Tactile Sensory Substitution Studies

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ABSTRACT: Forty years ago a project to explore late brain plasticity was initiated that was to lead into a broad area of sensory substitution studies. The questions at that time were: Can a person who has never seen learn to see as an adult? Is the brain sufficiently plastic to develop an entirely new sensory system? The short answer to both questions is *yes*, first clearly demonstrated in 1969 (Bach-y-Rita *et al.*, 1969). To reach that conclusion, it was first necessary to find a way to get visual information to the brain. That took many years and is still the most challenging aspect of the research and the development of practical sensory substitution and augmentation systems. The sensor array is not a problem: a TV camera for blind persons; an accelerometer for persons with vestibular loss; a microphone for deaf persons. These are common and fully developed devices. The problem is the brain–machine interface (BMI). In this short report, only two substitution systems are discussed, vision and vestibular substitution.

KEYWORDS: brain–machine interface; brain plasticity; vision substitution; blindness

TONGUE BRAIN–MACHINE INTERFACE

We have explored a wide range of interfaces, including vibrotactile devices interfacing to such anatomical regions as the back, the abdomen, the fingers, and the forehead (Bach-y-Rita, 1972, 1995; Kaczmarek and Bach-y-Rita, 1995). Electrotactile interface areas included many of the same regions. All had their advantages and disadvantages. A few years ago we initiated the development of what has turned to be an ideal interface: an electrotactile interface on the tongue.

The tongue is an ideal organ for sensory perception. The results obtained with a small electrotactile array developed for a study of form perception with a fingertip demonstrated that perception with electrical stimulation of the

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tongue is significantly better than with fingertip electrotactile stimulation, and the tongue requires only about 3% (5–15 V) of the voltage, and much less current (0.4–2.0 mA), than the fingertip. The electrode array for the initial tongue studies consisted of a 7 × 7 array of 0.89-mm diameter, flat-topped stainless-steel electrode "pins," each surrounded by a 2.36-mm diameter air gap insulator. A flat stainless-steel plate coplanar with the electrode pins served as the return current path. The electrodes were arranged on a square grid with 2.54-mm interelectrode spacing. The electronic system has been described elsewhere. The present array is a thin, flexible 12 × 12 (144 point) matrix of stimulators on 2.34-mm centers with no ground plane (Bach-y-Rita Kaczmarek, and Meier, 1998; Bach-y-Rita, Kaczmarek, Tyler, and Garcia-Lara, 1998).

These results (and similar research in progress) demonstrate that the tongue is capable of mediating complex spatial patterns and is therefore an ideal site for somatosensory system excitation. The availability of practical BMIs allows the development of sensory substitution systems that have the potential to dramatically improve the quality of life for large numbers of people worldwide. These devices will also allow these persons to contribute to society in ways that are not currently possible.

LATE BRAIN PLASTICITY

Our tactile sensory substitution studies are based on brain plasticity. Although they originated as experiments to test the capacity of the brain to reorganize following the introduction of a previously nonexistent sensory system, the early results also suggested the possibility of practical applications for persons with sensory loss, which will be discussed below.

For the brain to correctly interpret information from devices, it is not necessary that it be presented in the same form as in natural sensory information systems. We do not *see* with the eyes; the visual image does not go beyond the retina, where it is turned into patterns of pulses along nerves. It is the brain that recreates the image from the patterns of pulses. It is only necessary to present the information from a device in a form of energy that can be mediated by the receptors at the brain–machine interface, and for the brain, through a motor system, to know the origin of the information.

Changes in brain activity are associated with sensory loss and the adaptation to that loss; they have been considered to represent brain reorganization. Sensory substitution studies with persons with sensory loss have provided information on brain plasticity.

The capacity to not only utilize the new information, but also to develop visual strategies and distal attribution has permitted a series of experiments with both theoretical and practical implications. The work has been extended from visual substitution to several other sensory losses and to augmentation systems for sensorily intact persons.

