Human Factors Issues in the Neural Signals Direct Brain-Computer Interface

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ABSTRACT

Controlling a computer directly by brain signals has been made possible by the development of a neurotrophic electrode that is implanted in the human motor cortex. The success of this technology can be enhanced by researching and developing new human-computer interface paradigms for neural signal control. This paper summarizes progress to date on the software aspects of the Neural Signals brain-computer interface project and presents a vision and strategy for upcoming research.

Keywords

Neural signals, brain-computer interfaces, accessible software.

INTRODUCTION

One of the most tragic circumstances that can befall a human being is a disease or injury that does not impair the mind, but renders the person completely paralyzed and unable to speak. The term *locked-in syndrome* describes 500,000 people worldwide who are prisoners in their own bodies, intelligent and alert but unable to communicate even their most basic needs [2]. Until recently, there were few options for this population but to live in perpetual frustration and isolation, with little or no expectation of regaining a productive and rewarding life.

Medical technology, however, is now providing hope for patients with locked-in syndrome. An electrode implanted directly into the human motor cortex intercepts brain signals which can then allow a locked-in patient to control a computer. Successful trials in rats and monkeys [7],[8],[10] led to the implantation of the first human (MH) in 1996 [6]. This patient demonstrated that she could generate and control her brain signals in a binary mode before her death from her underlying disease 76 days after implantation. Subsequently two more patients were implanted with the electrodes, one in spring 1998 (JR) and one in summer of 1999 (TT). The second patient, JR, has been successful in controlling a computer cursor with his brain signals, allowing him to communicate using a virtual keyboard and other software[6]. The third patient has begun the training process, and although due to frequent illnesses he has not yet used a computer he has demonstrated some neural signals that activate the electrodes.

Along with the medical issues of this research, we have begun studying the human-computer interface aspects of direct brain-computer interfaces. We have created and adapted software to implement device control, to provide communication, and to assist in training the patients to control a computer using brain signals [6]. In the course of this work it has become clear that there are important user interface issues inherent in direct brain-computer interfaces. This area is virtually unexplored and offers a rich opportunity for discovering and developing completely new paradigms for human-computer interaction. This paper presents the current status of the work and describes a vision and a concrete plan for pioneering work in this promising research area that hopefully will provide life-changing options for the severely disabled.

A NEUROTROPHIC ELECTRODE

The core medical technology is a stable electrode that is implanted into the motor cortex of the human brain. The electrode consists of a tiny hollow glass cone attached to two gold wires. The cone is treated with a *neurotrophic factor*, which encourages brain cells to grow into and through the cone, holding it in a stable position in the brain. The two gold wires are attached to a small amplifier and FM transmitter which emit the brain signals to a receiver external to the patient's scalp. A power induction system allows the electronics to be powered externally through the scalp, so there are no batteries and no wires external to the patient's head. Fig. 1 shows the configuration of the electrode and electronics.

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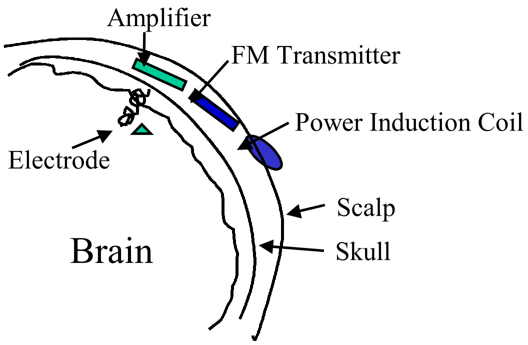


Fig. 1 - The Neurotrophic Electrode

Cursor Control

As the implanted electrodes intercept neural signals, each recorded waveshape is converted into a TTL pulse by a computer running a digital signal processor. The pulse outputs are routed to the patient's computer as a substitute for the "mouse" input, interpreted by a specialized device driver described below. The electrode is implanted in the left hand motor cortex area of the brain, so initially the patient "fires" the electrode by imagining movements of his left hand. This produces the signals that are intercepted by the electrode and sent to the patient's computer as pulses, which in turn move the cursor on the computer screen.

