Seeing with the Brain

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1. INTRODUCTION

We see with the brain, not the eyes (Bach-y-Rita, 1972); images that pass through our pupils go no further than the retina. From there image information travels to the rest of the brain by means of coded pulse trains, and the brain, being highly plastic, can learn to interpret them in visual terms. Perceptual levels of the brain interpret the spatially encoded neural activity, modified and augmented by nonsynaptic and other brain plasticity mechanisms (Bach-y-Rita, 1972, 1995, 1999, in press). However, the cognitive value of that information is not merely a process of image analysis. Perception of the image relies on memory, learning, contextual interpretation (e.g., we perceive intent of the driver in the slight lateral movements of a car in front of us on the highway), cultural, and other social factors that are probably exclusively human characteristics that provide "qualia" (Bach-y-Rita, 1996b). This is the basis for our tactile vision substitution system (TVSS) studies that, starting in 1963, have demonstrated that visual information and the subjective qualities of seeing can be obtained tactually using sensory substitution systems.[1] The description of studies with this system have been taken

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[1]The term "sensory substitution" is typically defined as the use of one human sense to receive information normally received by another sense (Kaczmarek, 1995). However, in the context of mediated reality systems, which may incorporate multiple modalities of both sensing and display, the use of one sense (in this article, touch) to display information normally acquired via another human sense (e.g., visual information acquired by a video camera) or alternatively via a "non-natural" sense such as sonar ranging, could be considered to be a form of sensory augmentation (i.e., addition of informa-

from our previous reports. Various sensory substitution devices intended for rehabilitation have been extensively reviewed by Collins (1985), Kaczmarek and Bach-y-Rita (1995), and Szeto and Riso (1990), while Mann (1997, 1998) describes a clothing-based radar-to-vibrotactile system that uses novel signal processing techniques to tactually convey both reflected energy and velocity information for both artistic and rehabilitative purposes.

The TVSS may be characterized as a humanistic intelligence system. It represents a symbiosis between instrumentation—for example, an artificial sensor array (TV camera)—computational equipment, and the human user. Consistent with the terminology of this issue, this is made possible by "instrumental sensory plasticity," the capacity of the brain to reorganize when there is: (a) functional demand, (b) the sensor technology to fill that demand, and (c) the training and psychosocial factors that support the functional demand. To constitute such systems then, it is only necessary to present environmental information from an artificial sensor in a form of energy that can be mediated by the receptors at the human-machine interface, and for the brain, through a motor system (e.g., a head-mounted camera under the motor control of the neck muscles), to determine the origin of the information.

2. HUMAN-MACHINE INTERFACE: THE SKIN

A simple example of sensory substitution system is a blind person navigating with a long cane, who perceives a step, a curb, a foot, and a puddle of water, but during those perceptual tasks is unaware of any sensation in the hand (in which the biological sensors are located), or of moving the arm and hand holding the cane. Rather, he perceives elements in his environment as mental images derived from tactile information originating from the tip of the cane. This can now be extended into other domains with modern technology and the availability of artificial sensory receptors, such as (a) a miniature TV camera for blind persons, (b) a MEMS technology accellerometer for providing substitute vestibular information for persons with bilateral vestibular loss, (c) touch and shear-force sensors to provide information for spinal cord injured persons, (d) instrumented condom for replacing lost sex sensation, or (e) a sensate robotic hand (Bach-y-Rita, 1999).