Brain plasticity mechanisms underlying sensory substitution have been extensively discussed elsewhere (e.g., Bach-y-Rita, 1972; 1995) and will not be further detailed here.

SENSORY LOSS

Changes in brain activity are associated with sensory loss and the adaptation to that loss; they have been considered to represent brain reorganization. Sensory substitution studies with persons with sensory loss have provided information on brain plasticity.

Most of our early sensory substitution studies were carried out with a 400-point vibrotactile array against the skin of the back. This severely challenged the then-current thought. The world's expert in tactile perception at that time was Princeton's Professor Frank Geldard. His studies had shown that it was not possible to have more than 13 simultaneous stimulus points, spread throughout the body. Most studies were based on the 2-point tactile discrimination threshold, which is worst on the skin of the back (2.5 cm), and thus should preclude its use. We developed a vibrotactile matrix of 400 points on the back, spaced approximately 1 cm apart, and had excellent perceptual results. I considered that although the 2-point threshold is an important measure of acuity, what is really important is pattern perception capability; vernier acuity is approximately 10 times better than the visual 2-point threshold, and for the skin the figure is comparable. We invited Geldard to visit the lab, observe our subjects, and try it himself, which he did, and expressed enthusiasm, but he subsequently reiterated his previous position.

Devices can be developed for many sensory losses, and each type of loss will have to be approached comprehensively. In addition to sensory substitution, a whole world of opportunities is opening for sensory augmentation, such as for night vision, sensate robots, sensate Internet and telecommunications, and many others.

Vision Substitution

We developed tactile vision substitution systems (TVSS) to deliver visual information from a TV camera to arrays of stimulators in contact with the skin of one of several parts of the body, including the abdomen, back, thigh, forehead, and fingertip (Bach-y-Rita, 1972; 1989; 1995; Bach-y-Rita *et al.*, 1969; Collins and Bach-y Rita, 1973; White *et al.*, 1970). Mediated by the skin receptors, energy transduced from any of a variety of artificial sensors (e.g., camera, pressure sensor, displacement) is encoded as neural pulse trains. In this manner, the brain is able to perceive environmental information such as "visual" images that originate in a TV camera. Indeed, after sufficient training with the TVSS, our blind subjects reported experiencing the images in space, instead of on the skin. They learned to make perceptual judgments using visual means of analysis, such as perspective, parallax, looming and zooming, and depth judgments. Although the TVSS systems have only had between 100- and 1032-point arrays, the low resolution has been sufficient to perform complex perception and "eye"-hand coordination tasks. These have included facial recognition, accurate judgment of speed, and direction of a rolling ball with more than 95% accuracy in batting the ball as it rolls over a table edge, and complex inspection-assembly tasks.

Camera movement must be under the control of one of the subject's motor systems (hand, head movement, or any other). Indeed, we have shown that this is possible once the blind person has learned the mechanics. This includes camera control: zooming, aperture, and focus, and the correct interpretation of the effects of camera movement, such as occurs when the camera is moved from left to right and the image seems to move from right to left. Once a blind person has learned with one motor system (e.g., hand-held camera, thus using the corresponding kinesthetic system), the camera can be switched to another system (e.g., mounted on the head) with no loss of perceptual capacity. And when the human–machine interface, the electro- or vibrotactile array, is moved from one area of skin to another (e.g., from the back to the abdomen or to the forehead), there is no loss of correct spatial localization, even when the array is switched from back to front, since the trained blind subject is not perceiving the image on the skin, but is locating it correctly in space.

Many phenomena associated with vision have to be learned; for example, when viewing a person seated behind a desk, the partial image of the person must be correctly interpreted as a complete person with the image of the desk interposed, rather than perceiving just half a person. The subjective experience is comparable (if not qualitatively identical to) vision, including subjective spatial localization in the three-dimensional world. Even the visual illusions that have been tested (e.g., waterfall effect) are the same as vision.

