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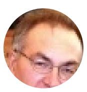
2 AUTHORS:



Yuri Danilov
University of Wisconsin–Madison

Mitchell Tyler
University of Wisconsin–Madison

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Danilov, Yuri; Tyler, Mitchell.
Wicab, Inc., 3510 West Beltline, Middleton, Wisconsin, 53563, USA

ABSTRACT.

Brain Computer Interface (BCI) technology is one of the most intensely developing areas of modern science; and has created numerous significant crossroads between neuroscience and computer science. The goal of BCI technology is to provide a direct link between the human brain and a computerized environment. The vast majority of recent BCI approaches and applications have been designed to provide the information flow from the brain to the computerized periphery. The opposite or alternative direction of flow of information (computer to brain interface – CBI) remains almost undeveloped. The BrainPort is a Computer Brain Interface that offers an alternative symmetrical technology designed to support a direct link from a computerized environment to the human brain- and to do it non-invasively. The ultimate goal of the BrainPort technology is to introduce the possibilities offered by changing the direction of information flow - from a computerized environment to the brain.

Keywords: sensory input, electrotactile stimulation, tongue, BrainPort

Introduction

In the majority of modern industrial and technological control processes, the human is still needed “in the loop” – perhaps even more urgently than ever before. This is because the complexity and scale of technology is increasing in parallel to the exponential development of available computational power. Paradoxically, rather than simplifying the human operator’s environment, these processes make ever-increasing demands on the operators' capabilities (i.e., necessity for constant and rapid learning of new knowledge-based skills, increased interaction with stored memory capacity, increased speed of reaction time while maintaining precision of decision making process, attention to task, etc.) These unavoidable and escalating demands can and do lead to critical psychological pressures on the human brain and a consequent weakening of the human link in the technological chain. This increasing information flow leads to the overloading of the human brain, increasing also the risk of human malfunctioning; from wrong decision-making to even the psychological break-down of the human-operator.

Brain Overload

Why does this happen? Let's look at the simplified sketch of the human operator (Fig. 1). In essence it is an analog of the physical "black box" diagram, where the brain (as a central processing unit) receives inputs from the various sensory systems and generates outputs to various muscular systems, producing muscular movement. The product of the motor output is then sensed and compared with the original motor plan. Subsequent motor outputs may be generated depending upon how well the resultant movement fit the initial sensory-motor action plan.

For the majority of mammals, environmental information input to the brain is typically organized by five special senses and a few non-specific ones. The five special senses are: vision, hearing, balance, smell and taste. They are "special" because the actual sensors (receptors) are localized and specialized (physically, chemically and anatomically) to acquire specific environmental data (and as a result), but within a limited range of changes. For example, the sensitivity of photoreceptors is limited in terms of wavelength: we cannot see in the infrared part of the spectra (as do snakes) or the ultraviolet range (as do some insects). We also cannot hear in the infra- or ultra-sonic ranges of sound frequency as do, respectively, elephants or bats.

Non-specific senses for mechanical signal (touch, vibration, etc.), thermal changes, or pain, do not have a specific location or specialized apparatus for reception. Nevertheless, all non-specific senses are also limited in terms of the ranges of environmental information that can be sensed (frequency of vibration, temperature range, etc)

