CONTENTS

Introduction

brain computer interface

A brain–computer interface (BCI), sometimes called a direct neural interface or a brain–machine interface, is a direct communication pathway between a brain and an external device. BCIs were aimed at assisting, augmenting or repairing human cognitive or sensory-motor functions.

Research on BCIs began in the 1970s at the University of California Los Angeles (UCLA) under a grant from the National Science Foundation followed by a contract from DARPA.[1][2] These papers also mark the first appearance of the expression *brain–computer interface* in the scientific literature.

The field has since blossomed spectacularly, mostly toward neuroprosthetics applications that aim at restoring damaged hearing, sight and movement. Thanks to the remarkable cortical plasticity of the brain, signals from implanted prostheses can, after adaptation, be handled by the brain like natural sensor or effector channels.[3] Following years of animal experimentation, the first neuroprosthetic devices implanted in humans appeared in the mid-nineties.

Neuroprosthetics is an area of neuroscience concerned with neural prostheses—using artificial devices to replace the function of impaired nervous systems or sensory organs. The most widely used neuroprosthetic device is the cochlear implant, which was implanted in approximately 100,000 people worldwide as of 2006.[4] There are also several neuroprosthetic devices that aim to restore vision, including retinal implants.

The differences between BCIs and neuroprosthetics are mostly in the ways the terms are used: neuroprosthetics typically connect the nervous system to a device, whereas BCIs usually connect the brain (or nervous system) with a computer system. Practical neuroprosthetics can be linked to any part of the nervous system—for example, peripheral nerves—while the term "BCI" usually designates a narrower class of systems which interface with the central nervous system.

The terms are sometimes used interchangeably, and for good reason. Neuroprosthetics and BCIs seek to achieve the same aims, such as restoring sight, hearing, movement, ability to communicate, and even cognitive function. Both use similar experimental methods and surgical techniques.

Types of Brain Computer Interface

Invasive Brain Computer Interfaces

Invasive Brain Computer Interface Devices are those implanted directly into the brain and has the highest quality signals. These devices are used to provide functionality to paralyzed people. Invasive BCIs can also be used to restore vision by connecting the brain with external cameras and to restore the use of limbs by using brain controlled robotic arms and legs.

The problem with this type of device though, is that scar tissue forms over the device as a reaction to the foreign matter. This reduces its efficiency and increases the risk to the patient.

Partially Invasive Brain Computer Interfaces

Partially Invasive BCIs, on the other hand, are implanted inside the skull but outside the brain. Although signal strength using this type of BCI device is a bit weaker, partially invasive BCIs has less risk of scar tissue formation.

Non Invasive Brain Computer Interfaces

Non invasive brain computer interface, although it has the least signal clarity when it comes to communicating with the brain (skull distorts signal), is also the safest. This type of device has been found to be successful in giving a patient the ability to move muscle implants and restore partial movement. One of the most popular devices under this category is the EEG or electroencephalography capable of providing a fine temporal resolution. It is easy to use, relatively cheap and portable.

Ethics and BCIs

Of course, the use of BCIs has sparked some debate among people especially since one of its future applications is the enhancement of human capabilities and mind control (brain pacemakers are now successful in treating depression). Nonetheless, this technology has not yet attained its full maturity and is therefore still relatively below the social radar. As of today, this technology is seen more to help much in fighting against disability through prosthetics and as a treatment for neurological ailments such as depression.

Animal BCI research

Rats implanted with BCIs in Theodore Berger's experiments

Several laboratories have managed to record signals from monkey and rat cerebral cortices in order to operate BCIs to carry out movement. Monkeys have navigated computer cursors on screen and commanded robotic arms to perform simple tasks simply by thinking about the task and without any motor output.In May 2008 photographs that showed a monkey operating a robotic arm with its mind at the Pittsburgh University Medical Center were published in a number of well known science journals and magazines. Other research on cats has decoded visual signals.

Early work

Studies that developed algorithms to reconstruct movements from motor cortex neurons, which control movement, date back to the 1970s. Work by groups led by Schmidt, Fetz and Baker in the 1970s established that monkeys could quickly learn to voluntarily control the firing rate of individual neurons in the primary motor cortex via closed-loop operant conditioning, a training method using punishment and rewards.

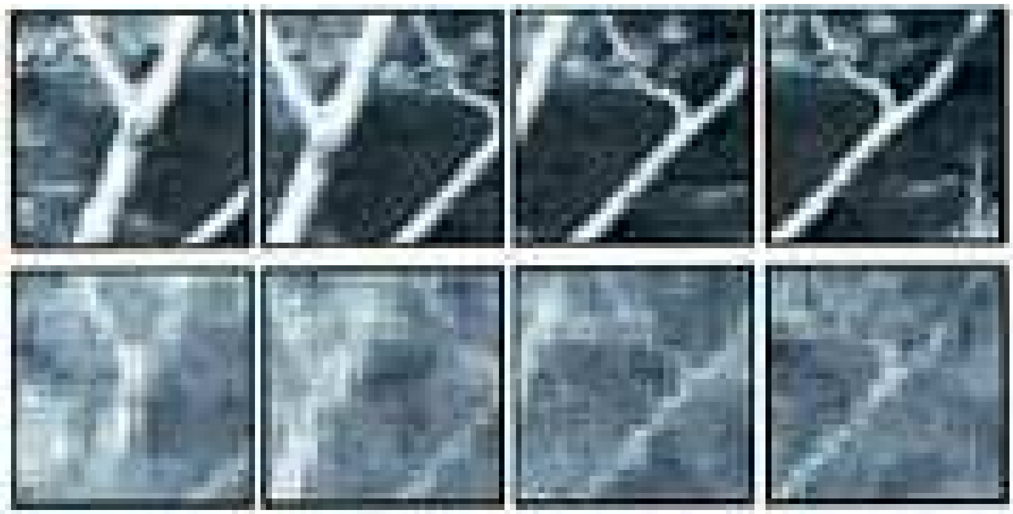
Monkey operating a robotic arm with brain–computer interfacing

In the 1980s, Apostolos Georgopoulos at Johns Hopkins University found a mathematical relationship between the electrical responses of single motor-cortex neurons in rhesus macaque monkeys and the direction that monkeys moved their arms (based on a cosine function). He also found that dispersed groups of neurons in different areas of the brain collectively controlled motor commands but was only able to record the firings of neurons in one area at a time because of technical limitations imposed by his equipment.

There has been rapid development in BCIs since the mid-1990s. Several groups have been able to capture complex brain motor centre signals using recordings from neural ensembles (groups of neurons) and use these to control external devices, including research groups led by Richard Andersen, John Donoghue, Phillip Kennedy, Miguel Nicolelis, and Andrew Schwartz.

Prominent research successes

Phillip Kennedy and colleagues built the first intracortical brain–computer interface by implanting neurotrophic-cone electrodes into monkeys.



Yang Dan and colleagues' recordings of cat vision using a BCI implanted in the lateral geniculate nucleus (top row: original image; bottom row: recording)

In 1999, researchers led by Yang Dan at University of California, Berkeley decoded neuronal firings to reproduce images seen by cats. The team used an array of electrodes embedded in the thalamus (which integrates all of the brain's sensory input) of sharp-eyed cats. Researchers targeted 177 brain cells in the thalamus lateral geniculate nucleus area, which decodes signals from the retina. The cats were shown eight short movies, and their neuron firings were recorded. Using mathematical filters, the researchers decoded the signals to generate movies of what the cats saw and were able to reconstruct recognizable scenes and moving objects. Similar results in humans have been since then achieved by researchers in Japan (see below).