In our first sensory substitution project, we developed tactile vision substitution systems (TVSS) to deliver visual information to the brain via arrays of stimulators in contact with the skin of one of several parts of the body (abdomen, back,

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tion to an existing sensory channel). This usage is supported by the existence of transmodal perception—the observation that multiple human senses (even artificial ones) can mediate similar perceptual constructs based on underlying information that is essentially amodal, or not specific to any given sensory system (Epstein, 1985). We therefore suggest that, at least in multimodality systems, new nomenclature may be needed to independently specify (a) the source of the information (type of environmental sensor, or virtual model); (b) the type of human information display (visual, auditory, tactual, etc.); and finally (c) the role of the information (substitutive or augmentative), all of which may play a role in reality mediation.

thigh). Optical images picked up by a TV camera were transduced into a form of energy (vibratory or direct electrical stimulation) that could be mediated by the skin receptors. In these sensory substitute systems, the visual information reaches the perceptual levels for analysis and interpretation via somatosensory pathways and structures. After sufficient training with the TVSS, our subjects reported experiencing the image in space, instead of on the skin (see, e.g., Figure 1). They learn to make perceptual judgments using visual means of analysis, such as perspective, parallax, looming and zooming, and depth judgments (Bach-y-Rita, Collins, Saunders, White, & Scadden, 1969; cf., Bach-y-Rita, 1972, 1989, 1995, 1996, 1999; Bach-y-Rita, Kaczmarek, & Meier, 1998; Bach-y-Rita, Kaczmarek, Tyler, & Garcia-Lara, 1998; Bach-y-Rita, Webster, Tompkins, & Crabb, 1987; Kaczmarek & Bach-y-Rita, 1995; White, Saunders, Scadden, Bach-y-Rita, & Collins, 1970).

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 over 95% accuracy in batting a ball as it rolls over a table edge, and complex inspection-assembly tasks. The latter were performed on an electronics company assembly line with a 100 point

FIGURE 1   Child reproducing perceived image of a teachers hand as displayed on a modified Optacon. The tactile image is picked up with one finger statically placed on the 6 × 24 vibrotactile array. LED monitor in foreground is visual representation of active pattern on the tactile display, which is obtained by the child's head-mounted camera.

vibrotactile array clipped to the work-bench against which the blind worker pressed the skin of his abdomen, and through which information from a TV camera (substituting for the ocular piece of a dissection microscope) was delivered to the human-machine interface (Bach-y-Rita, 1995, pp. 187–193).

3. TACTILE "COLORS"

In the TVSS studies cited above, the stimulus arrays presented only black-white information, without gray scale. However, the tongue electrotactile system does present gray-scaled pattern information, and multimodal and multidimensional stimulation is possible. Simultaneously, we have also modeled the electrotactile stimulation parameter space to determine how we might elicit tactile "colors." Aiello (1998a, 1998b) has identified six stimulus parameters: the current level, the pulse width, the interval between pulses, the number of pulses in a burst, the burst interval, and the frame rate. All six parameters in the waveforms can, in principle, be varied independently within certain ranges, and may elicit potentially distinct responses. For example, in a study of electrical stimulation of the skin of the abdomen, Aiello (1998a) suggested that the best way to encode intensity information independent of other percept qualities with a multidimensional stimulus waveform was through modulation of the energy delivered by the stimulus. In that case, the energy was varied in such a way that the displacement in the parameter space, corresponding to a given transition between energy levels, was minimal (gradient mode of stimulation). Although the gradient mode of stimulation requires a real-time fulfillment of mathematical constraints among all the parameters, its implementation could be included within a microelectronic package for signal treatment.

4. A TONGUE-BASED MACHINE INTERFACE

The skin systems we have used previously have allowed us to demonstrate the principle, but have had practical problems (Bach-y-Rita, Kaczmarek, Tyler, et al., 1998; Kaczmarek & Bach-y-Rita, 1995). The tongue interface overcomes many of these. The tongue is very sensitive and highly mobile. Since it is in the protected environment of the mouth, the sensory receptors are close to the surface. The presence of an electrolytic solution, saliva, assures good electrical contact. The results obtained with a small electrotactile array developed for a study of form perception with a finger tip demonstrated that perception with electrical stimulation of the tongue is somewhat better than with finger-tip electrotactile stimulation, and the tongue requires only about 3% of the voltage (5-15 V), and much less current (0.4-2.0 mA), than the finger-tip. The electronic system has been described elsewhere (Bach-y-Rita, Kaczmarek, Tyler, et al., 1998).