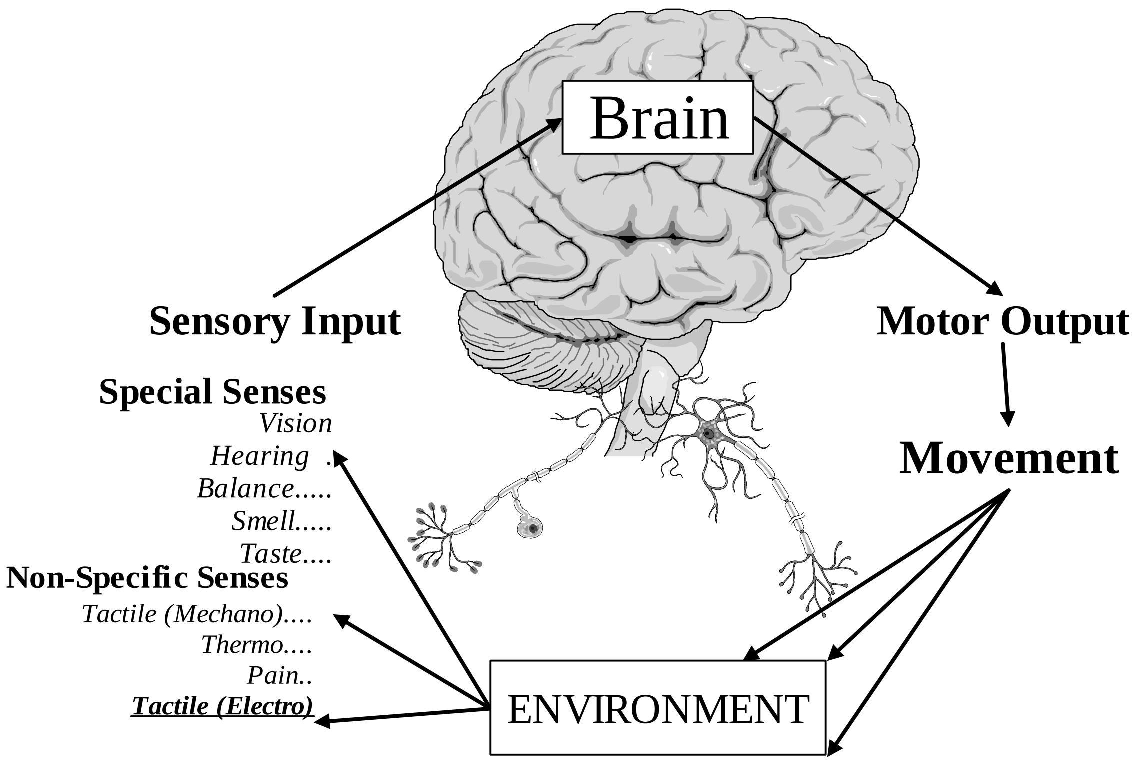

Figure 1. Diagram of major brain sensory-motor functions

During technological processes, we can also observe another stage of limitation. In the execution of their duties humans-operators mainly use vision, the most developed human sense. Occasionally other senses are used as principal inputs, typically as alarm signals: auditory stimuli, balance during walking on slippery surface or biking, smell and taste as "quality control" during cooking or brewing processes. Indeed, if one looks at the thousands of visual indicators and monitors that saturate the cockpit of a modern aircraft or a nuclear power station control room it makes one wonder: how it is possible to look attentively, and most importantly, to read, analyze, and understand all of the quantitative and qualitative information presented on all of the instrumentation during the hours of a working shift or an intercontinental flight?

Indeed, modern computers are increasingly utilized for monitoring and controlling most routine, if complex processes, and are indispensable when everything is operating smoothly. However their capabilities begin to diminish in situations of unpredictable change. Unexpected fluctuations, equipment malfunctions, and environmental disturbances –any of these events necessitates immediate operator intervention employing the human brain's innate and massively parallel or simultaneous analytical capabilities for decision making – something that modern computational technology is still missing.

A Simple Message

The technological output of the human-operator is action or, to be more precise - **movement**. In fact, the only output of the brain is a signal for control of movement. For example, just keeping the human body in upright posture seems mundane, yet it is an astonishingly complicated pattern of continuous action involving nearly every skeletal muscle in the human body. Emotional reactions too, immediately change the tension in many muscles of the human face and/or internal body musculature. Even voice commands might be considered as output alternatives to movement. But speech itself is the result of very sophisticated combination of movement patterns in different muscles in the tongue, laryngeal area, lungs and diaphragm.

The most complex and sophisticated output apparatus available to the operator is the human hand, - specifically the fingers. Pressing a button, turning a switch, keyboard typing, using a joystick control – all are complicated movement patterns, involving synchronous action of thousands of muscular fibers. The result can be as course as turning a valve handle, or as subtle as sensing the friction of a computer mouse. Yet we have only two hands – consequently the human-operator is also limited in his/her output options. These various motor outputs are shown in the upper left-hand portion of Figure 2.

Clearly, the natural biological and technological limitations of the human are the key factors in creating input/output information saturation and operator overload. The results can be likened to a traffic jam in the technological information loop.

Can information flow be improved?