Miguel Nicolelis has been a prominent proponent of using multiple electrodes spread over a greater area of the brain to obtain neuronal signals to drive a BCI. Such neural ensembles are said to reduce the variability in output produced by single electrodes, which could make it difficult to operate a BCI.

After conducting initial studies in rats during the 1990s, Nicolelis and his colleagues developed BCIs that decoded brain activity in owl monkeys and used the devices to reproduce monkey movements in robotic arms. Monkeys have advanced reaching and grasping abilities and good hand manipulation skills, making them ideal test subjects for this kind of work.

By 2000, the group succeeded in building a BCI that reproduced owl monkey movements while the monkey operated a joystick or reached for food.. The BCI operated in real time and could also control a separate robot remotely over Internet protocol. But the monkeys could not see the arm moving and did not receive any feedback, a so-called open-loop BCI.

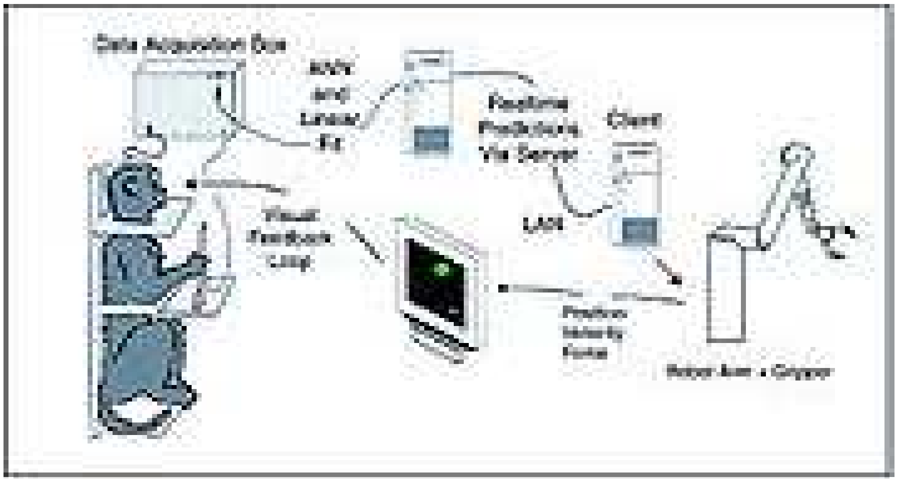


Diagram of the BCI developed by Miguel Nicolelis and colleagues for use on Rhesus monkeys

Later experiments by Nicolelis using rhesus monkeys, succeeded in closing the feedback loop and reproduced monkey reaching and grasping movements in a robot arm. With their deeply cleft and furrowed brains, rhesus monkeys are considered to be better models for human neurophysiology than owl monkeys. The monkeys were trained to reach and grasp objects on a computer screen by manipulating a joystick while corresponding movements by a robot arm were hidden. The monkeys were later shown the robot directly and learned to control it by viewing its movements. The BCI used velocity predictions to control reaching movements and simultaneously predicted hand gripping force.

Other labs that develop BCIs and algorithms that decode neuron signals include John Donoghue from Brown University, Andrew Schwartz from the University of Pittsburgh and Richard Andersen from Caltech. These researchers were able to produce working BCIs even though they recorded signals from far fewer neurons than Nicolelis (15–30 neurons versus 50–200 neurons).

Donoghue's group reported training rhesus monkeys to use a BCI to track visual targets on a computer screen with or without assistance of a joystick (closed-loop BCI). Schwartz's group created a BCI for three-dimensional tracking in virtual reality and also reproduced BCI control in a robotic arm. The group created headlines when they demonstrated that a monkey could feed itself pieces of zucchini using a robotic arm controlled by the animal's own brain signals.

Andersen's group used recordings of premovement activity from the posterior parietal cortex in their BCI, including signals created when experimental animals anticipated receiving a reward.

In addition to predicting kinematic and kinetic parameters of limb movements, BCIs that predict electromyographic or electrical activity of muscles are being developed.. Such BCIs could be used to restore mobility in paralyzed limbs by electrically stimulating muscles.

Miguel Nicolelis worked with John Chapin, Johan Wessberg, Mark Laubach, Jose Carmena, Mikhail Lebedev, Antonio Pereira, Jr., Sidarta Ribeiro and other colleagues showed that activity of large neural ensembles can predict arm position. This work made possible creation of brain–machine interfaces — electronic devices that read arm movement intentions and translate them into movements of artificial actuators. Carmena et al. (2003) programmed the neural coding in a brain–machine interface allowed a monkey to control reaching and grasping movements by a robotic arm, and Lebedev et al. (2005) argued that brain networks reorganize to create a new representation of the robotic appendage in addition to the representation of the animal's own limbs.

The biggest impediment of BCI technology at present is the lack of a sensor modality that provides safe, accurate, and robust access to brain signals. It is conceivable or even likely that such a sensor will be developed within the next twenty years. The use of such a sensor should greatly expand the range of communication functions that can be provided using a BCI.

Development and implementation of a Brain–Computer Interface (BCI) system is complex and time consuming. In response to this problem, Dr. Gerwin Schalk has been developing a general-purpose system for BCI research, called BCI2000. BCI2000 has been in development since 2000 in a project led by the Brain–Computer Interface R&D Program at the Wadsworth Center of the New York State Department of Health in Albany, New York, USA.

A new 'wireless' approach uses light-gated ion channels such as Channelrhodopsin to control the activity of genetically defined subsets of neurons in vivo. In the context of a simple learning task, illumination of transfected cells in the somatosensory cortex influenced the decision making process of freely moving mice.[20]

Human BCI research

<u>Brain implants</u>:

Brain implants, often referred to as **neural implants**, are technological devices that connect directly to a biological subject's brain - usually placed on the surface of the brain, or attached to the brain's cortex. A common purpose of modern brain implants and the focus of much current research is establishing a biomedical prosthesis circumventing areas in the brain, which became dysfunctional after a stroke or other head injuries. This includes sensory substitution, e.g. in vision. Other brain implants are used in animal experiments simply to record brain activity for scientific reasons. Some brain implants involve creating interfaces between neural systems and computer chips, which are part of a wider research field called brain-computer interfaces. (Brain-computer interface research also includes technology such as EEG arrays that allow interface between mind and machine but do not require direct implantation of a device.)

Purpose

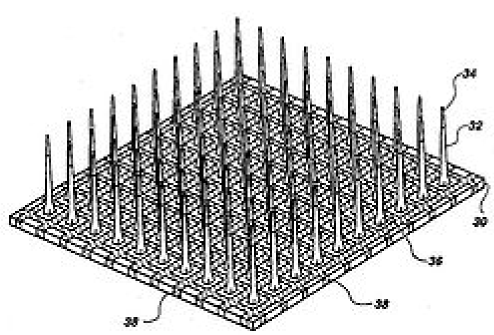
Brain implants electrically stimulate or block]or record (or both record and stimulate simultaneously from single neurons or groups of neurons (biological neural networks) in the brain. The blocking technique is called intra-abdominal vagal blocking[2]. This can only be done where the functional associations of these neurons are approximately known. Because of the complexity of neural processing and the lack of access to action potential related signals using neuroimaging techniques, the application of brain implants has been seriously limited until recent advances in neurophysiology and computer processing power.