The development of a practical human-machine interface, via the tongue (Bach-y-Rita, Kaczmarek, & Meier, 1998; Bach-y-Rita, Kaczmarek, Tyler, et al.,

1998), presents the opportunity to progress from laboratory prototypes to useful devices. The interface should permit the development of sensory systems that are coupled with other technology. In principle, any input that can be transduced into a two-dimensional display on the tongue array can reach the brain, and with a training program, can become part of a new sensory system.[2]

4.1. Tongue Display Unit

We have developed and tested both current control and voltage control systems for use on the fingertip and tongue (Kaczmarek & Tyler, 2000). Our results indicated that for the tongue, the latter (voltage control) has somewhat preferable stimulation qualities and results in simpler circuitry, which will lead to miniaturization using MEMS technology. The present tongue display unit (TDU, see Figure 2) has output coupling capacitors in series with each electrode guarantee zero dc current to minimize potential skin irritation. The output resistance is approximately 1 kΩ. The design also employs switching circuitry to allow all electrodes that are not active or "on image" to serve as the electrical ground for the array, affording a return path for the stimulation current.

4.2. Tongue Display

Electrotactile stimuli are delivered to the dorsum of the tongue via flexible electrode arrays (Figure 3) placed in the mouth, with connection to the stimulator apparatus (TDU) via a flat cable passing out of the mouth. The tongue electrode array and cable are made of a thin (100 μm) strip of polyester material (Mylar®) onto which a rectangular matrix of gold-plated copper circular electrodes has been deposited by a photolithographic process similar to that used to make printed circuit boards. In the "virtual ground" configuration shown, the electrodes are separated by 2.34 mm (center to center). All exposed metallic surfaces are gold plated for biocompatibility. Our present model has a 12 × 12 matrix of electrodes, although other patterns are easily fabricated with changes in lithographic artwork. Our studies have shown that this configuration is much more rugged and reliable, and spatial resolution performance was comparable to that for the same geometry with a concentric ground plane (Kaczmarek & Tyler, 2000).

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[2]It should be noted that while the tongue display described in this article is strictly speaking a display or output device, there is nothing to prevent the incorporation of pressure sensors or electrical impedance monitoring to sense the position and force of the tongue against the array, thereby creating a bidirectional mouth-based interface. It should also be noted that the tongue display is not presently intended (but could be suitably modified) to specifically elicit taste sensations (Ajdukovic, 1984) as part of a remote tasting or "teletaste" system by displaying gustatory information acquired by remote chemical sensors (Savoy et al.,1998).

FIGURE 2   TDU-1 with 144-point tongue array & laptop PC.

4.3. Waveform Parameters

The electrotactile stimulus consists of 40-μs pulses delivered sequentially to each of the active electrodes in the pattern. Bursts of three pulses each are delivered at a rate of 50 Hz with a 200 Hz pulse rate within a burst. This structure was shown previously to yield strong, comfortable electrotactile percepts (Kaczmarek et al., 1992). Positive pulses are used because they yield lower thresholds and a superior stimulus quality on the fingertips (Kaczmarek et al., 1994) and on the tongue (Kaczmarek, unpublished pilot studies).