The rate of increase of firing determines the velocity at which the cursor moves over the screen. Two electrodes were implanted in each patient, one to control horizontal movement and one to control vertical movement (at least initially). Visual feedback in the form of cursor motion is presented on the patient's computer screen and auditory feedback is provided by a brief tone that is distinct for each pulse.

PATIENT TRAINING APPROACHES

A critical component of this research is the training process by which the patients learn to control the production of brain signals (and therefore control the computer cursor). Here we describe the variety of tools and techniques we employ to accomplish this training.

Software Support

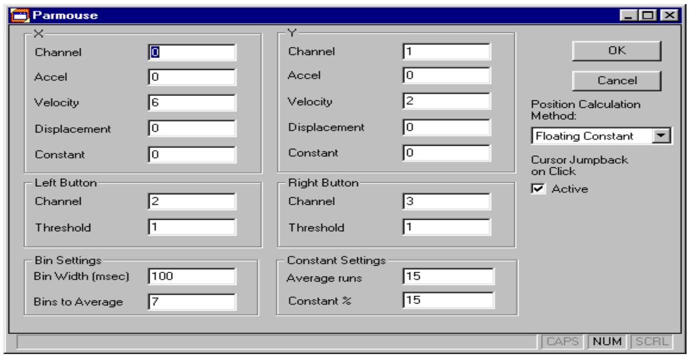
In the course of this research, we developed new software and customized off-the-shelf software components to support neural signal data acquisition and analysis, device control, communication, and training aids for the patients. This section outlines the software components used in the current neural signals system.

Data Acquisition and Analysis

Discovery - The Discovery package from DataWave Technologies [18] is a high performance data acquisition and experiment control package. We employ Discovery to acquire, display, and record data from the neural signals emanating from the implanted electrodes. The real-time cluster-cutting features allow us to discriminate and classify the spikes and write them to tape for later analysis. We customized the Discovery system to generate pulses based on the frequency of acquired neural signals in order to communicate with the device drivers on the patient's computer. The Discovery package also includes a playback module, which we employ to perform some of the data analysis from the recorded patient sessions.

Device Control

Parmouse - The Parmouse parallel mouse device driver [19] allows neural signals to drive a cursor on a computer screen. It emulates a mouse by translating the pulses received from the signal processing computer into cursor movements on the patient's screen. It contains a graphical user interface (shown in Fig. 2) that allows runtime parameters and mappings to be modified in order to tune the responsiveness of the interface.



X
Channel 0
Accel 0
Velocity 6
Displacement 0
Constant 0

Y
Channel 1
Accel 0
Velocity 2
Displacement 0
Constant 0

Left Button
Channel 2
Threshold 1

Right Button
Channel 3
Threshold 1

Bin Settings
Bin Width (msec) 100
Bins to Average 7

Constant Settings
Average runs 15
Constant % 15

Position Calculation Method: Floating Constant
Cursor Jumpback on Click
☑ Active

Fig. 2 - *Parmouse Graphical User Interface*

Communication and Training

TalkAssist - The TalkAssist program [22] was developed by Georgia Tech computer science students to assist nonverbal people in communicating. It contains a customizable database of icons that are associated with phrases, organized by common usage scenario categories. When the user selects an icon, TalkAssist produces the phrase via a voice synthesizer. The TalkAssist database was customized for our patient JR with phrases specific to his needs. Although TalkAssist was originally intended as a communication aid, we have also employed it in the training process by using the icons as navigation targets. An example of a TalkAssist screen is shown in Fig. 3.

