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Sensori-“motor” coupling by observed and imagined movement

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Abstract: Sensory systems are associated with motor systems for perception. 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 sensory-motor loop can be provided by artificial receptors leading to a brain-machine interface (BMI). We now propose that the motor component of the sensory-motor coupling can be replaced by a “virtual” movement. We suggest 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. We further suggest 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.

Key words: sensori-motor loop, spatial localisation, movement, mental image, tactile stimulation, multiplexing

Résumé : **Couplage sensori-moteur : mouvements observés et imaginés**. Les systèmes sensoriels et moteurs sont associés dans la perception. En l'absence d'un contrôle moteur sur l'orientation des entrées sensorielles, le sujet peut n'avoir aucune idée de l'origine des informations, et par conséquent aucune capacité à les localiser dans l'espace. Les études de substitution sensorielle ont démontré que la partie sensorielle d'une boucle sensori-motrice peut être « fournie » par des récepteurs artificiels et créer ainsi une interface cerveau-machine (ICM). Dans cet article, nous proposons que la partie motrice du couplage sensori-moteur peut être

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remplacée par un mouvement « virtuel ». Un mouvement prévisible, non observé autrement que par un signal indiquant son déclenchement, peut être imaginé de telle sorte que l'image mentale du mouvement se substitue à la composante motrice de la boucle. Nous suggérons également que la vitesse de la transmission de l'information par la peau, plus grande que celle de l'œil, permet d'utiliser des formes innovantes de présentation de l'information - telles que des séquences rapides et une division temporelle en multiplexe - et compenser en partie le petit nombre de points de stimulation tactile dans l'ICM. Dans le cadre des applications industrielles, l'incorporation des êtres humains dans la boucle du système est susceptible de rendre plus efficaces et plus humaines des tâches qui sont actuellement génératrices de stress.

Mots clés : Boucle sensori-motrice, localisation spatiale, mouvement, image mentale, stimulation tactile, multiplexe

INTRODUCTION

To people who operate large machines the "old salt" effect is well known. This is the situation in which a highly experienced operator (the "old salt") immediately knows the state of the machine from the overall feel. The intuitive feel of the experienced operator is far more reliable, and dramatically faster, than fathoming the state of a machine by conscious interpretations of numerical data. In the case of emergencies and breakdowns, the intuitive responses of the "old salt" literally mean the difference between life and death.

Human factors engineers have long understood that this phenomenon depends on the unconscious integration of sensory data over years of operating experience. Although such a level of competence in operators is urgently needed, few operators have the depth of experience that allow it to develop spontaneously. Nobody has devised a practical method of rapidly and deliberately developing that level connection between machine and operator, until now.

The key to human-machine interactions leading to unconscious immersion in, and conjoining with, the machine is the ability to capture the cues that reveal the state of the process, and to couple them to the operator's mind. Thus they can be experienced and directly integrated on the rapidly operating unconscious level, rather than being read and reflected on at the orders-of-magnitude slower conscious level.

An enabling technological breakthrough that makes such coupling possible and practical is the brain-machine interface (BMI) through the tongue. First developed for as a medical prosthesis to restore lost senses, tactile BMIs have been the technology through which it has been shown that the brain is capable of integrating the information from artificial receptors.

For proper integration of sensory data to occur, it is necessary for the user to have control of the movements and orientation of the sensor. In the absence of the sensory-motor loop, we have observed that the sensory stimulation through a tactile stimulus array is perceived as a purely tactile experience localized to the body part in contact with the stimulus array. Comparably, a remote robot controlled visually and with motor control of the robot's hands by the hands of the human operator, is unsatisfactory because the hand sensation is absent. Thus, it is an open-loop system rather than a sensory-motor loop; in this case, the motor control part of the loop is present, but the sensory part is not.

For persons without sensory loss, sensory augmentation systems that have the effect of expanding human sensibilities could be developed, such as for industrial quality-control tasks. The motor component of the sensory-motor coupling would be replaced by a "virtual" movement, enabling the person to experience electronically generated data by direct perception. Furthermore, it may be 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.

Television and other enabling technologies have provided access to some human-machine interactions leading to unconscious immersion in, and conjoining with, the machine. Thus, when pong games that could be connected to home television sets first appeared about 30 years ago, we modified that device to enable us to develop what would today be called "virtual reality". We disconnected one of the joy-sticks that controlled the pong paddle, and instead connected a device used for rehabilitation the upper extremities of persons who were partially paralyzed from a stroke. Arm movement was necessary to control the pong paddle on the television screen. Patients soon became immersed in the game, and forgot that they were making arm movements. It became a very motivating activity instead of a tedious, boring task (Cogan et al., 1977). We have recently expanded this concept of computer-assisted motivating rehabilitation (CAMR) (Bach-y-Rita et al., 2002).

