Controlling Computers with Neural Signals

Electrical impulses from nerves and muscles can command computers directly, a method that aids people with physical disabilities

by Hugh S. Lusted and R. Benjamin Knapp

In the classic science-fiction movie *Forbidden Planet,* space travelers from Earth land on a distant world, where they encounter the remnants of a technologically advanced civilization. Remarkably, the human visitors are able to communicate with one of the alien computers that is still functioning. Connected through glowing head probes, the men's thoughts and feelings are directly conveyed to the machine over a neural link.

Many similar examples of people having their minds coupled to computers have appeared in other works of fiction. As often depicted, a person simply thinks of a command, and the computer immediately responds—a scheme analogous to the computer voice recognition in use today. Thought recognition would be the ultimate computer interface, the machine acting as an extension of the human nervous system itself.

Computer technology has advanced markedly in the 40 years since *Forbidden Planet* was released, but constructing a versatile neural junction between a human brain and an electronic one remains a formidable challenge. Attempts to tie the nervous system to external electronic circuits are, however, well worth pursuing because the results may provide the means for effortless communication with computers. This work is already extremely valuable to people with devastating neuromuscular handicaps—a group usually without access to computers or indeed much opportunity to influence the world.

Our work over the past decade has helped make such "hands free" control of computers a reality. Neural linkages with computers can now satisfy a variety of needs, and we expect that enterprising people will soon find additional ways to harness this technique. A view of what the future holds in store requires only some imagination—and a clear understanding of how past work has led to today's accomplishments.

The Body Electric

The electrical nature of the human nervous system—the basis for direct neural control of computers—has been recognized for more than a century. In 1849 the German physiologist Emil Heinrich Du Bois-Reymond first reported the detection of minute electrical discharges created by the contraction of the muscles in his arms. He made these observations using a primitive device for measuring voltages called a galvanometer. Du Bois-Reymond attached the wires of this instrument to his body using pieces of saline-soaked blotting paper to keep electrical resistance in the connection to a minimum. But he soon realized that the skin acted as a barrier to the underlying muscle signals. So this dedicated researcher induced a blister on each arm, removed the skin and placed the paper electrodes within the wounds. Du Bois-Reymond was then able to capture electrical signals that were about 30 times stronger than those he could obtain with the skin intact.

These early investigations built the foundation for a technique that serves well today to monitor muscle contractions. With modern silver chloride electrodes and sensitive electronic amplifiers, tiny muscle impulses—even those muted by passage through the skin—provide easily registered voltages. Medical researchers first exploited this phenomenon during the 1970s to devise mechanized prostheses that could operate by sensing muscle contractions. Other scientists realized that electrical impulses from active muscle fibers could also help people who suffered from diseases or injuries that left them too weak to move any of their limbs: they needed only to have electrodes placed near unimpaired muscles. Following that strategy, even profoundly handicapped individuals can

STEPHEN FERRY

SELECTION FROM A MENU on a personal computer usually requires manipulation of a keyboard or mouse. Yet physically handicapped people, using their body's electrical signals, can also command a computer. For example, Heather Black has severe cerebral palsy, but she can operate a computer by fixing her gaze on one of many flashing squares on the screen. Electrodes on the back of her head pick up the signals evoked by the flashes, and the timing of these impulses identifies her choice.

manipulate electronic equipment with the electrical signal from muscles (called an electromyographic signal, or EMG, a name borrowed from the term for a paper tracing of such impulses).

But one cannot simply attach EMG sensors to a person's skin and plug the wires into the back of a conventional computer. The task requires specialized circuits and software to analyze and interpret the pattern of muscle impulses. To aid others involved in these efforts, we have designed equipment to serve as a general-purpose interface between a computer and the body's various electrical signals. We dubbed our creation the Biomuse.

The work of translating muscle impulses to a form more appropriate for a digital computer begins with the amplification of the raw signals sensed by the electrodes, which increases these voltages by a factor of about 10,000. Other circuits then convert the amplified EMG signals to digital form. After much additional processing of these digitized measurements, a computer can determine when muscle fibers near the electrodes are contracting and by how much. In this way, the muscle activity can direct the operation of a personal computer—just as one might employ a computer mouse or trackball.