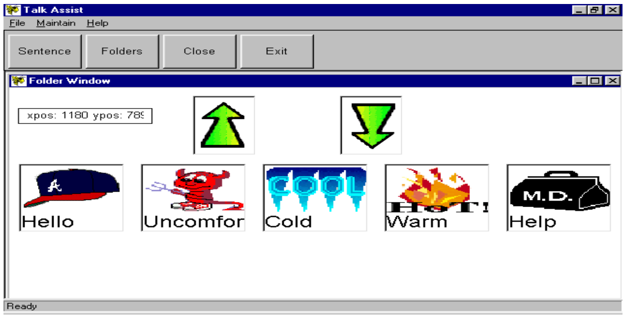


Fig. 3 - *TalkAssist*

WiViK - The Windows Visual Keyboard from Prentke-Romich [23] supports the creation and adaptation of graphical virtual keyboard emulators that allow a user to input keystrokes into any open application. Fig. 3 shows the customized keyboard we created for our patients containing letters in alphabetical order, a spacebar to separate words, a period to complete sentences, and a backspace key to erase mistakes. The parmouse driver was also adapted to force the cursor back to the top lefthand corner of the virtual keyboard any time a key is selected. This WiViK keyboard is used in conjunction with the WordPad, a simple word processor, and WiVox, a speech synthesizer that vocalizes words typed by the user when the space or period keys are selected.

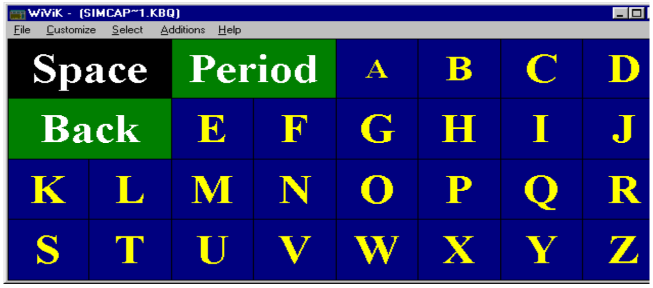


Fig. 3 - *WiViK customized keyboard*

Virtual Piano - Our patient JR began to lose his eyesight due to cataracts and other medical issues, making it difficult or impossible for him to see the computer screen. We experimented with various auditory representations for alphabetic keyboards, but they were too confusing for JR to use them. Because JR was a musician, we implemented a virtual piano in order to allow him to continue his neural-control training. The piano consists of four octaves in the key of C, each octave represented as a row of keys labeled with the note names. As the patient navigates horizontally across the screen, the C scale is played. As the patient navigates vertically down the screen, the same note is played an octave lower. The piano also includes a “target tone” capability that allows a researcher to select a tone that is played alternately with the tone representing the current position of the cursor. The patient’s task is to move the cursor until the two tones match in pitch. Fig. 4 shows the graphical representation of the virtual piano.

The virtual piano was used for trials in directionality, described in a later section.

Experimental Design and Results

We used the TalkAssist program, the WiViK virtual keyboard, and the Virtual Piano to train patient JR to control his brain signals. Initially we used the TalkAssist program, asking JR to move the cursor from the top left corner of the screen down to the row of icons, and then across the row of icons from left to right, pausing long enough on each icon to activate the auditory phrase associated with it. A second task was to select a particular icon within the row. Over time we observed improvement in accuracy indicating significant learning curves. The learning curve data is fully presented in [6], but Fig. 5 below summarizes average learning accuracy over a 3-day learning period (days 120, 121, 122 after implantation).

