



# Chips in Your Head

Damaged or diseased brains could soon get a boost from implanted prosthetics

By Frank W. Ohl and Henning Scheich

As many as 400,000 Americans are partially or totally paralyzed from spinal cord injuries, which interrupt the nerve cell signals relaying information between the brain and the body. Others lose the ability to move and communicate because of neurodegenerative disorders such as amyotrophic lateral sclerosis, or Lou Gehrig's disease, which causes the neurons controlling muscles to die. Still half a million more Americans suffer profound sensory deficits such as blindness or deafness. For more than a century, scientists have sought some type of electrical replacement for lost motor and perceptual functions to alleviate these conditions.

Only recently, however, have researchers and doctors begun testing such neuropros-

theses in humans. Existing prosthetic instruments transmit signals from areas in the body to the brain—cochlear implants in the inner ear, for example, can send signals to the auditory nerve to enable hearing. The next generation of devices, however, will move into the brain itself [see box on page 67]. Various research teams are now building so-called brain-computer interfaces (BCIs), which help to restore paralyzed patients' ability to communicate and move by translating neuron signals in their brains into commands that control computer cursors or robots. And a new wave of brain implants, including a type developed in our laboratory in Germany, is poised to transfer information *into* the brain, thereby reviving sensory function.

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# The latest in experimental brain prosthetics enabled a paralyzed person to control a robot.

## Making a Move

One class of neuroprosthetics is designed to tap into signals transmitted from paralyzed individuals' working muscles or motor neurons and use them to produce movement in either distant regions of their own body or external devices that they would otherwise be powerless to control. Peripheral devices that read out signals in this manner may connect with nerve fibers that innervate muscles to control hand, arm or leg movements artificially. The NeuroControl Freehand System, a prosthetic device made by NeuroControl Corporation in Cleveland and approved by the Food and Drug Administration, for example, can return some hand movement to quadriplegics by substituting for the neural signals controlling the hand and forearm that were interrupted after nerve damage from a spinal cord injury. A shoulder-position sensor transmits small shoulder movements, via radio waves and implanted wires, to eight electrodes attached to paralyzed hand and forearm muscles. Patients with some residual shoulder mobility can use that motor signal to open and close their opposite hand, allowing them to perform tasks such as picking up mail, changing television channels or eating a sandwich.

Currently under development are systems that enable paralyzed individuals to operate devices existing outside the body, such as computers, by "listening" to the neural murmurs inside the brain itself. In some of these BCIs, scalp elec-

trodes record the electrical waves emanating from groups of millions of brain neurons. Psychologist Niels Birbaumer of the University of Tuebingen in Germany and his colleagues have created something they call a "thought translation device," which converts such brain transmissions into movements of a cursor on a computer screen. Paralyzed volunteers learn to manipulate their thoughts so as to choose between two cursor positions or letters, enabling them to spell out words. In this way, a person who cannot speak or type can communicate through thought alone [see "Thinking Out Loud," by Nicola Neumann and Niels Birbaumer; SCIENTIFIC AMERICAN MIND, December 2004].

Other researchers are devising BCIs that are implanted within the brain to listen in on the chatter produced by either single or small groups of neurons. Several years ago a team headed by Duke University neurobiologist Miguel Nicolelis inserted electrodes in the cerebral cortex of a female owl monkey named Belle. The electrodes recorded neural activity while the animal moved a lever. A computer then transformed the neural signals into commands that were sent through the Internet to operate a robotic arm in a laboratory some 600 miles away. In later experiments, the Duke team has taught monkeys with implanted electrode arrays to operate computer cursors and robotic arms by altering their brain activity without moving at all.

Researchers working under neuroscientist John Donoghue of Brown University recently performed a similar experiment in four people. One of them was Matthew Nagle, a 26-year-old man who was paralyzed from the neck down as a result of a knife injury. Neurosurgeons implanted an array of hair-thin electrodes into Nagle's brain. The electrodes picked up signals from neurons in his motor cortex, the brain region primarily responsible for movement control. These signals were fed to a computer through a pedestal positioned on top of Nagle's head and then translated into the movement of a computer cursor, a prosthetic hand and a robotic arm.