Some arrangements to control computers using muscle signals have proved particularly valuable to handicapped people. For instance, in 1993 David J. Warner, a neuroscientist at Loma Linda University Medical Center in California, connected the electrodes from our EMG apparatus to the face of a 10-year-old boy who had been completely paralyzed below the neck in an automobile accident. By tensing certain facial muscles, the young patient could move objects

STEPHEN FERRY

ARM MUSCLES of a woman with cerebral palsy, Dawn Parkot (*foreground*), generate electrical signals that a computer can sense. Electrodes underneath the black band on her left arm pick up tiny voltage fluctuations that change when groups of muscle fibers begin contracting. With the computer displaying these biological signals, this engineering graduate student at the University of Notre Dame learns to vary muscle activity in her forearm from low (*left*) to high (*right*).

on the computer screen—the first time since his injury that the child could manipulate a part of his environment without aid.

But people do not have to be physically impaired to benefit from the ability of muscle signals to control a computer. We are, for example, now experimenting with a hands-free EMG mouse. With it, a person can adjust the position of a cursor on the screen using, for example, forearm muscles. Such a device allows someone to move the cursor without having to lift a hand from the keyboard.

Unrecognized Potential

Another approach to controlling computers with biological signals depends on a completely different electrical phenomenon of the human body: the corneal-retinal potential. This signal arises because the retina, the site of most metabolic activity within the eye, exhibits a slight negative voltage compared with the cornea. In a sense, the eye acts as a weak electric battery. Electronic circuits can detect the tiny voltage fluctuations on a person's face that arise when the eyes shift in orientation. These impulses are called an electrooculographic signal, or EOG (the name for recordings made of them).

Measurement of EOG signals has served researchers for decades as a convenient indicator of eye movement in various physiological studies. In 1953, for example, Nathaniel Kleitman of the University of Chicago and Eugene Aserinsky of Jefferson Medical College in Philadelphia used EOG recordings to document eye movement during certain periods of sleep. These particular intervals were accompanied by intense brain activity similar to that of the awake state, and so the investigators distinguished this curious type of slumber by calling it rapid-eye-movement, or REM, sleep.

Although investigators had previously used the EOG merely to record the overall motion of the eyes, by the late 1980s it seemed feasible that measurements of the corneal-retinal potential could also indicate the direction of a person's gaze. With the proper arrangement of electrodes, EOG voltages will vary proportionally with eye rotations over a range of about 30 degrees from center. By 1990 several research groups had reported some success in using this method to move a computer cursor. Still, skeptics continued to believe that electrical "noise" in the form of gradual changes in the voltage across the electrodes ("electrode drift") would render this approach unworkable for anything other than a laboratory demonstration.

Our efforts did, however, uncover a way to eliminate the interference and construct a practical device for controlling computers. To accomplish that result, we employed the same system we had used for detecting muscle signals but this time configured the apparatus as an EOG monitor. As with EMG processing, the EOG analyzer begins by amplifying and digitizing the voltages obtained from several electrodes (one pair of electrodes serves to detect vertical eye displacements; another set indicates horizontal eye movements). The system then applies so-called fuzzy logic to discriminate between true eye movement and electrode drift [see "Fuzzy Logic," by Bart Kosko and Satoru Isaka; SCIENTIFIC AMERICAN, July 1993].

With this equipment, a person can reliably operate a computer with eye movements—for instance, by positioning the cursor at various points on the screen. There are other techniques for tracking a person's gaze that utilize infrared beams or video cameras. But EOG equipment proves much less costly than alternative strategies, making it possible for more people to consider using eye motion to operate computers—in particular, as an aid for the disabled.

At Loma Linda in 1991, Warner tried our eye-tracking system to help a youngster who had sustained a serious injury to her spinal cord as an infant. Because of her age at the time of her accident, the doctors at the center were concerned that the girl's physical restrictions would compromise the development of her brain. Fitted with a special EOG headband and placed in front of a video monitor, the 18-month-old girl quickly discovered that she could move an icon (a smiling face) about the screen with just her eyes. She understood intuitively how to control the display without having been told how the system worked.