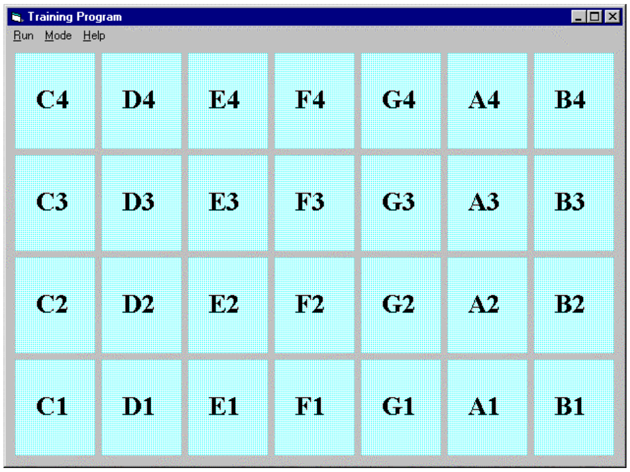


Fig. 4 - Virtual Piano

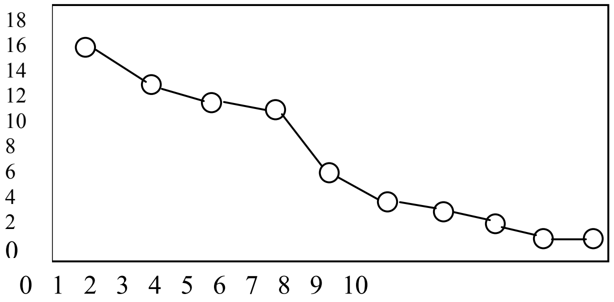


Fig. 5 - Average learning curve over days 120,121,122

The task was to move the cursor from the top left corner of the screen and drive it horizontally and vertically to enter the fourth icon in the TalkAssist panel. A high score indicates poor performance and a low score indicates a rapid descent to the target. Fig. 5 shows the performance on the vertical scale and the trial number on the horizontal scale. During each session, JR’s performance continued to improve through the first ten trials. Performance continued to be consistent until he was tired or toxic, at which time his performance worsened.

We also used the WiViK keyboard in subsequent trials, asking JR to spell his name ("JOHN"). We measured his accuracy (described in [6]) and saw improvement over time (again, performance degrading when tired). Gradually he began to spell other words and eventually we conducted conversations with JR as he became more proficient at using the virtual keyboard. His spelling rate is approximately 3 letters per minute.

When JR’s eyesight began to fail, we used the virtual piano, described in the “Directionality” section below.

EMERGENCE OF CURSOR CORTEX

As previously stated, initially the patient “fires” the electrode by imagining movements of his left hand. JR discovered that over time, the impetus for driving the cursor migrated to different parts of his body, such as his neck and eyebrow (which have slight residual motion). We encouraged him to disassociate the movement of his eyebrow from the movement of the cursor by placing an EMG switch on his eyebrow that would move the cursor down the screen. He was then tasked with driving the cursor horizontally across the screen to activate an entire row of icons without driving the cursor down. Fig. 6 shows the improvement in performance over time, the vertical axis denoting the number of seconds to complete the task and the horizontal axis denoting trial number. The time to perform the task decreased after the first few trials and then remained fairly constant until he became tired. Eventually we could not discern that he was moving any part of his body to drive the cursor, and when we asked him what he was thinking of to drive the cursor, he spelled out “NOTHING.”

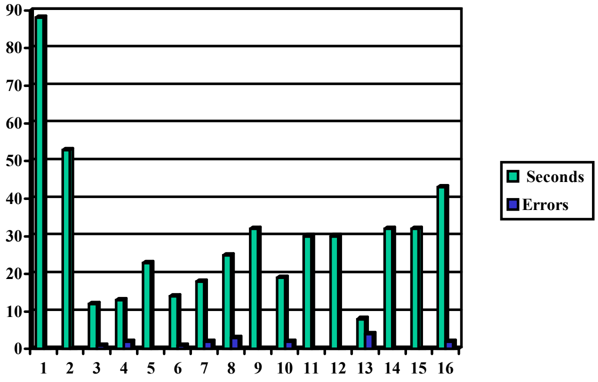


Fig. 6 - Emergence of Cursor Cortex

Recent results are suggesting that he can dissociate muscle activity from neural activity, and that when activating neural signals he is thinking only of driving the cursor. If this is borne out by further studies of performance and the underlying neural correlates, it implies that plastic changes can be induced in the underlying cortex. In other words, the patient may develop cortex devoted to controlling the cursor. We have expectantly named this phenomenon “cursor cortex.”