It is doubtful that following the present path of increasing technological development will lead to a *reduction* in information flow to the operator in the near future. Thus, there are two basic ways to address the present situation: 1) Improve the information processing capacity through education and training, to improve the operator's capacity and efficiency in solving process problems and thereby improve their analytical brain power; and 2) Improve the operator's input and output information processing capacity by optimizing the way in which the data is presented.

A contemporary technological solution to the latter challenge is to implement a Brain Computer Interface (BCI) – that is, to utilize an interface technology designed to transfer information from the brain to the computer or vice versa, by employing alternate but underutilized natural biological pathways. This novel approach is diagrammed in the Figure 2 below.

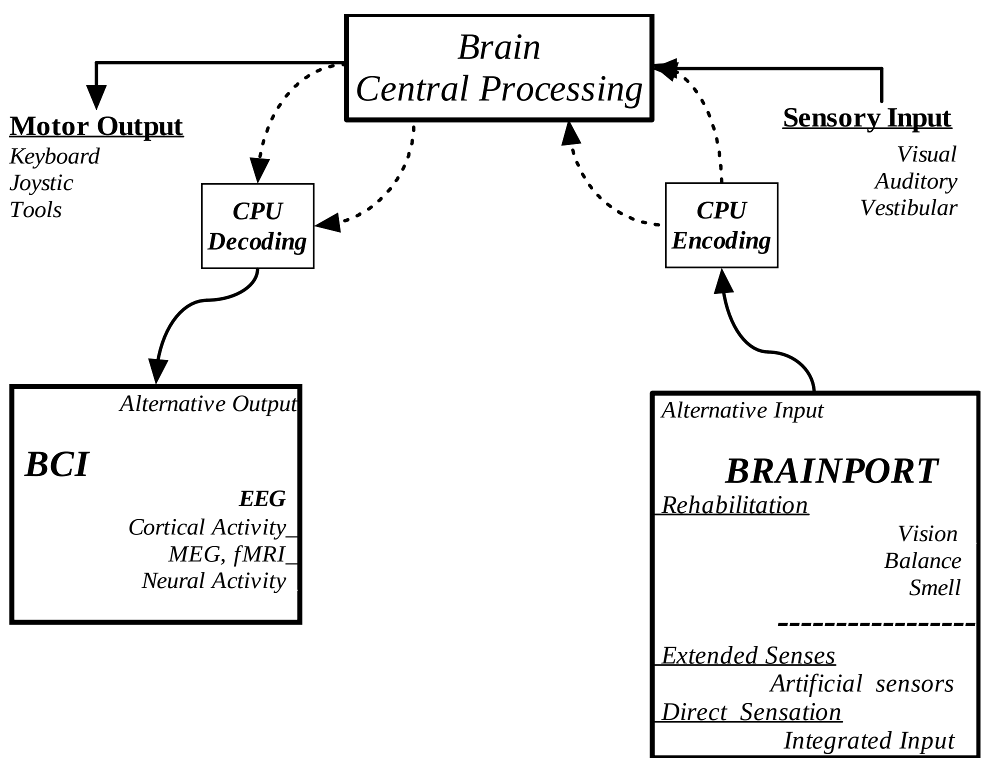

Figure 2. The two main branches of Brain Computer Interface technology

The majority of modern BCI technologies are designed to provide alternative *outputs* from the brain to a computer. An early application of BCI's was to aid completely paralyzed patients, who have lost ability to move, speak, or otherwise communicate. Various levels of neuronal activity can be considered as potential sources for output: from single fibers and neurons up to the sum total of signals from large cortical and subcortical areas, such as EEG or fMRI signals – the integrated output of which can range as high as thousands and even millions of neurons (for review, [21,23-26,29,38,42,45,46]).

In the vast majority of these BCI scenarios the main goal is to use "internal" brain signals derived from the outputs of various areas of the brain to control (through computer-based peripherals) cursor movement, select icons or letters, to operate neuroprosthesises . There are many successful examples of such an approach. [22,27,28,31-37,39,40,43]. Microchips implanted in a human's hand or animal brain can be used to transfer electronic copies of neural spike flows from goal-directed movements to another person's artificial limb to reproduce the exact replica of the original movement [14,30]. Another example involves using certain components of acquired EEG signals that can be extracted, digitized, and applied as supplemental flight controls for drones or other unmanned aircraft.