Other institutions dedicated to the rehabilitation of paralysis victims have used similar equipment in conjunction with "visual keyboard" software that displays a standard typewriter keyboard. Using eye movements alone, an operator can select letters from the keys presented on the screen. Although the process of forming words in this way is slow, with practice (and some clever software aids) people can complete multiple sentences, even whole documents, by a continuous succession of glances.

Tracking a person's gaze with EOG signals can be done so reliably that a number of groups are also attempting to integrate this mechanism in other settings. For instance, we have collaborated with physicians from Stanford University to develop a way to adjust the fiber-optic cameras used during endoscopic surgery (procedures performed remotely, inside the body). Our EOG device allows a doctor to change the camera's view with eye movements, while his or her hands are engaged in manipulating other surgical instruments.

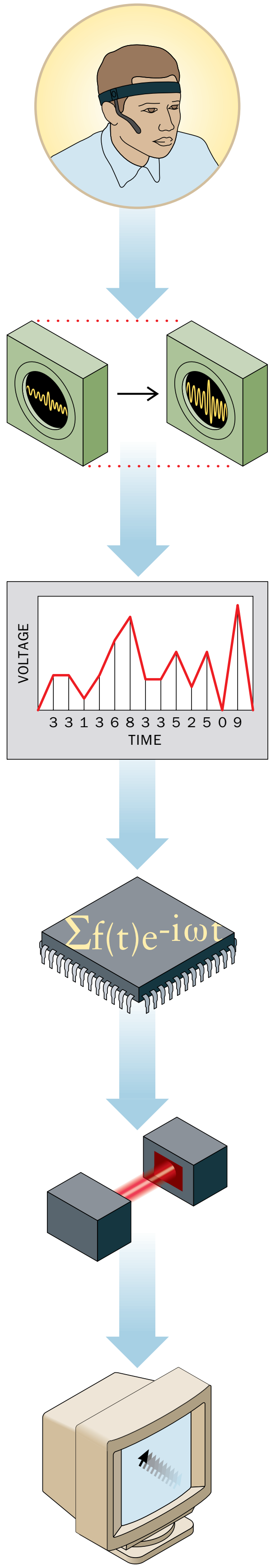
Mind Control

Devices that detect EMG or EOG signals have successfully linked humans to computers for a wide variety of applications, but in each case the process relies on tiny biological voltages from muscles or eyes. Is it possible to make a neural connection without those intermediaries? Indeed, some people have operated computers in a rudimentary fashion using the underlying electrical activity of the brain itself.

That the human mind produces measurable electrical signals is no surprise. In 1929 the German psychiatrist Hans Berger coined the term "electroencephalogram," commonly known as EEG, to describe recordings of voltage fluctuations of the brain that can be detected using electrodes attached to the scalp. These EEG signals arise from the cerebral cortex, a several-centimeter-thick layer of highly convoluted neuronal tissue. Neurophysiologists believe that the pyramidal cells of the cerebral cortex are the source of EEG voltages. Each of these nerve cells constitutes a tiny current dipole, with a polarity that depends on whether the net input to the cell is inhibitory or excitatory. Hence, the layer of densely packed pyramidal cells in the brain produces a constantly shifting configuration of electrical activity as the nerve impulses change. Measurements on the scalp can detect the underlying electrical patterns, albeit in a form that is attenuated and unfocused by passage through the skull.

For decades, researchers have sought to correlate various EEG signals with particular behaviors or sensations, and the results of these studies have slowly

Components of the Biomuse System



JARED SCHNEIDMAN DESIGN

USER
A person using the system to translate biological impulses into commands for an ordinary computer must wear a specially designed headband or armband. Within the band are several electrodes that can detect electrical signals that emanate from eyes or muscles and pass through the skin.