Research:

Research in sensory substitution has made slow progress in recent years. Especially in vision, due to the knowledge of the working of the visual system, eye implants (often involving some brain implants or monitoring) have been applied with demonstrated success. For hearing, cochlear implants are used to stimulate the auditory nerve directly. The vestibulocochlear nerve is part of the peripheral nervous system, but the interface is similar to that of true brain implants.

Multiple projects have demonstrated success at recording from the brains of animals for long periods of time. As early as 1976, researchers at the NIH led by Ed Schmidt made action potential recordings of signals from Rhesus monkey motor cortexes using immovable "hatpin" electrodes,[4] including recording from single neurons for over 30 days, and consistent recordings for greater than three years from the best electrodes.

The "hatpin" electrodes were made of pure iridium and insulated with Parylene-c, materials that are currently used in the Cyberkinetics implementation of the Utah array.[5] These same electrodes, or derivations thereof using the same biocompatible electrode materials, are currently used in visual prosthetics laboratories,[6] laboratories studying the neural basis of learning,[7] and motor prosthetics approaches other than the Cyberkinetics probes.[8]



Schematic of the "Utah" Electrode Array

A competing series of electrodes and projects is sold by Plexon including Plextrode Series of Electrodes. These are variously the "Michigan Probes",[9] the microwire arrays first used at MIT,[10] and the FMAs from MicroProbe that emerged from the visual prosthetic project collaboration between Phil Troyk, David Bradley, and Martin Bak.

Other laboratory groups produce their own implants to provide unique capabilities not available from the commercial products.

Breakthroughs include studies of the process of functional brain re-wiring throughout the learning of a sensory discrimination,control of physical devices by rat brains, monkeys over robotic arms, remote control of mechanical devices by monkeys and humans, remote control over the movements of roaches, electronic-based neuron transistors for leeches,the first reported use of the Utah Array in a human for bidirectionalsignalling.Currently a number of groups are conducting preliminary motor prosthetic implants in humans. These studies are presently limited to several months by the longevity of the implants.

Invasive BCIs

Invasive BCI research has targeted repairing damaged sight and providing new functionality to persons with paralysis. Invasive BCIs are implanted directly into the grey matter of the brain during neurosurgery. As they rest in the grey matter, invasive devices produce the highest quality signals of BCI devices but are prone to scar-tissue build-up, causing the signal to become weaker or even lost as the body reacts to a foreign object in the brain.

Jens Naumann, a man with acquired blindness, being interviewed about his vision BCI on CBS's The Early Show

In *vision science*, direct brain implants have been used to treat non-congenital (acquired) blindness. One of the first scientists to come up with a working brain interface to restore sight was private researcher William Dobelle.

Dobelle's first prototype was implanted into "Jerry", a man blinded in adulthood, in 1978. A single-array BCI containing 68 electrodes was implanted onto Jerry's visual cortex and succeeded in producing phosphenes, the sensation of seeing light. The system included cameras mounted on glasses to send signals to the implant. Initially, the implant allowed Jerry to see shades of grey in a limited field of vision at a low frame-rate. This also required him to be hooked up to a two-ton mainframe, but shrinking electronics and faster computers made his artificial eye more portable and now enable him to perform simple tasks unassisted.

Dummy unit illustrating the design of a BrainGate interface

In 2002, Jens Naumann, also blinded in adulthood, became the first in a series of 16 paying patients to receive Dobelle's second generation implant, marking one of the earliest commercial uses of BCIs. The second generation device used a more sophisticated implant enabling better mapping of phosphenes into coherent vision. Phosphenes are spread out across the visual field in what researchers call the starry-night effect. Immediately after his implant, Jens was able to use his imperfectly restored vision to drive slowly around the parking area of the research institute.

BCIs focusing on *motor neuroprosthetics* aim to either restore movement in individuals with paralysis or provide devices to assist them, such as interfaces with computers or robot arms.

Researchers at Emory University in Atlanta led by Philip Kennedy and Roy Bakay were first to install a brain implant in a human that produced signals of high enough quality to simulate movement. Their patient, Johnny Ray (1944-2002), suffered from 'locked-in syndrome' after suffering a brain-stem stroke in 1997. Ray's implant was installed in 1998 and he lived long enough to start working with the implant, eventually learning to control a computer cursor; he died in 2002 of a brain aneurysm.[22]

Tetraplegic, Matt Nagle became the first person to control an artificial hand using a BCI in 2005 as part of the first nine-month human trial of Cyberkinetics Neurotechnology's BrainGate chip-implant. Implanted in Nagle's right precentral gyrus (area of the motor cortex for arm movement), the 96-electrode BrainGate implant allowed Nagle to control a robotic arm by thinking about moving his hand as well as a computer cursor, lights and TV.[23]

Partially-invasive BCIs

Partially invasive BCI devices are implanted inside the skull but rest outside the brain rather than within the grey matter. They produce better resolution signals than non-invasive BCIs where the bone tissue of the cranium deflects and deforms signals and have a lower risk of forming scar-tissue in the brain than fully-invasive BCIs.

Electrocorticography (ECoG) measures the electrical activity of the brain taken from beneath the skull in a similar way to non-invasive electroencephalography (see below), but the electrodes are embedded in a thin plastic pad that is placed above the cortex, beneath the dura mater.[24] ECoG technologies were first trialed in humans in 2004 by Eric Leuthardt and Daniel Moran from Washington University in St Louis. In a later trial, the researchers enabled a teenage boy to play Space Invaders using his ECoG implant.[25] This research indicates that control is rapid, requires minimal training, and may be an ideal tradeoff with regards to signal fidelity and level of invasiveness.

(Note: These electrodes were not implanted in the patients for BCI experiments. Implanting foreign objects into people's brains solely for experimental purposes is controversial. The patients were suffering from severe epilepsy and had the electrodes temporarily implanted to help their physicians localize seizure foci; the researchers simply took advantage of this.)

Light Reactive Imaging BCI devices are still in the realm of theory. These would involve implanting a laser inside the skull. The laser would be trained on a single neuron and the neuron's reflectance measured by a separate sensor. When the neuron fires, the laser light pattern and wavelengths it reflects would change slightly. This would allow researchers to monitor single neurons but require less contact with tissue and reduce the risk of scar-tissue build-up.

This signal can be either subdural or epidural, but is not taken from within the brain parenchyma itself. It has not been studied extensively until recently due to the limited access of subjects. Currently, the only manner to acquire the signal for study is through the use of patients requiring invasive monitoring for localization and resection of an epileptogenic focus.