Tactile sensory substitution studies (with blind, vestibular loss, and persons with tactile loss from Leprosy) have shown that the brain is capable of integrating the information from an artificial receptor, arriving via a brain-machine interface (BMI), in a perceptual experience that depends upon the nature of the information gathered by the specific artificial receptor (Bach-y-Rita et al., 1969; Bach-y-Rita, 1972; 1995; in press). For this to occur, however, it is been necessary for the user to have control of the movements and orientation of the sensor. In the absence of the sensory-motor loop, we have observed that the sensory stimulation through a tactile stimulus array is perceived as a purely tactile experience localized to the body part in contact with the stimulus array.

We suggest here that for persons without sensory loss, sensory augmentation systems could be developed in which the motor component of the sensory-motor coupling is replaced by a “virtual” movement. The user would observe the movement visually, either directly or on a TV screen. For an industrial quality-control task (see below), extensive training in a specific task, so that the user became completely familiar with the particular process, could lead to the ability to mentally recreate its movement without the need to move the input (sensor). This would, however, require a cue to inform the worker when to initiate the mental “observation” of the movement involved in the particular industrial task.

With such a system, BMIs may incorporate humans in a brain-instrumentation loop to perform specific tasks without motor control of the input. During that learned task, the data stream from an electronic circuit would be led directly into the human nervous system, by means of the BMI (which would, essentially, play a passive relay role), to enable a person to experience the data streams by direct perception.

Furthermore, we suggest that, due to the much faster information transmission of the skin than the eye, innovative information presentation, such as fast sequencing, could be used (Bach-y-Rita, 1974). One such method is time division multiplexing (Bach-y-Rita & Hughes, 1985; Kaczmarek et al., 1984; 1985). Such an approach to information transmission would be a way to partially compensate for the relatively small number of tactile stimulus points in the BMI. This would be particularly applicable to certain industrial quality-control tasks, such as in the production of precision tubing, or of automobile engine blocks.

Sensory substitution systems, for persons who have lost critical senses, are possible because of the brain’s enormous plasticity, both structural and functional. There are multiple mechanisms for information transmission, both synaptic and nonsynaptic (*e.g.*, Bach-y-Rita, 2001), as well as complex brain network organizations (Aiello & Bach-y-Rita, 2001). Visual experiences obtained by blind persons through a tactile BMI are predicated on the fact that they have not necessarily lost the capacity to see, since we do not see with the eyes, but with the brain (Bach-y-Rita, 1995). In normal sight, the optical image does not get beyond the retina. >From the retina to the central perceptual structures, the image, now transformed into nerve pulses, is carried over nerve fibers. It is in the central nervous system that pulse-coded information is interpreted resulting in a subjective visual experience. Volume transmission mechanisms play a role in the sensory information relays such as in the thalamus (Bach-y-Rita, 1995) and probably in the interpretative functions (elsewhere we have explored the possibility that the higher human functions which appear to be related to the large human pro-frontal cortex may be largely volume transmission-mediated (Bach-y-Rita & Aiello, 2001).

We have previously developed tactile vision substitution systems (TVSS) to deliver visual information from a TV camera to the brain through BMI's consisting of arrays of vibrotactile and electrotactile stimulators in contact with the skin of one of several parts of the body (*c.f.*, Bach-y-Rita, in press). Mediated by the skin receptors, energy transduced from any of a variety of artificial sensors (*e.g.*, camera, pressure sensor, displacement, *etc.*) is encoded as neural pulse trains. In this manner, the brain is able to recreate "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. And 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 the ball as it rolls over a table edge, and complex inspection-assembly tasks (*c.f.*, Bach-y-Rita, in press). Others have demonstrated that vibrotactile torso displays can be used to effectively interpret dynamic stimuli that fall below human sensory threshold and compensate for those that contribute to illusory motion displays in both actual and simulated flight using fixed and rotary wing aircraft and remotely piloted vehicles (Diamond et al., in press; Raj et al., 2000; 2001).

Thus, it appears that the same subjective experience that is produced by a visual image on the retina can be produced by an optical image captured by an artificial eye (a TV camera), when a way is found to deliver the image from the camera to a sensory system that can carry it to the brain. The visual information reaches the perceptual levels for analysis and interpretation via somatosensory pathways and structures. Visual illusions that have been tested (*e.g.*, waterfall effect) are also obtained with the TVSS (Bach-y-Rita, 1972; 1974). Heil (1983) and Morgan (1977) consider that since blind TVSS subjects are receiving similar information as that which causes sighted to see and are capable of giving similar responses, one is left with little alternative but to admit that they are seeing (and not merely "seeing").