AMPLIFIER
The tiny signals detected by the electrodes first need to be amplified so that they are many thousands of times stronger. The chief technical difficulty is that small amounts of electrical noise can easily become amplified as well—unless certain precautions are taken. One common strategy is to use a so-called differential amplifier, a device that amplifies only the difference in voltage between two points. This tactic works because most sources of electrical noise tend to affect all signals equally. Hence, the difference in electrode voltages will remain uncontaminated.

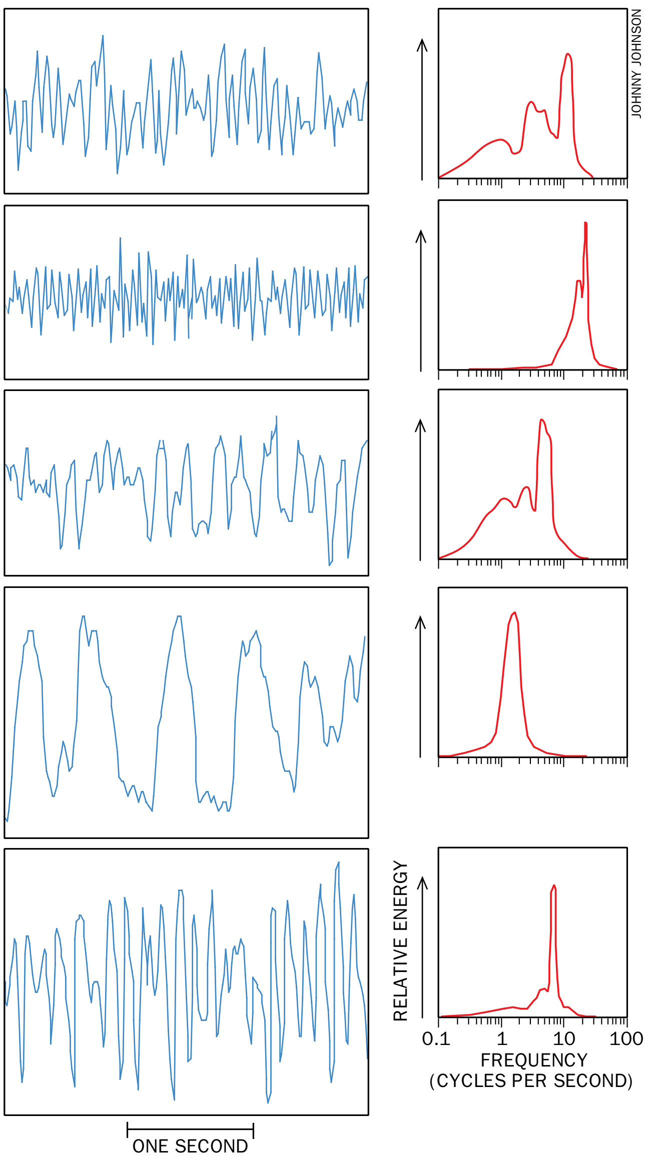
ANALOG-TO-DIGITAL CONVERTER
The amplified voltages need to be translated to a form that a computer can understand. To accomplish this task, a specialized circuit called an analog-to-digital converter repeatedly samples the incoming signal—doing so as rapidly as 4,000 times a second. This circuitry then converts the voltage levels to a series of numbers. The precision of this conversion is such that the error introduced by translation to digital form is limited to a small fraction of a percent of typical signal levels.

DIGITAL-SIGNAL PROCESSOR
The digital-signal processor is a computer "chip" that is similar in many ways to the integrated circuits that serve as central processing units in personal computers. A digital-signal processor is, however, designed to perform certain numerical calculations swiftly and efficiently. In this system it acts to extract important features in the sequence of numbers it receives from the analog-to-digital converter and to recognize particular patterns in this data stream. Then, using these results, it recognizes which muscles generated the original electrical signals.

OPTICAL ISOLATION
Because electric shock can occur whenever electrodes on the skin are connected to a high-voltage appliance (in this case, a computer), precautions have to be taken to avoid injury. In this system the electrical signal is interrupted at one point and transformed to an optical signal that is transmitted over a short distance. By breaking the electrical path with an optical link, the signal can pass unimpeded, but the possibility of electric shock is greatly reduced.