DIRECTIONALITY

During the analysis of JR’s recorded brain signal data from the patient trials, we observed a difference in the waveshapes produced from a single electrode when he was navigating the cursor horizontally versus vertically. We also observed that phase relationships between the spikes also changed when the direction of the cursor changed, indicating that there may be interpretable patterns in the brain signal recordings. Recognizing these patterns could possibly allow JR to “think” the direction of the cursor, navigating in two dimensions with a single electrode.

We cluster-cut the signals to separate them into “up” signals (signal peak above a certain threshold) and “down” signals (signal peak below a certain threshold). We then mapped the “up” signals to horizontal cursor movement and the “down” signals to vertical cursor movement. Using the virtual piano, we then asked JR to try to move the cursor in a straight line either horizontally or vertically to measure his control over the direction of the cursor. We also took baseline recordings to measure the random movement of the cursor. Initial results showed that JR’s control of the direction of the cursor is better than baseline recordings, at least until he becomes tired. Fig. 7 shows the data from three trials, each consisting of six to ten attempts to move the cursor vertically after the cursor was placed in the upper left hand corner of the screen. Error rates are calculated by observing the point at which he exited the screen at the bottom and assigning a number indicating how far the cursor was away from the vertical. For example, if he exited in a straight line, at the note “C1,” he would receive a score of zero (zero errors). Exiting at the note “E1” would receive a score of two. For the first two trials, JR was able to achieve a better error rate than the baseline recordings. On the third trial he was tired and achieved an error rate identical to baseline readings, indicating sense of effort was maximal (5/5).

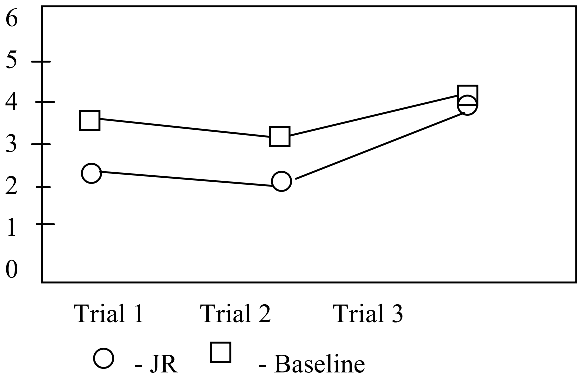


Fig. 7 - Directionality Trials: Error Rates

We are currently performing a more in-depth analysis of the directionality phenomenon, but these preliminary data indicate that JR can influence the direction of the cursor by changing patterns in his neural signals.

A RESEARCH AGENDA

Our initial results are very encouraging and open a myriad of possibilities and applications for direct brain-computer interfaces. In the near future, we will focus on five major areas:

- Signal understanding
- Patient Training
- Navigation paradigms
- Control of neural prosthetics
- Communication

Signal Understanding

The initial results from the directionality studies indicate that understanding the neural signals and their relationships is critical to improving brain-computer interface technology.

Signal Mappings

We are currently experimenting with different mappings of signal-to-pulse ratios by performing real-time analysis of neural signal ratios. We have implemented techniques such as a software "gyroscope" that may help increase accuracy and speed of cursor navigation.

Signal Patterns

Another very significant issue is the phase relationship patterns of the neural signals. Ideally, if we can differentiate these patterns we may be able to provide an arbitrary number of signals that could be mapped to various tasks. For example, if a patient was implanted with ten electrodes and we can differentiate 26 different signal patterns, then the patient does not need a virtual keyboard; he could simply "think" the letter and it would appear.

Training

Patients with neural electrode implants must learn to generate and control the brain signals that allow them to operate a computer. As described above, we employed iconic communication software and a virtual keyboard to train patients to control neural signals. However, these tools were not designed for this purpose and therefore contain inadequacies as training vehicles. For example, there is no way to adjust for level of difficulty, little reinforcement of success, and no automated capture of training data. We will study ways of improving the training and acclimation process by developing software customized for training patients to control neural signals with precision and accuracy.