However, few BCI's address alternate information inputs ***to*** the brain, or to be more precise – CBI's (Computer Brain Interface). This technology is realized in the BrainPort, which offers a unique way of presenting meaningful information to the brain by ***electrotactile stimulation*** of the tongue.

The BrainPort

The BrainPort, which can be succinctly described as a universal "information port" to the brain, is the product of 35 years of scientific and clinical research, led by Dr. Paul Bach-y-Rita, MD, on the combined phenomena of brain plasticity and sensory substitution. [1-4,6-8,10-13]. The BrainPort is also a platform technology, i.e. one that can be used as the foundation for launching potentially hundreds of new applications that employ other devices, technologies and systems.

The technical aspects of the BrainPort

The tongue display system described below was developed under grants from the NIH-National Eye Institute, the University-Industry Research Office of the University of Wisconsin (UW-UIR), and a contract from DARPA. The technology has been assigned to the Wisconsin Alumni Research Foundation (WARF), which holds the US Patent, No. 6,430,450.

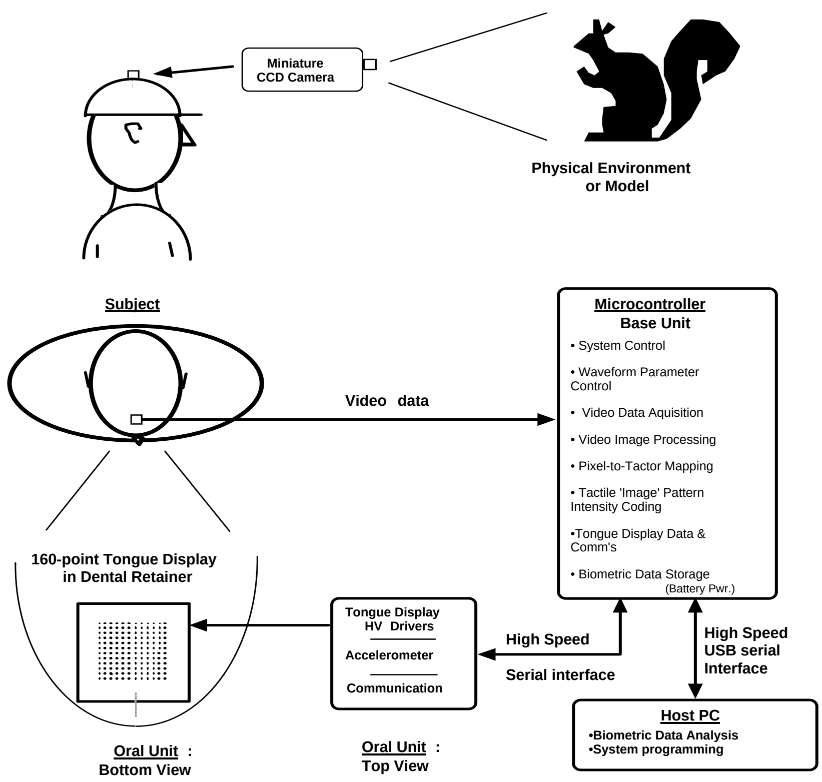

Figure 3. Schematic diagram of the prototype BrainPort System

The present configuration of the BrainPort consists of two components: the intra-oral tongue display unit, and the microcontroller base-unit. These two elements are connected by a thin 12 strand tether carries power, communication, and stimulation control data between the base and oral units, as shown in the schematic diagram (Figure 3).

The oral unit contains circuitry to convert the controller signals from the base unit into individualized zero to +60 volt monophasic pulsed stimuli on the 160-point distributed ground tongue display. The gold plated electrodes are on the inferior surface of a PTFE circuit board using standard photolithographic techniques and electroplating processes. This board serves as both a false palate for the tongue array and the foundation to the surface-mounted devices on the superior side that will drive the ET stimulation. This unit will also has a MEMS-based 2-axis accelerometer for tracking head motion during visual image scanning and for vestibular feedback applications. This configuration utilizes the vaulted space above the false palate to place all necessary circuitry to create a highly compact and wearable sub-system that can be fit into individually molded oral retainers for each subject. With this configuration, only a slender 5mm diameter cable protrudes from the corner of the subject's mouth and connects to the belt-mounted base unit.