PERSONAL COMPUTER
A personal computer displays the signals detected and processed by the other components of the system. Depending on the electrical signals generated initially by eye movements or muscle contractions, the computer can operate another computer or a separate electronic device. The computer also allows easy adjustment of the system's controls, including the overall level of amplification and the specific actions of the digital-signal processor.

A Sampling of Brain Waves



ALPHA WAVES, brought on by unfocusing one's attention, have relatively large amplitude and moderate frequencies.

BETA WAVES, the result of heightened mental activity, typically show rapid oscillations with small amplitudes.

THETA WAVES, which can accompany feelings of emotional stress, are characterized by moderately low frequencies.

DELTA WAVES result from an extremely low frequency oscillation that occurs during periods of deep sleep.

MU WAVES, which resemble croquet wickets in shape, are associated with physical movements or the intention to move.

outlined a functional map of the human cerebral cortex. Scientists can now tailor their EEG experiments by placing electrodes on one part of the scalp, directly over the source of activity they desire to monitor. In order to use this electrical activity to operate a computer, some workers have attempted to isolate specific EEG signals that people can adjust at will. Unfortunately, the electrical output of the brain is not easily controlled. A common strategy calls for measuring a variety of EEG signals continuously and filtering out the unwanted components.

The analysis of continuous EEG signals, or brain waves, is something of a science in itself, complete with its own set of perplexing nomenclature. Different waves, like so many radio stations, are categorized by the frequency of their emanations or, in some cases, by the shape of their waveforms. Five types are particularly important.

Alpha waves (those in the frequency band between eight and 13 hertz) can be brought on easily by actions as simple as closing one's eyes; these waves are usually quite strong, but they diminish in amplitude when a person is stimulated by light, concentrates on vivid imagery or attempts other mental efforts. Beta waves (typically from 14 to 30 hertz) are associated with an alert state of mind and can reach frequencies near 50 hertz during intense mental activity. Theta waves (four to seven hertz) arise from emotional stress, especially frustration or disappointment. Delta waves (below 3.5 hertz) occur during deep sleep. Mu waves (also known as the wicket rhythm because the rounded EEG traces resemble the wickets used in the lawn game croquet) appear to be associated with the motor cortex: they diminish with movement or the intention to move.

Most attempts to control a computer with continuous EEG measurements work by monitoring alpha or mu waves, because people can learn to change the amplitude of these two rhythms by making the appropriate mental effort. A person might accomplish this result, for instance, by recalling some strongly stimulating image or by raising his or her level of attention.

Over the past decade Jonathan R. Wolpaw and Dennis J. MacFarland of the New York State Department of Health Wadsworth Center in Albany have taught patients to control the amplitude of their mu waves by visualizing various motor activities, such as smiling, chewing or swallowing. With enough practice, the trainees could learn to manipulate a computer cursor that was programmed to shift with changes in the amplitude of the measured mu waves.

We have also experimented with brain waves. In 1987 we first configured one of our Biomuse devices to act as an EEG monitor and set it to adjust a music synthesizer. That exercise provided a dramatic demonstration of the power of this technique. We arranged the system to detect bursts of alpha-wave activity, which can be brought on at will, for example, by unfocusing one's attention. Such equipment constitutes a brain-activated electronic switch, a device that even a person with severe physical disabilities can trigger.

For example, we have developed similar equipment for a Brazilian patient immobilized with advanced amyotrophic lateral sclerosis (also known as Lou Gehrig's disease). To type words, he employs our alpha-wave switch and a personal computer using special visual keyboard software. It is a laborious process because he can make only yes or no responses and must go through as many as six iterations before he can narrow the search to a single key. Still, he now has an electronic aid that allows him to communicate, a vital ability that had previously been completely lost to him.