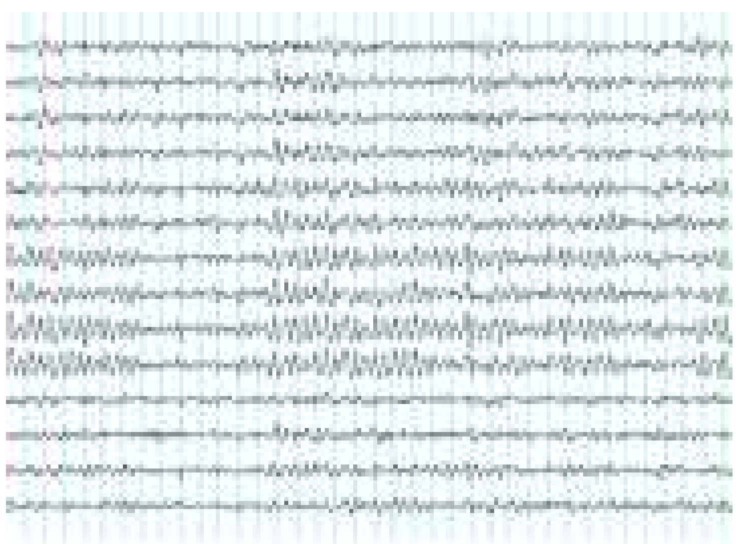
ECoG is a very promising intermediate BCI modality because it has higher spatial resolution, better signal-to-noise ratio, wider frequency range, and lesser training requirements than scalp-recorded EEG, and at the same time has lower technical difficulty, lower clinical risk, and probably superior long-term stability than intracortical single-neuron recording. This feature profile and recent evidence of the high level of control with minimal training requirements shows potential for real world application for people with motor disabilities.

Non-invasive BCIs

As well as invasive experiments, there have also been experiments in humans using non-invasive neuroimaging technologies as interfaces. Signals recorded in this way have been used to power muscle implants and restore partial movement in an experimental volunteer. Although they are easy to wear, non-invasive implants produce poor signal resolution because the skull dampens signals, dispersing and blurring the electromagnetic waves created by the neurons. Although the waves can still be detected it is more difficult to determine the area of the brain that created them or the actions of individual neurons.

EEG

Main article: Electroencephalography



Recordings of brainwaves produced by an electroencephalogram

Electroencephalography (EEG) is the most studied potential non-invasive interface, mainly due to its fine temporal resolution, ease of use, portability and low set-up cost. But as well as the technology's susceptibility to noise, another substantial barrier to using EEG as a brain–computer interface is the extensive training required before users can work the technology. For example, in experiments beginning in the mid-1990s, Niels Birbaumer of the University of Tübingen in Germany used EEG recordings of *slow cortical potential* to give paralysed patients limited control over a computer cursor. (Birbaumer had earlier trained epileptics to prevent impending fits by controlling this low voltage wave.) The experiment saw ten patients trained to move a computer cursor by controlling their brainwaves. The process was slow, requiring more than an hour for patients to write 100 characters with the cursor, while training often took many months.

Another research parameter is the type of waves measured. Birbaumer's later research with Jonathan Wolpaw at New York State University has focused on developing technology that would allow users to choose the brain signals they found easiest to operate a BCI, including *mu* and *beta* waves.

A further parameter is the method of feedback used and this is shown in studies of P300 signals. Patterns of P300 waves are generated involuntarily (stimulus-feedback) when people see something they recognize and may allow BCIs to decode categories of thoughts without training patients first. By contrast, the biofeedback methods described above require learning to control brainwaves so the resulting brain activity can be detected.

Lawrence Farwell and Emanuel Donchin developed an EEG-based brain–computer interface in the 1980s. Their "mental prosthesis" used the P300 brainwave response to allow subjects, including one paralyzed Locked-In syndrome patient, to communicate words, letters, and simple commands to a computer and thereby to speak through a speech synthesizer driven by the computer. A number of similar devices have been developed since then. In 2000, for example, research by Jessica Bayliss at the University of Rochester showed that volunteers wearing virtual reality helmets could control elements in a virtual world using their P300 EEG readings, including turning lights on and off and bringing a mock-up car to a stop.

In 1999, researchers at Case Western Reserve University led by Hunter Peckham, used 64-electrode EEG skullcap to return limited hand movements to quadriplegic Jim Jatich. As Jatich concentrated on simple but opposite concepts like up and down, his beta-rhythm EEG output was analysed using software to identify patterns in the noise. A basic pattern was identified and used to control a switch: Above average activity was set to on, below average off. As well as enabling Jatich to control a computer cursor the signals were also used to drive the nerve controllers embedded in his hands, restoring some movement.

Electronic neural networks have been deployed which shift the learning phase from the user to the computer. Experiments by scientists at the Fraunhofer Society in 2004 using neural networks led to noticeable improvements within 30 minutes of training.

Experiments by Eduardo Miranda aim to use EEG recordings of mental activity associated with music to allow the disabled to express themselves musically through an encephalophone

The Emotiv company plans to produce a commercial video game controller (known as the Epoc) in 2009, which uses electromagnetic sensors.

MEG and MRI

Main articles: Magnetoencephalography and Magnetic resonance imaging

Magnetoencephalography

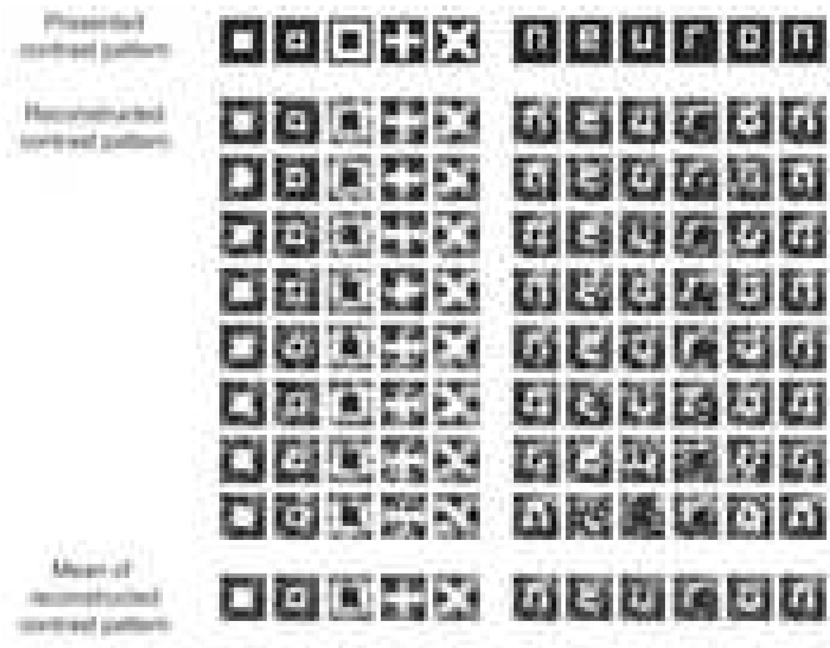
Magnetoencephalography (**MEG**) is an imaging technique used to measure the magnetic fields produced by electrical activity in the brain via extremely sensitive devices such as superconducting quantum interference devices (SQUIDs). These measurements are commonly used in both research and clinical settings. There are many uses for the MEG, including assisting surgeons in localizing a pathology, assisting researchers in determining the function of various parts of the brain, neurofeedback, and others.
In research, MEG's primary use is the measurement of time courses of activity. MEG can resolve events with a precision of 10 milliseconds or less, while fMRI, which depends on changes in blood flow, can at best resolve events with a precision of several hundred milliseconds. MEG also accurately pinpoints sources in primary auditory, somatosensory and motor areas, whereas its use in creating functional maps of human cortex during more complex cognitive tasks is more limited; in those cases MEG should preferably be used in combination with fMRI. It should be noted, however, that neuronal (MEG) and hemodynamic (fMRI) data do not necessarily agree and the methods complement each other. However, the two signals may have a common source: it is known that there is a tight relationship between LFP (local field potentials) and BOLD (blood oxygenation level dependent) signals. Since the LFP is the source signal of MEG/EEG, MEG and BOLD signals may derive from the same source (though the BOLD signals are filtered through the hemodynamic response).