Support for Patient Training

A customized neural signal training package called Research Implant Training Software [21] has been prototyped by Georgia Tech students, consisting of a series of games designed to give patients practice targeting particular areas or icons on the screen. Next we will augment it to include a series of gradually more difficult exercises in starting and stopping the neural signals to target and select icons. RITS will also include support for conditioning, providing sensory feedback including auditory feedback such as a rising intermittent tone when nearing a target, visual feedback such as icons flashing when they are selected, and cognitive feedback such as a visible score for each trial. RITS will also provide the capability of introducing different motivators and reinforcers, such as auditory or visual cues when success is achieved.

New Navigation Paradigms

The signals produced from neural fire individually with varying rates controlled by the patient. They cannot be started and stopped instantaneously, but usually build to a peak and then dissipate. In our current system, the device drivers move the cursor only when increasing neural activity is detected. If neural activity is decreasing or remains the same, the cursor does not move. Hence we have termed this interaction technique *hysteretic*, because it depends on frequency of activity over time. We are currently researching ways of improving the speed, accuracy, and precision of hysteretic user interfaces. We will evaluate hysteretic user interfaces by implementing applications in two important areas: environmental control and Internet access.

"Nudge and Shove" Interfaces

Patient trials have revealed that the most effective way of controlling cursor motion with neural signals is to generate brain signals to create a series of "nudges" (for small distances) or "shoves" (for larger distances). Traditional interfaces that require a user to accurately target an icon and click within its borders can be a challenge because stopping the signals once they have peaked is difficult. Therefore, we propose to incorporate simulations of kinetic forces such as gravity, acceleration, and friction to improve targeting and selection accuracy of a "nudge and shove" user interface paradigm. We will also experiment with paradigms that enhance navigation of graphical user interfaces such as implemented in the *Mercator* [15] system. Although Mercator was designed to assist blind users, its provisions for hierarchically navigating windows, icons, and text reduces the precision and motion required a graphical user interface and may enhance neural signal control.

Intelligent Adaptation

Another observation from patient trials is that the firing rate of neural signals can be affected by the patient's state of health, tiredness, or pain medications. Many factors can affect the frequency of the signals, requiring adjustment of brain signal-to-cursor motion ratios in order for the patient to retain control of the cursor. In our previous work, we adapted the sensitivity of the signal-to-cursor-motion ratios manually, requiring interruption of the training session while a researcher adjusted software parameters. We are developing and experimenting with intelligent adaptive controls that evaluate signal occurrence over time and dynamically change threshold levels to adjust to changing trends in signal frequency. The goal is to gain finer control of the cursor to enable the patients to use virtually any application, even when tired or ill. We plan to evaluate the efficacy of the automated controls by measuring reductions in cognitive effort load as defined by Baker [1].

Control of Neural Prosthetics

Another promising area for neural signal control is to study whether brain signals can be used to control Functional Electrical Stimulation (FES), possibly restoring motion to paralyzed limbs. Initially we plan to implement a virtual arm, a simulation of a human arm implanted with FES stimulators, to see if our neural implant patients can "move" the arm with neural signals. The virtual arm could later be used as a training or evaluation device for patients who are considering FES implants.

Communication

Patients with locked-in syndrome cannot speak and have little or no movement, making communication difficult or impossible. Our first two patients could blink their eyes, once for “no” and twice for “yes.” Our second patient can spell by closing his eyes while the letters of the alphabet are recited, and opening his eyes when the desired letter is reached. Our third patient cannot blink, but can move his eyes enough to use a letter chart by looking at the desired letter while an assistant tries to guess the letter. These methods are very slow and tedious and are extremely error-prone. We hope to substantially improve the communication rate for locked-in patients using neural signals and assistive interface technology.

Our patients have successfully communicated via a standard alphabetic virtual keyboard [23] and an iconic phrase application [22]. We propose to experiment further with different types of alternative communication of increasing levels of abstraction to assess their efficacy and controllability with neural signals.

