conducted by neural pathways to the brain for processing. In this regard we must consider a major difference in the central nervous system processing of visual information and of proprioceptive or kinesthetic information. The visual input provides our major source of sensory information as to our external environment, and much of it interpreted cortically at a conscious level. In contrast, kinesthetic input is important in regulating our motor response to the external environment, but it does not significantly enter consciousness. The ultimate aim of the amputee, using a TKSS, would be to have the information processed automatically and subconsciously. Only in this way would he be able to manipulate his prosthesis to achieve a goal, such as picking up an object, without consciously thinking of degrees of flexion, etc. at each joint. One example may suffice to indicate why we fell that the amputee may achieve this ultimate goal. When one is learning to use a typewriter by the touch system, one must concentrate on the relative position of each letter on the keyboard, and on the relative positions of all the fingers. Yet once the learning process is complete, full attention can be given to the meaning of the words being typed; the fingers do the actual typing without conscious direction.

In conclusion, our results with the tactile vision substitution system suggest that it may be possible to deliver highly detailed "sensory" information from a prosthesis to the brain, using the skin and its neural pathways and structures as the relay system. Our blind subjects using the TVSS have learned to externalize the sensations, responding to them as if they carried visual information rather than cutaneous. In the same way an amputee, using a prosthesis that included a high resolution tactile display delivered to a suitable area of skin (upper arm, torso) should learn to respond to the stimulation as if it originated in the appropriate part of the prosthesis. Thus the ultimate result could be that the prosthesis would become functionally a part of his body.

REFERENCES

1 Alles, D. S., "Kinesthetic Feedback System for Amputees via the Tactile Sense", Ph. D. thesis, Massachusetts Institute of Technology, 1968.

2. Bach-y-Rita, P., "Convergent and Long Latency Unit Responses in the Reticular Formation of the Cat", *Exp. Neurol.*, *9*: 327—344, 1964.

3. Bach-y-Rita, P., "Sensory Plasticity: Applications to a Vision Substitution System", *Acta Neurol. Scand.*, *43:* 417—426, 1967.

4. Bach-y-Rita, P., "Neurophysiological Basis of a Tactile Vision Substitution System", *Proc. Tactile Display Conf.*, 1969 (in press).

5. Bach-y-Rita, P., Collins, C. C., Saunders, F., White, B., and Scadden, L., "Vision Substitution by Tactile Image Projection", *Nature, 221:* 963—964, 1969.

6. Bach-y-Rita, P., Collins, C. C., White, B., Saunders, F., Scadden, L., and Blomberg, R., "A Tactile Vision Substitution System", *Amer, J. Optom.*, *46:* 109—111, 1969.

7. Bliss, J., "Kinesthetic-Tactile Communications", *I.R.E. Trans.*, *I-T8* 92—99, 1962

8. Collins, C. C., "Tactile Television: Mechanical and Electrical Image Projection", *Proc. Tactile Display Conf.*, 1969 (in press).

9. Collins, C.C. and Saunders, F., "Tactile Television: Electrocutaneous Perception of Pictorial Timages", *Proc. Neuroelectric Conf.*, 1969 (in press).

10. Desmedt, J. E., *Neurophysiological Mechanisms Controlling Acoustic Input in Neural Mechanisms of the Auditory and Vestibular Systems*, G. L. Rasmussen and W. F. Windle, eds, Charles C Thomas, Springfield, Ill., 1960.

11. Desmedt, J. E., Debecker, J., and Manil, J. Mise, "En évidence d'un signe électrique cérébral associé a'la détection par le sujet, d'un stimulus sensoriel tactile", *Bulletin de l'Academie Royale de Medecine de Belgique, 5:* 887—936, 1965.

12. Eskildsen, P., Morris, A., Collins, C. C., and Bach-y-Rita, P., "Simultaneous and Successive Cutaneous Two-Point Thresholds for Vibration", *Psychon. Sci., 14(4):* 146—147, 1969.

13. Fessard, A., *Sensory Communication*. W. H. Rosenblith, ed., John Wiley and Sons, New York, pp. 585-606, 1961.

14. Galambos, R., Norton, T. T., Frommer, G. P., "Optic Tract Lesions Sparing Pattern Vision in Cats", *Exp. Neurol., 18:* 8—25, 1967.

15. Gilmer, B. v. H., "Problems in Cutaneous Communication from Psychophysics to Information Processing", *Amer. Foundation for the Blind*, New York, 1966.

16. Howell, W. C., "On the Potential of Tactual Displays: An Interpretation of Recent Findings", *Symposium on Cutaneous Sensitivity*, G. Hawkes, ed., U. S. Army Med. Res. Lab. Rep. No. 424, Washington, D. C., pp. 103-113 1960.

17. Livingston, R. B., "Central Control of Receptors and Sensory Transmission Systems", *Handbook of Physiology*, J. Field, ed., Amer. Physiol. Soc., Washington, D. C., *1*:741—760, 1959.

18. Murata, K., Cramer, H., and Bach-y-Rita, P., "Neuronal Convergence of Noxious Acoustic and Visual Stimuli in the Visual Cortex of the Cat", *J. Neurophysiol., 28:* 1223—1240, 1965.

19. Pribram, K. H., "The Neurophysiology of Remembering", *Scientific American, 220*:73—86 ,1969.

20. Rushton, W. A. H., "Peripheral Coding in the Nervous System", *Sensory Communication.* W. A. Rosenblith, ed., John Wiley and Sons, New York, pp. 169—181, 1961.

21. Sinclair, D., *Cutaneous Sensation.* Oxford Univeresity Press, London, 1967.

22. Scadden, L., "A Tactual Substitute for Sight", *New Scientist, 41*:677—678, 1969.

23. White, B. W., Saunders, F. A., Scadden, L., Bach-y-Rita, P., and Collins, C. C., "Seeing with the Skin", *Perception and Psychophysics* (in press).