In a very recent trial, within an hour of being introduced to the TVSS, a blind person was able to discern a ball rolling on the floor to him; he was able to reach for a soft drink on a table; and he was able to play the old game of paper, scissors, rock. Later, he walked down a hallway, saw the door openings, examined a door and its frame, actually noting that there was a sign on the door. Three examples from our earlier studies follow:

Batting a Ball

The perceptual task in catching an object is to pick up information about two components, the object to be caught and the catching body part or tool.

Both may be moving and the catching person needs not only information about their continuously changing positions, but also about the direction of their motions in order to be able to make proper preparations for their encounter. The time available for this activity is often very short. Can tactile information obtained from a matrix of point stimuli replace visually obtained information in this situation?

An experiment with a stationary version of the TVSS displaying the tactile matrix on the subject's back (Jansson and Brabyn, 1981) indicated that touch can replace vision to some extent in such a situation. The blind subject was seated in a chair with everything in the field of view of the camera painted black, except for the white ball and bat. The subject leaned his back against the tactile matrix (20 × 20 vibrators). In his hand he had a response bar with which he had to bat a ball rolling towards him. The only perceptual information about its motion was provided via the tactile matrix on his back, which also contained information about the position of the response bat. The total time of approach was about 3.5 sec. The ball rolled off the table, but the subject did not know the position on the table edge that would be reached by the ball, since the trough could be moved from one side to another in front of the blind subject. Thus, the subject had to identify the rolling ball, calculate the time it would take to reach the edge of the table, calculate the position on the table (to his left or right or middle), identify the location in his "visual" field of the bat, and correctly time his movement of the bat in order to bat the ball.

The experimental result with two well-trained blind subjects was that the mean of the performance was rather close to perfect. It is thus possible to pick up information from a tactile display of the type used here and prepare and perform the appropriate movements within a few seconds (Jansson, 1983).

Industrial Trial on the Hewlett Packard Assembly Line: Electronic Assembly and Inspection

A vocational test more than 25 years ago of an earlier version of the BMI, with the array consisting of vibrotactors on the abdomen, revealed its potential application to jobs presently reserved for sighted workers. A person totally blind since 2 months of age spent three months on the miniature diode assembly line of the electronics manufacturer Hewlett Packard. During the assembly process, he received a frame containing 100 small glass cylinders with attached wires, as the frame emerged from an automatic filling machine that filled each cylinder with a small piece of solder. The automatic process was 95% efficient, and so approximately 5% of the cylinders remained unfilled. His first task after receiving each frame was to inspect each of the cylinders and to fill by hand those that remained unfilled. This was accomplished with a small TV camera mounted in a dissecting microscope, under which the blind worker passed the frame containing the cylinders. The information from the cylinders was passed through an electronic commutator, in order to transform it into a tactile image, and was delivered to the skin of the abdomen of the worker by means of 100 (10 × 10) small vibrating rods in an array clipped to the workbench.

In order to receive the image, the blind worker had only to lean his abdomen against the array (without removing his shirt). He did not wear any special apparatus and his hands were left free to perform the inspection and assembly tasks under the microscope. He filled the empty cylinders by means of a modified injection needle attached to a vacuum; he placed the needle in a dish filled with small pieces of solder. The needle picked up only one piece, since the suction was then blocked. He then brought the needle with the solder into the "visual" field under the microscope, and by hand–"eye" coordination placed the needle in an empty cylinder, at which point he released the suction, and the solder dropped in. He repeated the process for each empty cylinder encountered, and then passed the frame to another loading machine where it was automatically filled with diode wafers. Again, the task was then to fill the approximately 5% cylinders that did not have a diode wafer, which he did as above, except that this stage offered two extra problems: the wafers were very thin and flat and did not always fall flat into the cylinders. Sometimes they landed on edge. Furthermore, the wafers were gold on one side and silver on the other, and they had to be correctly oriented. He had the additional task of turning over 50% of the wafers. This task was accomplished by identifying the color on the basis of light reflectance, since the silver side reflected more light.