Sensory substitution for other loses, such as hand sensation in Leprosy patients, has also been demonstrated (*c.f.*, Bach-y-Rita, in press). In recent studies, Tyler, Danilov and Bach-y-Rita (submitted) have shown that such a system is feasible for persons with vestibular damage who have lost the sense of balance; it may also lead to a vestibular augmentation system for astronauts and pilots subject to spatial disorientation.

There are similarities between the retina and the skin as sensory surfaces: "…. in its capacity to mediate information.....the receptor surface of the skin and the retina are capable of mediating displays in two dimensions as well as having the potential for temporal integration. Thus, there is no need for complex topographical transformation or for temporal coding for the direct presentation of pictorial information onto..... the skin. Certain types of sensory inhibition, including the Mach-band phenomenon and other examples of lateral inhibition originally demonstrated for vision, have been shown to be equally demonstrable on the skin. The skin... becomes part of an exploratory organ when self-induced camera movement is incorporated into the tactile vision substitution system" (Bach-y-Rita, 1972, pp. 11-12). This would allow the operator of a tactile BMI to appreciate trends the data stream and, thus, maintain and update a contextual mental model of the dynamics of represented process.

The various sensory substitution experiments previously performed with the BMI showed that, irrespective of the electronic sensor type (camera, accelerometer, *etc.*), the data from the sensor are properly used by the subject (experienced as sight, balance, *etc.*) despite the fact that the data are nothing more than bit streams coupled through *the same interface*. This suggests that the nervous system might be able to make sense of any sort of data coupled into it through the BMI. The capacity of the nervous system to make sense of electronically generated data could have dramatic implications for commercial applications such as industrial process control.

We therefore suggest that a quality-control worker could become highly proficient in extracting complex information from the tactile input on the tongue or any other area of the body. Initially, the worker would have control of the camera and simple forms would be experienced, then forms in three-dimensions. Then, without direct control of the camera, a learning process would allow the information to be experienced in three-dimensional space with the visual motion (observing the tube extruding from the machine) presented in novel ways. One previously discussed is time-division-multiplexing (Bach-y-Rita & Hughes, 1985; Kaczmarek et al., 1984; 1985), in which an image could be broken down into several discrete segments and presented sequentially.

For example, the image of a face could be divided into a 3 x 3 matrix, and presented sequentially to the entire BMI stimulus array, starting from the top left 1/9 of the image, followed by the middle segment of the top row, and so on completing a left - right sweep from the top to the bottom rows. With experience, this could be presented much faster (given the characteristics of the skin mentioned above) than could be perceived visually. Thus, a complex object, such as of the outer and inner surfaces of a molded engine-block, could be inspected rapidly.

With considerable experience, it may even be possible to eliminate the visual perception of the movement (*e.g.*, the tube being extruded from the machine); it may be sufficient to predict the moment of the beginning of the extrusion, based on experience and a clue such as a sound from the machine. In this case the mere imagining of the movement may be sufficient for the sensory-"motor" coupling. Bohm (1980) has stated: "....thought itself is an actual process of movement. That is to say, one can feel a sense of flow in the stream of consciousness not dissimilar to the sense of flow in the movement of matter in general". This may provide the "motor" component of the sensory-motor coupling, with relevance to perception in space and the performance of tasks such as those discussed here. In a very different application, mental practice has been shown to be effective in improving music and athletic performance as well as motor recovery from stroke (Page, 2001). In those cases, it appears that the mental activity is providing both the motor and the sensory equivalents.

In a process monitoring task, sensori-"motor" coupling would occur in a subtle way. In addition to being able to directly experience the process via the BMI, the operator would be able to exert a variety of control actions on the process, and then be able to directly experience the effect of the control action. Through repetitions of this interaction, operating mostly at an unconscious level of learning, the operator would develop sensori-"motor" coupling. The experience would be akin to that of simultaneously being affected by and affecting, through the fingers, the quality of the unfired clay in the wall of the pot on a potter's wheel. The difference being that the BMI enables this sort of experience to be extended to extreme situations such as controlling data flows in computer networks, or the properties of orange-hot steel.

As an example, in the production of precision steel tubing a thickness gauge in a tube-piercing mill produces a thickness profile consisting of approximately 3000 numbers per tube in about 30 seconds. Interpreting the numbers to tell whether or not the tube is acceptable is difficult and tedious with present analog and digital technology and is unfeasible in real-time. Incorporating humans-in-the-loop, the operator would experience the tube passing through the gauge in much the same way as one experiences the feeling of sliding the finger over a surface. The experience might feel smooth, or it might feel rough, or somewhere in between. The well-trained operator could distinguish directly from experiencing the perception whether or not the tube is smooth enough to meet the requirements, and thus make the decision to accept or reject the tube. Unlike conventional controls, the operator would be able to anticipate problems from “precursor” events, basing judgments of interpretation of ambiguous cues hidden in the data. This is a level of understanding and control that is utterly unavailable in either electromechanical or algorithmic control systems. By design, such systems necessarily ignore ambiguity (Kercel, 2002).