4.4. Perceived Pattern Intensity Compensation

In previous studies, we have determined that both the threshold of sensation and useful range of intensity, as a function of location on the tongue, are significantly inhomogeneous. Specifically, the front and medial portions of the tongue have a relatively low threshold of sensation, whereas the thresholds for the rear and lateral regions of the stimulation area are as much as 32% higher (Tyler & Braun, 2000). We believe that this is due primarily to the differences in tactile sensor density and distribution. Concomitantly, the useful range of sensitivity to electrotactile stimulation varies as a function of location, and in a pattern similar to that for
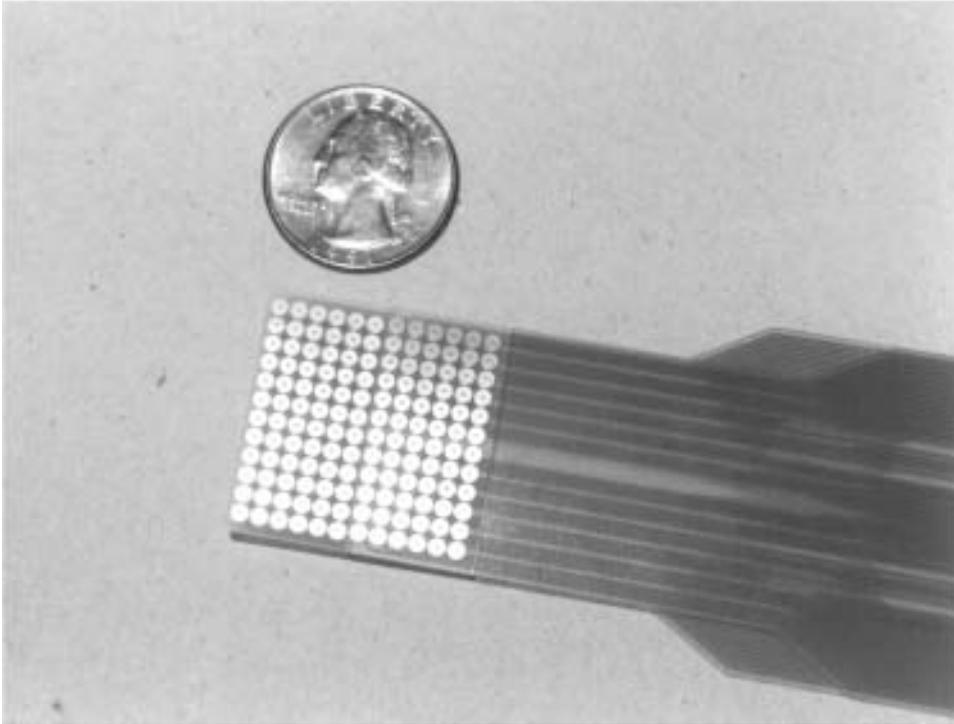
FIGURE 3   Close-up of 144-point (12 x 12) "virtual ground" electrotactile tongue display.

threshold. To compensate for this sensory inhomogeneity, we have developed a set of algorithms that allows the user to individually adjust both the mean stimulus level and the range of available intensity (as a function of tactor location) on the tongue. The algorithms are based on a linear regression model of the experimental data.

5. IMPLICATIONS FOR MEDIATED PERCEPTION

It now appears possible to develop tactile human-machine interface systems that are practical and cosmetically acceptable. For blind persons, a miniature TV camera, the microelectronic package for signal treatment, the optical and zoom systems, the battery power system, and an FM-type radio signal system to transmit the modified image wirelessly could be included in a glasses frame. For the mouth, an electrotactile display, a microelectronics package, a battery compartment, and the FM receiver will be built into a dental retainer. The stimulator array could be a sheet of electrotactile stimulators of approximately 27 × 27 mm. All of the components including the array could be a standard package that attaches to the molded retainer with the components fitting into the molded spaces of standard dimen-

sions. Although the present system uses 144 tactile stimulus electrodes, future systems could easily have four times that many without substantial changes in the system's conceptual design.

For all applications, the tongue display system may be essentially the same, but the source of the information to be delivered to the brain through the human-machine interface would determine the sensor instrumentation for each application. Thus, as examples, for hand amputees or quadriplegics, the source would be sensors on the surface of the hand prosthesis; for astronauts, the source would be sensors on the surface of the astronaut glove; for night vision, the source would be an infra-red camera. Similarly, for blind persons the system would employ a camera sensitive to the visible spectrum; and for pilots and race car drivers whose primary goal is to avoid the retinal delay (much greater than the signal transduction delay through the tactile system) in the reception of information requiring very fast responses, the source would be built into devices attached to the automobile or airplane. Robotics and underwater exploration systems would require other instrumentation configurations, each with wireless transmission to the tongue display.