The base unit is built around a Motorola 5249 controller running custom Dynamic C++ compiled code to manage all control, communications, and data processing for pixel-to-tactor image conversion. It is user configurable for personalized stimulation iso-intensity mapping, camera zooming and panning, and other features. The unit will has a single removable 512 MB compact flash memory cards on board that can be used to store biometric data from the mobile experiments planned in the latter stage of the research. Programming and experimental control is achieved by a high-speed USB between the controller and a host PC. An internal battery pack supplies the 12 volt power necessary to drive the 150 mW system (base + oral units) for up to 8 hours in continuous use.

The BrainPort is a computer-based environment designed to represent qualitative and quantitative information on the superior surface of the tongue, by electrical stimulation through an array of surface electrodes. The electrodes form what can be considered an "electrotactile screen", upon which necessary information is represented in real time as a pattern or image with various levels of complexity. The surface of the tongue (usually the anterior third, since it is the most sensitive area), is a universally distributed and topographically organized sensory surface, where a natural array of mechanoreceptors and free nerve endings can "read" the contents of 'screen', encode this information and then transfer it to the brain as a "tactile image". With only minimal training the brain is capable of decoding this information (in terms of spatial, temporal, intensive, and qualitative characteristics) and utilizing it to solve an immediate need. This requires solving numerous problems of signal detection and recognition.

To detect the signal (as with the ability to detect any changes in an environment), one needs sensors of the highest absolute or differential sensitivity,, e.g. luminance change, indicator arrow displacement, or the smell of burning food. Additionally, the detection of the sensory signals, especially from survival cues (about food, water, prey or predator), usually must be fast if reaction times are to be small in life threatening situations. It is important to note that the sensitivity of biological sensors is usually directly proportional to the size of the sensor and inversely proportional to the resolution of the sensorial grid. Information utilized during this type of detection task is usually **qualitative** information, the kind necessary to make quick alternative decisions (Yes/No), or simple categorical choices (Small/Medium/Large; Green/Yellow/Red).

The recognition process is typically based on the comparison of given stimuli (usually a complex one such as a pattern or an image, e.g. a human face) with another one (e.g. a standalone image or a set of original alphabet images). To solve the recognition problem one needs sensors with maximal precision (or maximal resolution of the sensorial grid) to gather as much information as possible about small details. Often this is related to the measurement of signal parameters, gathering **quantitative** information (relative differences in light intensity, color wavelength, surface curvature, speed and direction of motion, etc.), where and when precision is more important than speed.

The BrainPort is capable of noninvasive transferring both **qualitative and quantitative** information to the brain with different levels of a "resolution grid", providing basic information for detection and recognition tasks. The simple combination of two kinds of information (qualitative and quantitative) and two kinds of a stimulation grid (low and high resolution) results in four different application classes. Each class can be considered as a root (platform) for multiple applications in research, clinical science and industry, and are shown in Figure 4 below.