Magnetic Resonance Imaging (MRI)

Magnetic Resonance Imaging (**MRI**), or **nuclear magnetic resonance imaging** (**NMRI**), is primarily a medical imaging technique most commonly used in radiology to visualize the internal structure and function of the body. MRI provides much greater contrast between the different soft tissues of the body than computed tomography (CT) does, making it especially useful in neurological (brain), musculoskeletal, cardiovascular, and oncological (cancer) imaging. Unlike CT, it uses no ionizing radiation, but uses a powerful magnetic field to align the nuclear magnetization of (usually) hydrogen atoms in water in the body. Radio frequency (RF) fields are used to systematically alter the alignment of this magnetization, causing the hydrogen nuclei to produce a rotating magnetic field detectable by the scanner. This signal can be manipulated by additional magnetic fields to build up enough information to construct an image of the body.[1]:36

Magnetic Resonance Imaging is a relatively new technology. The first MR image was published in 1973[2][3] and the first cross-sectional image of a living mouse was published in January 1974[4]. The first studies performed on humans were published in 1977.[5][6] By comparison, the first human X-ray image was taken in 1895.

Magnetic Resonance Imaging was developed from knowledge gained in the study of nuclear magnetic resonance. In its early years the technique was referred to as nuclear magnetic resonance imaging (NMRI). However, as the word *nuclear* was associated in the public mind with ionizing radiation exposure it is generally now referred to simply as MRI. Scientists still use the term NMRI when discussing non-medical devices operating on the same principles. The term Magnetic Resonance Tomography (MRT) is also sometimes used.



ATR Labs' reconstruction of human vision using fMRI (top row: original image; bottom row: reconstruction from mean of combined readings)

Magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI) have both been used successfully as non-invasive BCIs.[33] In a widely reported experiment, fMRI allowed two users being scanned to play Pong in real-time by altering their haemodynamic response or brain blood flow through biofeedback techniques.

fMRI measurements of haemodynamic responses in real time have also been used to control robot arms with a seven second delay between thought and movement.

More recently, research developed in the Advanced Telecommunications Research (ATR) Computational Neuroscience Laboratories in Kyoto, Japan allowed the scientists to reconstruct images directly from the brain and display them on a computer. The article announcing these achievements was the cover story of the journal Neuron of 10 December 2008[. While the early results are limited to black and white images of 10x10 squares (pixels), according to the researchers further development of the technology may make it possible to achieve color images, and even view or record dreams.[37][38]

Commercialization and companies

John Donoghue and fellow researchers founded Cyberkinetics. Now listed on a US stock exchange and known as Cyberkinetic Neurotechnology Inc, the company markets its electrode arrays under the BrainGate product name and has set the development of practical BCIs for humans as its major goal. The BrainGate is based on the Utah Array developed by Dick Normann.

Philip Kennedy founded Neural Signals in 1987 to develop BCIs that would allow paralysed patients to communicate with the outside world and control external devices. As well as an invasive BCI, the company also sells an implant to restore speech. Neural Signals' Brain Communicator BCI device uses glass cones containing microelectrodes coated with proteins to encourage the electrodes to bind to neurons.

Although 16 paying patients were treated using William Dobelle's vision BCI, new implants ceased within a year of Dobelle's death in 2004. A company controlled by Dobelle, Avery Biomedical Devices, and Stony Brook University are continuing development of the implant, which has not yet received Food and Drug Administration approval in the United States for human implantation.

Ambient, at a TI developers conference in early 2008, demoed a product they have in development call The Audeo. The Audeo is being developed to create a human–computer interface for communication without the need of physical motor control or speech production. Using signal processing, unpronounced speech representing the thought of the mind can be translated from intercepted neurological signals.

Mindball is a product developed and commercialized by Interactive Productline in which players compete to control a ball's movement across a table by becoming more relaxed and focused. Interactive Productline is a Swedish company whose objective is to develop and sell easy understandable EEG products that train the ability to relax and focus.

There are three main consumer-devices commercial-competitors in this area (expected launch date mentioned in brackets) which are going to launch such devices primarily for gaming- and PC-users:

- Neural Impulse Actuator (April - 2008)
- Emotiv Systems (Summer - 2009)
- NeuroSky (MindSet - June 2009, Uncle Milton Force Trainer - Fall 2009, Mattel MindFlex - Summer 2009)

Ethical considerations

This section **may contain original research or unverified claims**. Please improve the article by adding references. See the talk page for details. *(July 2009)*

Discussion about the ethical implications of BCIs has been relatively muted. This may be because the research holds great promise in the fight against disability and BCI researchers have yet to attract the attention of animal rights groups. It may also be because BCIs are being used to acquire signals to control devices rather than the other way around, although vision research is the exception to this.

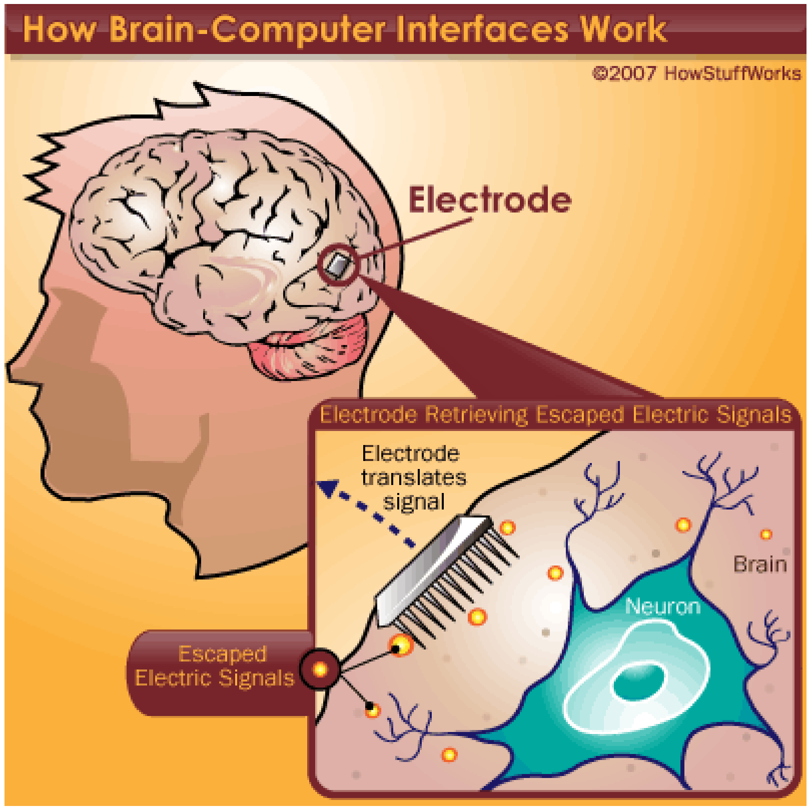
This ethical debate is likely to intensify as BCIs become more technologically advanced and it becomes apparent that they may not just be used therapeutically but for human enhancement. Today's brain pacemakers, which are already used to treat neurological conditions such as depression could become a type of BCI and be used to modify other behaviours. Neurochips could also develop further, for example the artificial hippocampus, raising issues about what it actually means to be human.

Some of the ethical considerations that BCIs would raise under these circumstances are already being debated in relation to brain implants and the broader area of mind control.