The blind worker was able to perform the tasks, but was much slower than the line workers and became more fatigued than they did. Thus, he would not have been a competitive worker on that line. However, it did demonstrate the feasibility of developing jobs in an industrial setting in the future (for illustrations, see Bach-y-Rita, 1995).

Education of Blind Children

We have demonstrated that it is possible to develop an understanding, in congenitally blind students, of the visual world including visual means of analysis (Miletic, Hughes and Bach-y-Rita, 1988). Children learn to understand and use visual means of analysis such as monocular cues of depth, and interposition; for the latter, one example of the training is to view three candles lined up one behind the other. Only one is perceived because the view of the others is blocked; the child then moves his/her head to see the three candles appearing as they are viewed from the side. For an additional rewarding learning experience with the candles, one is lit, and the child views the flame and blows on it to produce waving of the flame, which is perceived with interest and excitement. Blind children were taught to perceive the body movements of the instructor and to imitate body position.

Vestibular Substitution

Persons who have bilateral vestibular damage, such as that occurring from an adverse reaction to antibiotic medications, experience functional difficulties that include postural "wobbling" (both sitting and standing), unstable gait, and oscillopsia that make it impossible, for example, to walk in the dark without risk of falling. We have developed a simple vestibular substitution system and demonstrated that head–body postural coordination can be restored using a head-mounted accelerometer and a brain–machine interface that employs a unique pattern of electrotactile stimulation on the tongue (Tyler, Danilov and Bach-y-Rita, submitted). The results provide evidence that the presence of meaningful substitutive input to the multisensory postural control process is sufficient to produce stability approaching that of unaffected individuals. Conversely, in the absence of valid data from vestibular, visual, and tactile sources, the system appears inherently noisy and unstable.

SENSORIMOTOR LINKS

Extensive experience with TVSS and many reported studies of the mechanisms of sensorimotor integration, reviewed by Mariño, Martinez, and Canedo (1999), demonstrate that somatosensory activity is linked to active exploration of the environment. It is required for the discrimination of texture and for the interpretation of complex spatiotemporal patterns of stimuli activating different classes of mechanoreceptors. The interplay between sensory and motor systems culminates in the subjective perception of shape, form, size, surface structure, and mechanical properties of objects as they are actively explored. The complex limb movements of primates have been shown to be under elaborate feedback from skin, deep muscular, and joint receptors ascending in the dorsal column system. Animals with well-developed explorative and manipulative skills have a greater number of dorsal root fibers innervating the forelimb than do less dexterous animals, and most of those fibers are cutaneous. Sensorimotor integration begins at the level of the second-order neurons of the somatosensory system, at the dorsal column nucleus. Several mechanisms, including efferent control by the cerebral cortex, enhance the activity of second-order neurons. The sensorimotor cortex can discriminate wanted from unwanted sensory information.

Sensorimotor integration is common to all the sensory systems, and has been important in the development of our sensory substitution systems. Our studies have revealed the capacity for interchangeability of the location of the interface on the body and of the motor control systems, with maintenance of perceptual characteristics.

CONCLUSIONS

In the absence of motor control over the orientation of the sensory input, a person may have no idea from where the information is coming, and thus no ability to locate it in space. Sensory substitution studies have demonstrated that the sensory part of a sensorimotor loop can be provided by artificial receptors leading to a brain–machine interface (BMI). We recently proposed that the motor component of the sensorimotor coupling can be replaced by a "virtual" movement. We have suggested that it is possible to progress to the point where predictable movement, not observed except for some sign of its initiation, could be imagined and by that means the mental image of movement could substitute for the motor component of the loop (Bach-y-Rita and Kercel, 2003). We further suggested that, due to the much faster information transmission of the skin than the eye, innovative information presentation, such as fast sequencing and time division multiplexing can be used to partially compensate for the relatively small number of tactile stimulus points in the BMI. With such a system, incorporating humans in the loop for industrial applications could result in increased efficiency and humanization of tasks that presently are highly stressful.

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