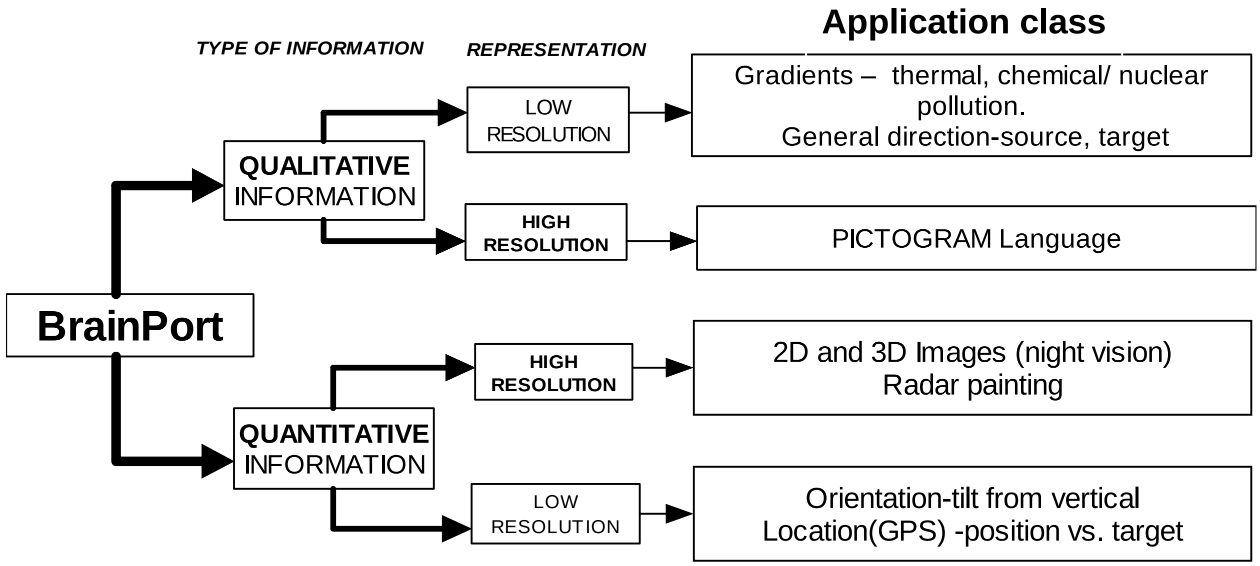

Figure 4. Four classes of BrainPort applications.

<u>The First Class</u> (qualitative information, low resolution) can be illustrated by the combination of external artificial sensors (i.e. radiation, chemical) with the BrainPort for detection of environmental changes (chemical or nuclear pollution), or explosives detection. The presence of selected chemical compounds (or sets of compounds) in the air or water can be detected using the BrainPort simply as "Yes/No" paradigms. By using a distributed array of sensors and a corresponding presentation of signal gradients on the BrainPort array it is also possible to use the system for source orientation relative to the operator.

<u>The Second Class</u> (qualitative information, high resolution) can be illustrated by an existing application for underwater navigation and communication. A simple alphabet of images (sets of moving bars in four directions, a flashing bar in the center and flashing triangles on left and right sides of BrainPort array) constitute a system of seven navigation cues that are used to correct deviation and direction of movement along a designated path. In our experiments, after 40-60 minutes of preliminary training, blindfolded subjects are capable of navigating through a computer generated 3-D maze using a joystick as a controlling device and the BrainPort for navigation signal feedback.

<u>The Third Class</u> (quantitative information, low resolution) can be illustrated by another existing application for the improvement of balance and the facilitation of posture control in persons with bilateral damage of their vestibular sensory systems (BVD - causing postural instability or "wobbling", and characterized by an inability to walk or even stand without visual or tactile cues). A quantitative signal acquired from a MEMS accelerometer (positioned on the head of subject) is transferred through the BrainPort array as a small, focal stimulus on the tongue array. Tilt and sway of the head (and therefore the body) are perceived by the subject as deviations of the stimulus from the center of the BrainPort array, providing artificial dynamic feedback in place of the missing natural signals critical for posture control. The current prototype has been tested on 11 BVD subjects and successfully demonstrated the BrainPort's high efficiency[15, 41].

<u>The Fourth Class</u> (quantitative information, high resolution) can be illustrated by another existing prototype that implements a great scientific challenge – that of 'vision' through the tongue. Signals from a miniature CCD video camera (worn on the forehead) are processed and encoded on a PC and transferred through the BrainPort array as a real-time electrotactile image. Using this electrotactile display subjects are capable of solving many visual detection and recognition tasks, including simple navigation and catching a ball. On the basis of the current prototype it is easy to imagine adapting the system for night (infrared) or ultraviolet vision.

The ultimate potential of the BrainPort for image or pattern representation has yet to be realized. As for the functional capacity of the human tongue as an information interface (as well as for sensory substitution in general), that is too also remains undiscovered.

On the basis of the four strategic classes of BrainPort applications it is possible to develop multiple practical industrial applications which can include a human operator in the loop, especially given the modern tendency toward increased density and complexity of visual representations. This situation begs for the development of alternative information interfaces. For example, the numerous light and arrow indicators of past displays are being replaced by computer monitors which further complicates the visual stimuli by condensing the information into lumped static and dynamic 2D and 3D images or video streams.

There are various rationales behind the development of these kinds of cumulative information presentations. One is to decrease the area of the visual information field, thereby limiting the space requiring the observer's visual attention. Another is to condense multiple parameters into one single image. However, to control modern technological processes an operator must be able to efficiently observe and make decisions about hundreds of changing parameters. If each parameter is represented by a simple indicator, like a light or arrow, the control panel will consist of hundreds of the same kinds of indicators. By miniaturizing and grouping all of these indicators, the resultant ergonomically designed displays become extremely intensive information panels, like the ones presently found in modern aircraft (Electronic Flight Instrument Systems, EFIS) or nuclear power stations.