Other handicapped people have benefited from a second type of brain-wave-measuring apparatus, one that monitors what is called the evoked potential, or EP, action of the brain. The EP signal arises in response to certain stimuli—such as a loud noise or a flash of light—a tiny fraction of a second after it is provoked. The method of EP detection has been used by a number of researchers for controlling computers with the brain's electrical activity. In particular, Erich E. Sutter of the Smith-Kettlewell Eye Research Institute in San Francisco has developed a system that allows physically handicapped people to select words or phrases from a menu of flashing squares on a computer monitor. By keeping a gaze fixed on the appropriate square for a second or two, a person wired with scalp electrodes can convey a choice to the computer. The machine monitors the form and timing of the EP response and so can discriminate which of the coded flashes caused the evoked electrical activity in the brain. The computer can then pick out the one item chosen from the group of words or phrases presented on the screen.

Like Sutter, Grant McMillan and his colleagues at the Alternative Control Technology Laboratory of Wright-Patterson Air Force Base in Dayton, Ohio, are similarly experimenting with EP signals. They hope to help military pilots by teaching them how to modify the magnitude of EP signals at will. This mechanism provides a coarse auxiliary control—one that pilots can operate even when their hands and feet are busy flying the airplane.

Future Shocks

Although it is clear that an immense amount of electrical activity accompanies the thought processes of the human brain, researchers can recognize only a few of these underlying patterns from voltage fluctuations on a person's scalp. There has been little success, for example, in pinpointing which particular set of brain waves will consistently arise when a person thinks of something as specific as a single word or letter of the alphabet. But more advanced systems for unraveling complex brain waves might yet succeed in accomplishing this feat.

The prospects for controlling computers through neural signals are indeed difficult to judge because the field of research is still in its infancy. Much progress has been made in taking advantage of the power of personal computers to perform the rapid-fire operations needed to recognize patterns in biological impulses, and the search continues for new signals that may be even more useful than those tapped so far. Newly developed software is also just now being distributed that can use the existing speed and sophistication of modern computer hardware most effectively.

If the advances of the next century match the strides of the past few decades, direct neural communication between humans and computers may ultimately mature and find widespread use. Perhaps newly purchased computers will one day arrive with biological signal sensors and thought-recognition software built in, just as keyboard and mouse are commonly found on today's units. If so, computer buffs of the 21st century may be surprised to find that this method of directing their machines had first been developed in the 1990s through the efforts of a handful of academic researchers and a determined group of physically handicapped pioneers. SA

STEVE MUREZ *Black Star*

MUSICAL COMPOSITIONS that depend only on muscle signals have been performed by Atau Tanaka. The signals sensed by electrodes within the composer's two armbands operate a computer that in turn controls various electronic instruments.

The Authors

HUGH S. LUSTED and R. BENJAMIN KNAPP have worked together for a decade. Lusted received a doctoral degree from the Stanford University School of Medicine in 1980 before spending a year studying nerve regeneration at the University of London. He then returned to Stanford to help develop an electronic cochlear implant—a device he and his colleagues casually referred to as a "bionic ear." It was during this time that he met Knapp, who had come to Stanford after completing a bachelor's degree in electrical engineering at North Carolina State University. In 1989 Knapp earned his doctorate in electrical engineering at Stanford, and he now serves on the faculty at San Jose State University. Lusted and Knapp founded Biocontrol Systems in 1989. They each have an interest in music (particularly, electronically generated forms), and both maintain affiliations with the Center for Computer Research in Music and Acoustics at Stanford.

Further Reading

An EEG-Based Brain-Computer Interface for Cursor Control. J. R. Wolpaw, D. J. McFarland, G. W. Neat and C. A. Forneris in *Electroencephalography and Clinical Neurophysiology*, Vol. 78, No. 3, pages 252–259; March 1991.

Biocontrollers for the Physically Disabled: A Direct Link from Nervous System to Computer. R. B. Knapp and H. S. Lusted in *Virtual Reality and Persons with Disabilities: Proceedings*. Edited by H. J. Murphy. California State University, 1992.

Communication Technology for Disabled Persons. Erich E. Sutter in *Handbook of Amyotrophic Lateral Sclerosis*. Edited by Richard Alan Smith. Marcel Dekker, 1992.

Medical Instrumentation, Application and Design. Edited by John G. Webster. Houghton Mifflin, 1992.