When Nagle simply imagined performing a movement in a particular direction, the computer, robot or hand prosthesis would respond accordingly. Through this method he was able to open simulated e-mail, perform a "pinching" ges-

### FAST FACTS

#### Brain Prosthetics

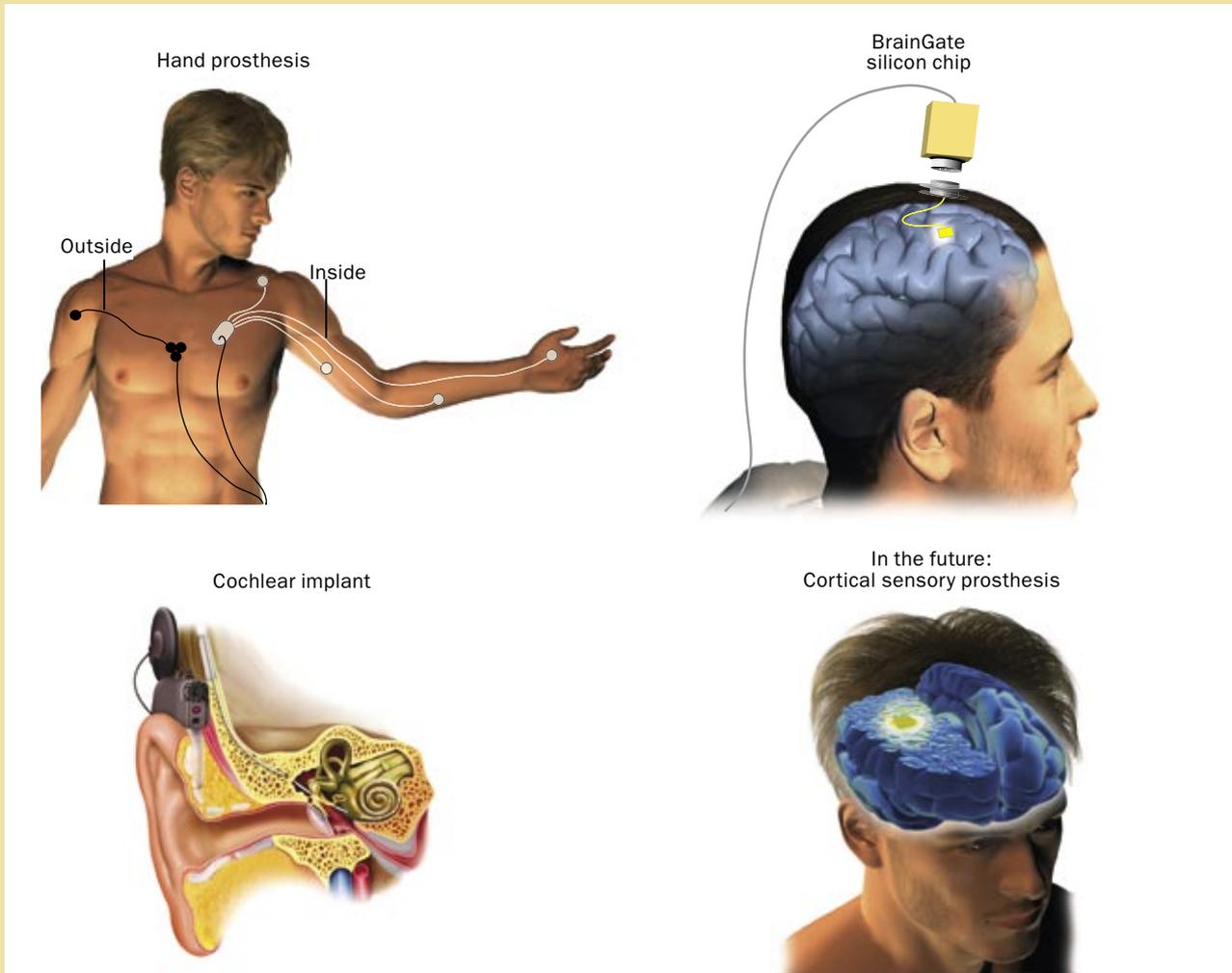
**1>>** Scientists are building devices that help to restore the ability of paralyzed patients to communicate and move by translating neuron signals in their brain into commands that control computer cursors or robots.

**2>>** Now a new wave of brain implants is poised to transfer information *into* the brain, thereby reviving sensory function for patients.