Virtual Keyboards

Our patients have used a traditional, row-and-column layout virtual keyboard, which is navigated by moving the cursor across the columns and down the rows to select the desired letter. This requires at least two distinct neural signals, one to drive the cursor across and one to drive it down. A third signal can be used to select the letter, or a timed dwell interval can automatically select the letter. It is possible that other arrangements of keyboards, such as a linear layout with all the letters on a single row, or a binary-search arrangement such as described in [11], may increase the speed with which the patient can spell words because of the properties of hysteretic user interfaces. We propose to implement several virtual keyboard strategies and compare them for speed and accuracy when controlled by neural signals.

Our patient’s current spelling rate with the traditional layout keyboard is three letters per minute. This is very slow compared to spoken communication, which generally runs at up to 120 words per minute (wpm). Word prediction, although highly ambiguous, has been shown to speed input up to as much as 10 wpm [12]. It is possible that by exploring interface issues relating to ambiguity this could be further increased. In addition, in settings such as internet browsing, where there are fewer possible interpretations of the user’s input (the past history of URLs, for example), word prediction can be even more helpful. We plan to incorporate word prediction strategies such as described in [12] in order to enhance communication speed for neural implant patients.

Codes

Another form of spelling words is to use a code such as Morse Code. It is possible that two distinct neural signals could be used as the “dot” and “dash,” or one signal could be used with short and long bursts of neural activity. However, this limitation to binary interpretations of the signals is not the most effective use of the richness of the neural signals and will not be the focus of our study.

Phonemes and symbol sets

One method of speeding communication is to reduce the number of “keystrokes” required to indicate a word or concept. We plan to assess the possibility of composing phrases with sets of phonemes or symbols such as shorthand. Phonemes have been used as output for hearing assistance [16], using a phoneme symbol layout which could be adapted for phoneme input from neural signals.

Iconic languages

At the highest level of abstraction, iconic languages such as *Minspeak* [20] allow basic concepts, represented by icons, to be combined to create more expressive concepts. The semantic compaction of Minspeak could be a powerful tool for locked-in patients if the icons can be selected efficiently using neural signals. We propose to experiment with ways of organizing icons into a usage hierarchy, categorized by situations (such as turning on radio or TV, or expressing pain in body parts) in order to ease navigation of the icon set.

Direct Mapping of Neural Signal Patterns

As described above, we have seen preliminary evidence that multiple signals can emanate from a single electrode, and that these signals occur in identifiable temporal relationships. The implications of being able to intercept multiple signals and signal patterns from a single electrode opens myriad possibilities for user interfaces. Reaching beyond the two-dimensional screen navigation paradigm, it is possible that with increased numbers of implanted electrodes, signal patterns could be directly mapped to concepts such as letters of the alphabet. This direct-mapping concept, if validated, could eventually extend to other communication methods such as phonemes or iconic languages such as *Minspeak* [20].

We propose to lay the groundwork for signal differentiation by augmenting the Discovery System [18] with customized clock sequence programs to implement differentiation of acquired signals and temporal pattern matching. The aim is to demonstrate that multiple signals from a single electrode can be used to control a cursor in multiple directions (such as vertical and horizontal, or right and left), providing greater control for the user.

CONCLUSIONS

In the report *More than Screen Deep*: *Toward Every-Citizen Interfaces to the Nation’s Information Infrastructure*[4], a steering committee of human-computer interface experts propose a research agenda which includes direct thought control of computers. For the half-million people with locked-in syndrome and for many others with severe disabilities such as quadriplegia, the impacts and implications of researching and improving neural implant technology are extremely significant. The initial task of controlling a computer with thought can restore the ability to communicate and the ability to alter the environment for health and comfort. Access to the internet can provide global communication, education and recreation, and possibly opportunities for a locked-in patient to become self-supporting via investments or even employment. Further research in direct brain-computer interfaces could lead to thought control of prosthetics or muscle stimulators that could restore movement in paralyzed limbs. The initial successful results and discoveries from prior research in direct brain-computer interfaces encourage vigorous pursuit of refinements and improvements in this technology.

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