How Brain-computer Interfaces Work

As the power of modern computers grows alongside our understanding of the human brain, we move ever closer to making some pretty spectacular science fiction into reality. Imagine transmitting signals directly to someone's brain that would allow them to see, hear or feel specific sensory inputs. Consider the potential to manipulate computers or machinery with nothing more than a thought. It isn't about convenience -- for severely disabled people, development of a **brain-computer interface** (BCI) could be the most important technological breakthrough in decades. In this article, we'll learn all about how BCIs work, their limitations and where they could be headed in the future.

Brain Image Gallery

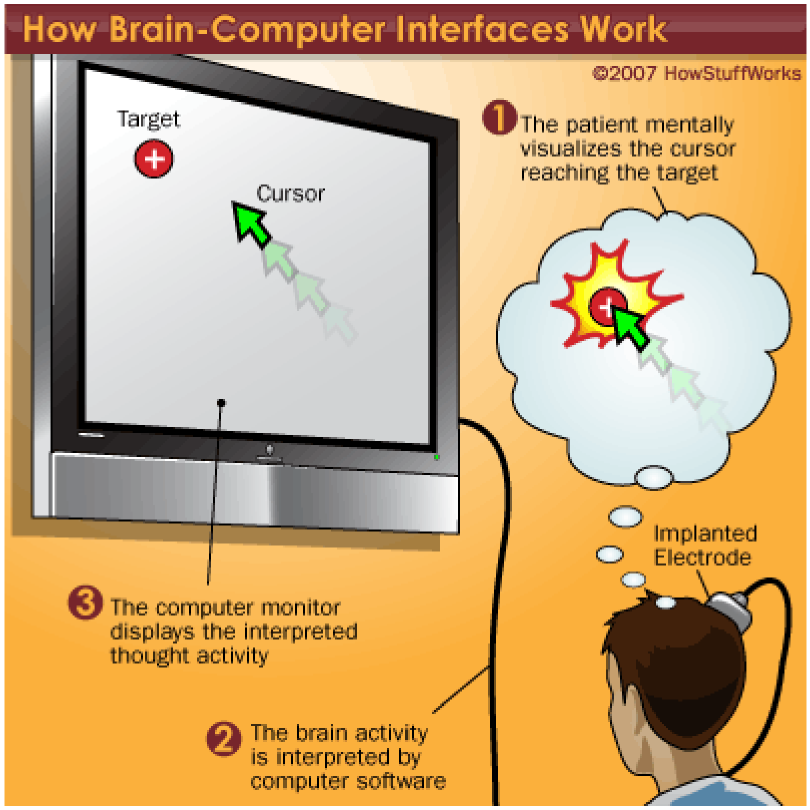


The Electric Brain

The reason a BCI works at all is because of the way our brains function. Our brains are filled with **neurons**, individual nerve cells connected to one another by dendrites and axons. Every time we think, move, feel or remember something, our neurons are at work. That work is carried out by small electric signals that zip from neuron to neuron as fast as 250 mph [source: Walker]. The signals are generated by differences in electric potential carried by ions on the membrane of each neuron. Although the paths the signals take are insulated by something called myelin, some of the electric signal escapes. Scientists can detect those signals, interpret what they mean and use them to direct a device of some kind. It can also work the other way around. For example, researchers could figure out what signals are sent to the brain by the optic nerve when someone sees the color red. They could rig a camera that would send those exact signals into someone's brain whenever the camera saw red, allowing a blind person to "see" without eyes.

BCI Input and Output

One of the biggest challenges facing brain-computer interface researchers today is the basic mechanics of the interface itself. The easiest and least invasive method is a set of electrodes -- a device known as an **electroencephalograph** (EEG) -- attached to the scalp. The electrodes can read brain signals. However, the skull blocks a lot of the electrical signal, and it distorts what does get through.



To get a higher-resolution signal, scientists can implant electrodes directly into the gray matter of the brain itself, or on the surface of the brain, beneath the skull. This allows for much more direct reception of electric signals and allows electrode placement in the specific area of the brain where the appropriate signals are generated. This approach has many problems, however. It requires invasive surgery to implant the electrodes, and devices left in the brain long-term tend to cause the formation of scar tissue in the gray matter. This scar tissue ultimately blocks signals.

Regardless of the location of the electrodes, the basic mechanism is the same: The electrodes measure minute differences in the voltage between neurons. The signal is then amplified and filtered. In current BCI systems, it is then interpreted by a computer program, although you might be familiar with older analogue encephalographs, which displayed the signals via pens that automatically wrote out the patterns on a continuous sheet of paper.

In the case of a sensory input BCI, the function happens in reverse. A computer converts a signal, such as one from a video camera, into the voltages necessary to trigger neurons. The signals are sent to an implant in the proper area of the brain, and if everything works correctly, the neurons fire and the subject receives a visual image corresponding to what the camera sees.

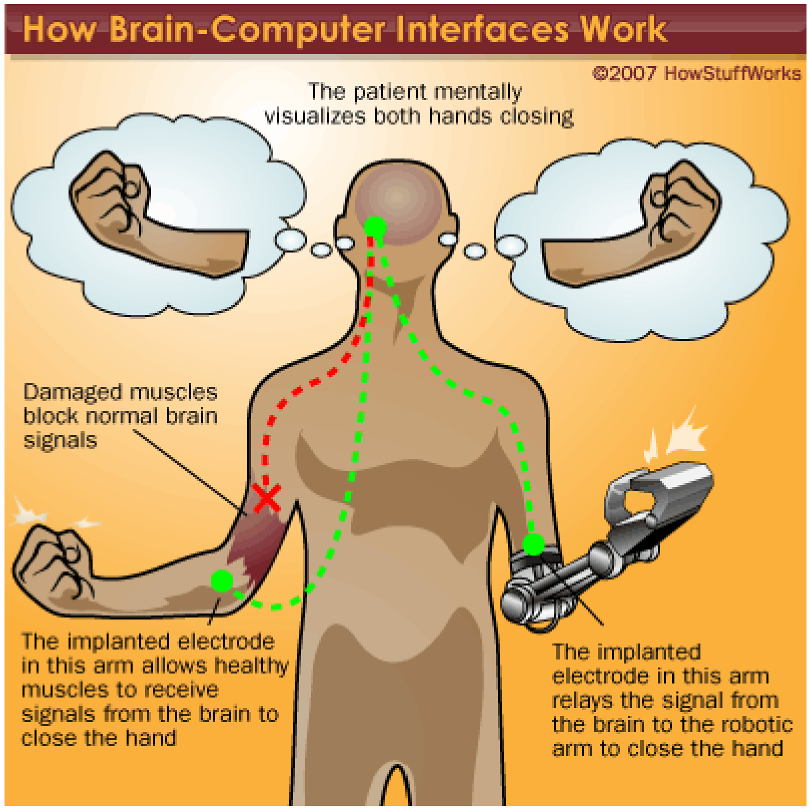
Another way to measure brain activity is with a **Magnetic Resonance Image** (MRI). An MRI machine is a massive, complicated device. It produces very high-resolution images of brain activity, but it can't be used as part of a permanent or semipermanent BCI. Researchers use it to get benchmarks for certain brain functions or to map where in the brain electrodes should be placed to measure a specific function. For example, if researchers are attempting to implant electrodes that will allow someone to control a robotic arm with their thoughts, they might first put the subject into an MRI and ask him or her to think about moving their actual arm. The MRI will show which area of the brain is active during arm movement, giving them a clearer target for electrode placement.