Instead of a tube, imagine (for ease of visualization) a plate where you could put your finger on one side and your thumb on the other, and then run your hand down the length of it such that you feel the thickness move through your fingertips. The quality of the product, if it were experienced by direct sense perception, would be perceived as a feeling of ripple in the thickness as the product slides through the fingertips. In a defective product the feel of the ripple would be pronounced; in a good product, it would be slight.

In addition to the overall quality, subtle differences in the feel of the ripple pattern would be an indication of the state of the piercing machine. A smooth periodic ripple might indicate that everything is adjusted properly. A periodicity that is regular, but asymmetrical within the period, might indicate that the roll pressures are out of balance. If the fine ripple pattern is modulated with a long slow ripple pattern, it might indicate a problem with worn rolls. If the feel is rough rather than rippling, it may indicate that the piercing head is defective. In addition, several of these phenomena may occur simultaneously, and the patterns may be overlaid.

Such patterns are readily apparent in the output data stream of a laser-ultrasonic thickness gauge. It might be asked if a computer could not extract the same qualitative information from the data, and the answer is yes. However, the extraction requires the use of sophisticated and extremely slow pattern recognition algorithms. They are infeasible for on-line real-time operation, especially when the signatures of several simultaneous process defects are overlaid in the data.

On the other hand, if the laser-ultrasonic thickness gauge were directly coupled to an experienced operator through the BMI, he/she would be able to identify all the defects immediately by feel. The experience would be akin to the experience of the potter feeling the quality of the clay wall of a pot as it moves on the potter's wheel.

It might also be asked why the laser ultrasonic gauge and BMI might be needed for such inspections. If the “fingertip method” is so effective why doesn't the steel industry do inspections that way now. There are three reasons. First, the wall being inspected is not a plate, it is a tube about 20 feet long, 6 inches in diameter and with a wall a half-inch thick. It is geometrically impossible to pass the entire length of the wall through the fingertips of a real hand. Second, the ripples are on a scale from sub-millimeter to microscopic; without amplification the wall feels smooth to human sensibilities. Third, and most compelling, the on-line measurement must be made when the tube emerges from the mill, when it is orange-hot, and just below the melting point of steel. A human cannot touch it directly. Nevertheless, using the laser-ultrasonic thickness gauge and the BMI, the human can have the same experience, as if the wall could pass through the fingertips.

The BMI is the key to practical sensory substitution and augmentation systems, enabling the incorporation of humans in the loop with instruments. Tactile display systems have proven to be useful for this purpose. Although many sites, including the back, the abdomen, the fingertip, and the forehead have been shown to be adequate, the tongue is an ideal site for a practical electrotactile BMI. The tongue is very sensitive, has excellent spatial resolution, and is highly mobile. An electrolytic solution (saliva) assures good electrical contact. Perception with electrical stimulation of the tongue appears to be better than with finger-tip 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 finger-tip (Bach-y-Rita et al., 1998; Bach-y-Rita, Tyler & Kaczmarek, in press).

In regard to the faster information transmission capability of the somatosensory system, "...the tuning curves of the rapidly-adapting receptors....are capable of detecting vibratory stimuli over the frequency range from 5 to 300 Hz." (Bach-y-Rita, 1972, p.13). "The ability to detect a break in a steady stimulation has been calculated by Geldard for several senses. The minimal perceptible break was on the order of 3 ms for the ear, 10 ms for the skin, and more than 30 ms for the eye...the reaction time for touch is lower than that for vision. Also, the skin can mediate a higher fusion frequency than the retina - over 400 Hz compared with 100 Hz for the eye" (ibid., p. 16). The very fast information transmission capabilities of the sensory-motor system, in comparison to the visual system, may allow innovative information presentation techniques for large data streams to be received.

In the present practice of industrial control, the human operator is treated as a "wet machine," whose job is to read numbers and push buttons. It is notoriously dehumanizing, ignoring what the human is good at doing, and forcing the human to act just like a machine, resulting in low efficiency and high stress and fatigue. In contrast, the proposed scheme would enable the human and the mechanism to be complementary elements in the process. The purely mechanical part of the task would be relegated to the machine. The operator's cognitive power, particularly as it relates to deciding what to do next in an ambiguous situation, would be harnessed to do those things that the machine is incapable of doing, thus humanizing the task. The proposed scheme would enable the human and the mechanism to be complementary elements in the process.

It should be fascinating to read a review of this field in 20 years. So many practical applications should be in common use by that time!

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