The main problem with these approaches is the distribution of attention required by observer. In the presence of multiple visual stimuli, the operator is forced to limit his/her attention capacity to a single element being displayed. Furthermore, this ability continues to diminish during extended periods of observation. One possible solution is to decrease the number of indicators and replace them with more condensed, more complicated visual images that combine multiple parameters into a single image. For example, a single 3D scatter plot can represent up to 12 simultaneously changing parameters, using multiple features of single elements as coding variables (e.g. size, dimension, shape, color, orientation, opacity, pattern of single elements, etc.) – mainly all possible visually representable features.

An alternative approach would be to use the BrainPort as a supplemental environment input for processing information. As previously mentioned, the BrainPort is capable of working in various modes of complexity: As a simple indicator (first application class) for signal detection; as a target location device (third application class) for position control of signals on a 2D BrainPort array, much like a "long range" target location radar plot; in almost all computer action games; as a simple GPS monitor.

The BrainPort can also work in more complex modes such as a vision substitution device, an infrared or ultraviolet imaging system creating complex electrotactile images using in addition to two dimensions of its electrode array, the amplitude and frequency of the main signal, the spatial and temporal frequency of the signal modulation, and a few internal parameters of the signal waveform. In other words the BrainPort is capable of creating a complex multidimensional electrotactile image – similar to that of visual imagery.

Can the human brain reliably utilize information from electrotactile image?

Unequivocally. In numerous experiments performed by Dr. Paul Bach-y-Rita and his colleagues over three and a half decades with both unaffected subjects and patients who are blind or have balance dysfunctional, the results undeniably confirm that tactile and electrotactile sensory substitution is very efficient[1,5,7-11,16-18,41,44]. Moreover, recent fMRI research exhibits key evidence that electrotactile stimulation of the tongue can indeed be considered as an information port to the brain [20]. After training with the BrainPort, fMRI screening of the brain activity in blind subjects during the electrotactile presentation of visual images revealed strong activation in areas of the primary visual cortex This means that after training with BrainPort, the blind person's brain begins to use the most sophisticated analytical part of the cortex for analysis of electrotactile information *displayed on the tongue* during *visual* tasks. (Before training these areas were not active.) It is a dramatic demonstration of the meaning of Dr. Bach-y-Rita's statement: "We see with the brain, not the eyes,"[5,10].

The activation of normal analytical resources (e.g. the 'visual' part of the brain) in response to artificial sensory stimulation (the BrainPort) occurring as it does through natural, but non-traditional pathways (mechanosensitive tactile pathways) is indicative of the unique opportunities offered by this technology. These possibilities arise in the form of systems that afford processing of artificial sensory signals (from potential any source) by natural brain circuitry and organizational behavioral, thereby providing the possibility for so-called direct sensation or direct perception by the operator.

We usually don't think about such natural behavioral acts like breathing or digestion as fully "automatic", internally "built-in" processes. Even if we think about them, we can't stop or permanently change them. Walking, swimming, riding a bike or driving a car are other examples of very complex biomechanical processes that also use multiple sensory and motor coordination, but we learn them early in our lives; performing them also almost naturally (without thinking about each component), quickly and with great precision and efficiency.

Direct sensation is the highest form of the sensory perception automatization, providing as it does, the most efficient input to behavioral circuitry and the shortest loop of sensorimotor coordination [19]. We have theoretical as well as experimental evidence that electrotactile imagery created with the BrainPort, even in a very complex mode, can be incorporated into natural sensory information flows, and can be incorporated into behavioral processes as easily as natural sensory signals.

In summary, the BrainPort is a unique sensory substitution device based on the electrotactile stimulation of the brain. It is also a universal Brain Computer Interface, in the sense that its' potential for application development is limited only by our imaginations. And finally, because of it's ability to provide to the human brain with information about the environment far beyond limits of our natural sensory systems. It is also an "extrasensory" or augmentative device, due to its capacity to extend the limits of our natural senses, and by doing so, to create new sensory opportunities.
The BrainPort is a simple way to improve the environment of the modern human-operator, to decrease the load on visual systems and related stress factors, to increase the capacity of human resources, and, as a result – to maximize the general efficiency of the human in the loop.

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