BCI Applications

One of the most exciting areas of BCI research is the development of devices that can be controlled by thoughts. Some of the applications of this technology may seem frivolous, such as the ability to control a video game by thought. If you think a remote control is convenient, imagine changing channels with your mind.

However, there's a bigger picture -- devices that would allow severely disabled people to function independently. For a quadriplegic, something as basic as controlling a computer cursor via mental commands would represent a revolutionary improvement in quality of life. But how do we turn those tiny voltage measurements into the movement of a robotic arm?

Early research used monkeys with implanted electrodes. The monkeys used a joystick to control a robotic arm. Scientists measured the signals coming from the electrodes. Eventually, they changed the controls so that the robotic arm was being controlled only by the signals coming form the electrodes, not the joystick.



A more difficult task is interpreting the brain signals for movement in someone who can't physically move their own arm. With a task like that, the subject must "train" to use the device. With an EEG or implant in place, the subject would visualize closing his or her right hand. After many trials, the software can learn the signals associated with the thought of hand-closing. Software connected to a robotic hand is programmed to receive the "close hand" signal and interpret it to mean that the robotic hand should close. At that point, when the subject thinks about closing the hand, the signals are sent and the robotic hand closes.

A similar method is used to manipulate a computer cursor, with the subject thinking about forward, left, right and back movements of the cursor. With enough practice, users can gain enough control over a cursor to draw a circle, access computer programs and control a TV [source: Ars Technica]. It could theoretically be expanded to allow users to "type" with their thoughts.

Once the basic mechanism of converting thoughts to computerized or robotic action is perfected, the potential uses for the technology are almost limitless. Instead of a robotic hand, disabled users could have robotic braces attached to their own limbs, allowing them to move and directly interact with the environment. This could even be accomplished without the "robotic" part of the device. Signals could be sent to the appropriate motor control nerves in the hands, bypassing a damaged section of the spinal cord and allowing actual movement of the subject's own hands.

Military applications

The United States military has been exploring applications for BCIs, to enhance troop performance as well as develop systems to interfere with the communications of perceived adversaries. As one report concluded,

The most successful implementation of invasive interfaces has occurred in medical applications in which nerve signals are used as the mechanism for information transfer.

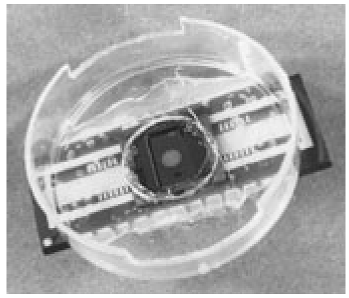
The DARPA budget for the fiscal year 2009 to 2010 includes $4 million for a program named *Silent Talk*, which aims to "allow user-to-user communication on the battlefield without the use of vocalized speech through analysis of neural signals." A further $4 million was allocated by the Army to the University of California to investigate computer-mediated "synthetic telepathy".The research aims to detect and analyze the word-specific neural signals, using EEG, which occur before speech is vocalized, and to see if the patterns are generalizable. The research is part of a wider $70 million project that began in 2000 which aims to develop hardware capable of adapting to the behavior of its user.

Sensory substitution:

Sensory substitution means to transform the characteristics of one sensory modality into stimuli of another sensory modality. It is hoped that sensory substitution systems can help handicapped people by restoring their ability to perceive a certain defective sensory modality by using sensory information from a functioning sensory modality. A sensory substitution system consists of three parts: a sensor, a coupling system, and a stimulator. The sensor records stimuli and gives them to a coupling system which interprets these signals and transmits them to a stimulator. Sensory substitution concerns human perception and the plasticity of the human brain; and therefore, allows us to study these aspects of neuroscience more through neuroimaging.

Cell-culture BCIs

Researchers have built devices to interface with neural cells and entire neural networks in cultures outside animals. As well as furthering research on animal implantable devices, experiments on cultured neural tissue have focused on building problem-solving networks, constructing basic computers and manipulating robotic devices. Research into techniques for stimulating and recording from individual neurons grown on semiconductor chips is sometimes referred to as neuroelectronics or neurochips.



World first: Neurochip developed by Caltech researchers Jerome Pine and Michael Maher

Development of the first working neurochip was claimed by a Caltech team led by Jerome Pine and Michael Maher in 1997 The Caltech chip had room for 16 neurons.

In 2003, a team led by Theodore Berger at the University of Southern California started work on a neurochip designed to function as an artificial or prosthetic hippocampus. The neurochip was designed to function in rat brains and is intended as a prototype for the eventual development of higher-brain prosthesis. The hippocampus was chosen because it is thought to be the most ordered and structured part of the brain and is the most studied area. Its function is to encode experiences for storage as long-term memories elsewhere in the brain.

Thomas DeMarse at the University of Florida used a culture of 25,000 neurons taken from a rat's brain to fly a F-22 fighter jet aircraft simulator. After collection, the cortical neurons were cultured in a petri dish and rapidly began to reconnect themselves to form a living neural network. The cells were arranged over a grid of 60 electrodes and used to control the pitch and yaw functions of the simulator. The study's focus was on understanding how the human brain performs and learns computational tasks at a cellular level.

Better sensing systems

Earlier this year, researchers indeed trained four people suffering epilepsy to move a computer cursor with the power of thought. The patients, who were waiting to have brain surgery, were already fitted with small sheets of signal-detecting electrodes on the surfaces of their brains.

The patients were asked to perform certain tasks - such as opening and closing their hands and sticking out their tongue - while scientists determined what brain signals were associated with these movements.

Next, the signals from these movements were matched up with movements of the cursor on the screen. For example, the thought of opening of the right hand might move the cursor to the right. The subjects were then asked to move the cursor from one spot to another on the screen by thinking about making the movements.

The patients had some difficulty at first, but each was able to control the cursor with their thoughts and with over 70 percent accuracy after a few minutes. One patient was operating at 100 percent accuracy by the end of the trial.

"All our subjects were able to control the computer cursor using imagined representations of motor movements," said Daniel Moran of Washington University.

This study was the first to prove that sensors placed on the surface of the brain are preferable to the standard forms of sensors - either embedded deep in the brain tissue or worn as a cap. They are less intrusive than an embedded variety and potentially more stable and powerful than the cap, which receives weak brain signals that have passed through the skull.

The BrainGate

Only a handful of clinical studies include quadriplegics as participants. One at Brown University and Cyberkinetics Neurotechnology Systems, Inc., is working to develop a system called BrainGate.

In this-one patient pilot study, a sensor is implanted on the surface of the primary motor cortex, the area of the brain responsible for movement. The sensor, smaller than a penny, has hair-thin electrode probes that penetrate about a millimeter into the brain and are designed to pick up electrical impulses from the motor neurons.

About twice a week the participant performs cursor-moving tasks with his thoughts that are meant to demonstrate proof of principle of the technology and to evaluate the quality, type, and usefulness of neural output control that patients can achieve.

BrainGate offers several advantages over other systems, its creators say.

"First, BrainGate provides an interface with a computer that works immediately, without weeks or months of training," John Donoghue, director of Brown's Brain Science Program and a co-founder of Cyberkinetics Neurotechnology Systems Inc., told *LiveScience*. "Secondly, a user can operate the device without requiring great concentration.