Examples of these potential applications include a microgravity sensor that could provide vestibular information to an astronaut or a high performance pilot, and robotic and minimally invasive surgery devices that include MEMS technology sensors to provide touch, pressure, shear force, and temperature information to the surgeon, so that a cannula being manipulated into the heart could be "felt" as if it were the surgeon's own finger. Present recreational activities can be expanded: a video game might include dimensions of a simulated situation that are not transmittable via the visual and auditory interfaces used by present video games, and a moving picture might provide a wide range of information through the tactile human-machine interface from artificial sensors. We have received DARPA support to explore the feasibility of presenting navigational and other information to Navy SEALs under water, and comparable applications are being explored at present.

For mediated reality systems using visible or infrared light sensing, the image acquisition and processing can now be performed with advanced CMOS based photoreceptor arrays that mimic some of the functions of the human eye. They offer the attractive possibility to convert light into electrical charge and to collect and further process the charge on the same chip. These "Vision Chips" permit the building of very compact and low power image acquisition hardware that is particularly well suited to portable vision mediation systems. A prototype camera chip with a matrix of 64 by 64 pixels within a 2×2 mm square has been developed using the conventional 1.2 μm double-metal double-poly CMOS process. The chip features adaptive photoreceptors with logarithmic compression of the incident light intensity. The logarithmic compression is achieved with a FET operating in the sub-threshold region and the adaptation by a double feedback loop with different gains and time constants. The double feedback system generates two different logarithmic response curves for static and dynamic illumination respectively following the model of the human retina.

The vision substitution system has been discussed here in the context of a humanistic intelligence system. In some ways, the use of such systems differs from the use of natural sensory systems. For example, we found that while experienced blind TVSS subjects could perceive faces and printed images, they were very disappointed when perception was not accompanied by qualia: A Playboy centerfold carried no emotional message, and the face of a girl-friend or a wife created an unpleasant response since it did not convey an affective message. We consider this to be comparable to the lack of emotional contact of curse-words in a language that has been learned as an adult. It is possible that the emotional content could be developed over a long period of usage. On the other hand, a blind infant using a vision substitution system smiles when he recognizes a toy and reaches for it, and a blind 10-year-old child perceiving a flickering candle flame by means of a TVSS is enchanted. These issues of qualia have been explored elsewhere (Bach-y-Rita, 2002).

6. CONCLUSIONS

Tactile vision substitution, with which the brain of a blind person can learn to see, is one of a class of humanistic intelligence systems made possible by instrumental sensory plasticity. Comparable systems can be developed for persons with other sensory losses, such as deafness, tactile sensation loss (e.g., caused by Leprosy or diabetes), and bilateral vestibular loss. Given that it is possible to provide information from any device that captures and transforms signals from environmental sensors, it should be possible to develop humanistic intelligence systems for not only sensory loss, but also to augment and manipulate that sensory information to afford the user a superior perceptual experience.

In comparison to biology, human-machine interface technology is in its early infancy. The brain is much more complex and efficient than any present or even foreseeable electronic device. Even the nervous systems of insects—which allow highly developed functions such as the ability to identify and localize potential mates at great distances in moths, and the pattern perception and homing and complex motor and social behavior of Monarch butterflies—defy simulation on the most advanced computers (Bach-y-Rita, 1995), and all of that is managed in a tiny speck of a "brain." This can only improve in the future, and thus technology will provide access to biological-like capabilities.

The instrumental aspects of humanistic intelligence devices based on instrumental sensory plasticity provide only information acquisition, but training and practical use will lead to function comparable to our biological systems. Although the technology of the devices is crude in comparison to the biological systems, the brain is a very noise-tolerant processor. It can put up with a messy image on the retina (especially under adverse conditions such as a foggy night), and extract precise information by processing methods that we are just beginning to understand. From this ensemble of data, it can obtain a complex experience, in-

cluding qualia. It is the enormous plasticity of the brain that allows us to develop humanistic intelligence devices.

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