Cursor control is "about as natural as using one's own arm," Donoghue said. The patient can, for example, carry on a conversation while moving the cursor.

"And, thirdly, because BrainGate connects directly to the part of the brain that ordinarily controls hand movement and gestures, it provides significantly more utility than devices that rely on 'substitutes' for the brain's own arm movement signal, such as eye movements. Using eye movements, for example, to control a computer prevents one from looking elsewhere during use -- something that is very unnatural and cumbersome."

The goal of Donoghue's study and its follow-ups is to develop a safe, effective, and unobtrusive universal system for physically disabled people to control a wide array of devices, such as computers and wheelchairs, with their thoughts.

"Moving a wheelchair with BrainGate is beyond the scope of this study," said Donoghue. "Although, our first trial participant has used his thoughts to control a TV and move a robotic hand and arm."

Future of brain computer interfacing:

Commercial application of brain-computer interface systems is still years away, and developers have set the bar high.

Moran would like to return movement to the body, saying his "overall research goal is to transmit cortical signals over a break in a spinal cord." He would also like to see the development of better neuroprosthetic limbs.

Donoghue has similar goals for the near-term usage of the BrainGate. In addition to developing a smaller, wireless device for the patient to wear, he is demonstrating that human brain waves could be used to control neuroprosthetic limbs.

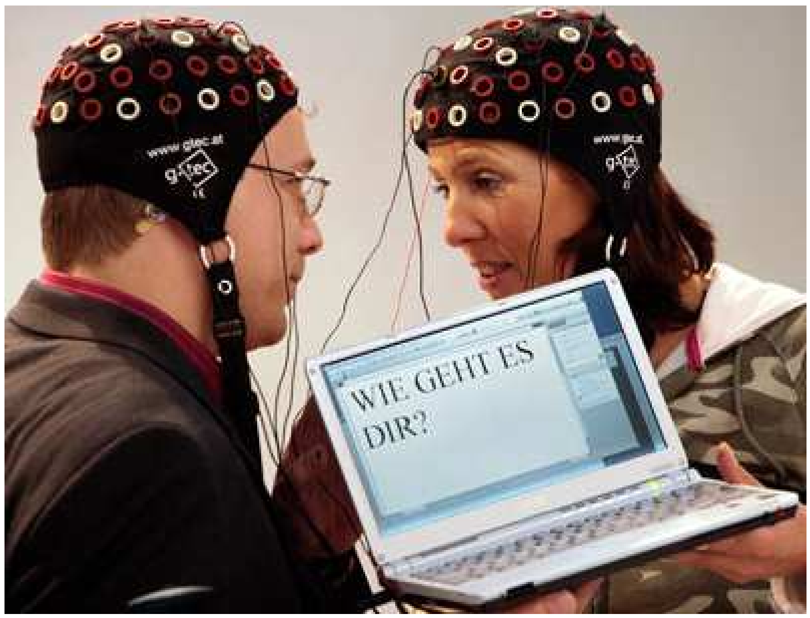
"The ultimate goal of the neuromotor prosthesis is to use physical systems - smart sensors and implantable electronics - to restore a considerable degree of function to paralyzed limbs," Donoghue said. A neural sensing system with adequate processing of signals could potentially drive muscles through implanted stimulators."

BCI Drawbacks and Innovators

Although we already understand the basic principles behind BCIs, they don't work perfectly. There are several reasons for this.

1. The brain is incredibly complex. To say that all thoughts or actions are the result of simple electric signals in the brain is a gross understatement. There are about 100 billion neurons in a human brain [source: Greenfield]. Each neuron is constantly sending and receiving signals through a complex web of connections. There are chemical processes involved as well, which EEGs can't pick up on.

2. The signal is weak and prone to interference. EEGs measure tiny voltage potentials. Something as simple as the blinking eyelids of the subject can generate much stronger signals. Refinements in EEGs and implants will probably overcome this problem to some extent in the future, but for now, reading brain signals is like listening to a bad phone connection. There's lots of static.
3. The equipment is less than portable. It's far better than it used to be -- early systems were hardwired to massive mainframe computers. But some BCIs still require a wired connection to the equipment, and those that are wireless require the subject to carry a computer that can weigh around 10 pounds. Like all technology, this will surely become lighter and more wireless in the future.



Volker Hartmann/AFP/Getty Images

Two people in Germany use a brain-computer interface to write "how are you?"

BCI Innovators

A few companies are pioneers in the field of BCI. Most of them are still in the research stages, though a few products are offered commercially.

- Neural Signals is developing technology to restore speech to disabled people. An implant in an area of the brain associated with speech (Broca's area) would transmit signals to a computer and then to a speaker. With training, the subject could learn to think each of the 39 phonemes in the English language and reconstruct speech through the computer and speaker [source: Neural Signals].

- NASA has researched a similar system, although it reads electric signals from the nerves in the mouth and throat area, rather than directly from the brain. They succeeded in performing a Web search by mentally "typing" the term "NASA" into Google [source: New Scientist].
- Cyberkinetics Neurotechnology Systems is marketing the BrainGate, a neural interface system that allows disabled people to control a wheelchair, robotic prosthesis or computer cursor [source: Cyberkinetics].
- Japanese researchers have developed a preliminary BCI that allows the user to control their avatar in the online world Second Life [source: Ars Technica].

Summary

The brain-computer interface excites the imagination in its potential(good or evil) applications to modify human performance. However, thepresent reality of medical interfaces falls far short of these imaginary scenarios.While interventions such as EEG-brain control for tetraplegicsorcochlearimplants for hearing impairment have large positive impacts onquality-of-life for those with medical disabilities, the ultimate level of performanceachieved remains far below that of a normal function. This is in
part due to the early stage of development of the associated technologies,and in part due to limited understanding of the central nervous system. Atthis time, it is unknown how far, or in what directions, applications of braincomputerinterfaces will develop.It is possible, however, to consider various speculative scenarios in thecontext of present medical capabilities in brain-computer interfaces, as follows:

Scenario 1:

Speculation: Direct signals from the brain could be used to direct oralert external equipment, as an auxiliary to direct human actions.State of the art: External signals from the cerebral cortex, picked up
either by EEG or by implanted electrodes, have severely limited information transfer rates and are susceptible to interference if the subject is not closely focused on the one task being directed. It is possible that this may reflect a fundamental limitation, as the natural function of the cerebral cortex is not directly linked to action control, but instead directs action through a complex circuit of lower-lying neural circuitry. Future developments: More detailed mapping of brain function, and improvements in making direct connections with implanted electrodes,are

certain to yield new capabilities. Any applications outside of medical intervention will be limited to adversaries with access to state-ofthe-
art research capabilities. The most likely types of applications will be in controls, such as ofprosthetics, where output nerve signals can be coupled to a strong feedback mechanism in training.

Scenario 2:

Speculation: Brain-computer interfaces could be used for enhanced sensory input, information input, or control signals to enhance the performance of a combatant. State of the art: Modifying the input to the brain through external nerves is well-known, and in the case of sensory nerves has reasonably
well-defined responses. Subjects require training to learn how to adapt to the signal inputs, and willing participants can adapt well. Unwitting subjects (rats) can be induced to adapt to simple control patterns, but technology for more sophisticated control of behavior or modification of emotions or thought patterns has limited specificity or efficacity (e.g.,MS or vagus nerve stimulation).

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