**3>>** With a hearing neuroprosthesis in their brain, deaf gerbils could differentiate between high- and low-frequency tones and changes in interval, as well as more complex sound patterns. The rodents detected these sounds just as well as gerbils that heard them with their ears.

# Replacement Parts for the Nervous System

Neuroprostheses may be implanted in the peripheral (*left*) or central nervous system (*right*). Read-out implants (*top row*) control muscle activity or movement, whereas write-in implants (*bottom row*) lead to sensory perceptions.



ture with the prosthetic hand, and make the robot arm pick up and drop a piece of candy. Of late, he has even used the device, called BrainGate, to make precise copies of geometric figures.

## Supplying Sensation

Whether in the body's periphery or the brain, such "read-out" prostheses detect and relay existing neuronal information—in these cases, motor information—rather than supplying their own signals and data. In contrast, "write-in" prosthetics feed information *into* the brain. Often they supply sensory input by transmitting signals from the environment to elicit sensations such as sight, sound and touch.

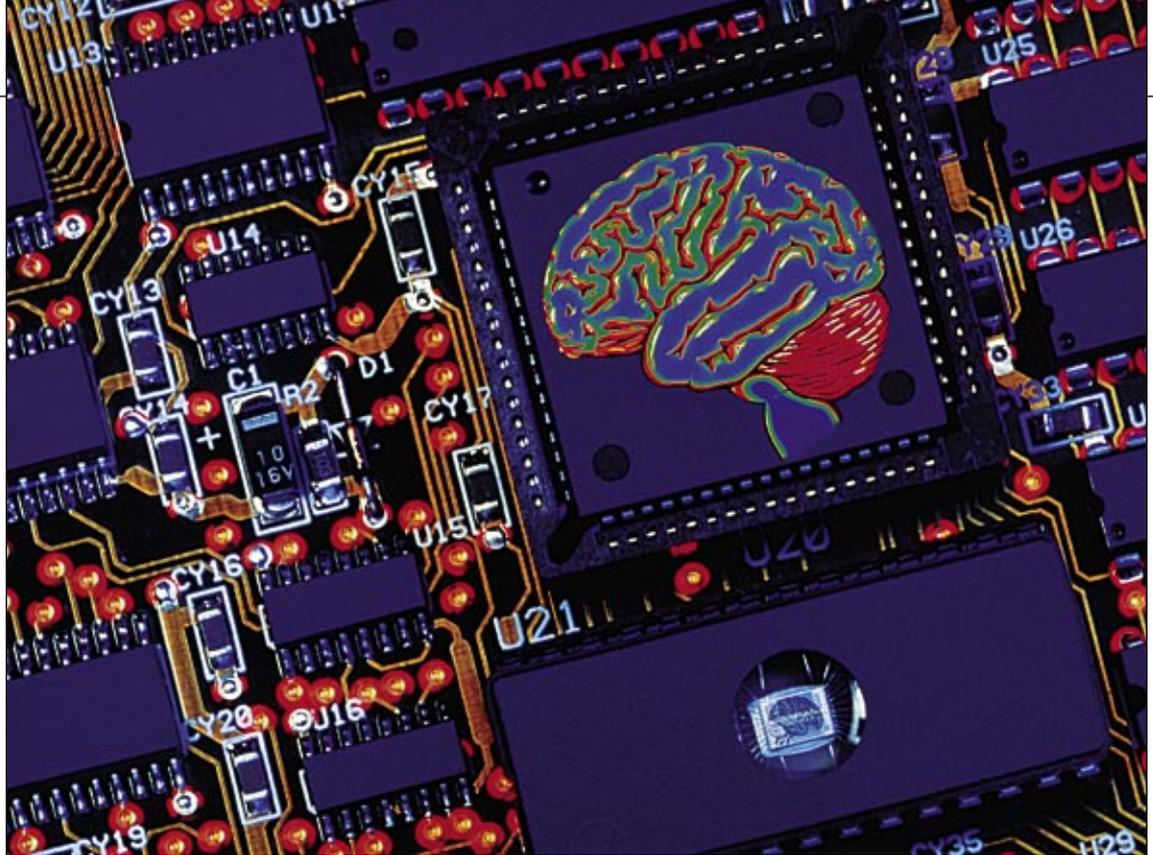
Write-in neuroprostheses are still limited to the

periphery, that is, body regions outside the brain; some, for instance, are located in the sensory nerve tracts that conduct information to the brain from the eye or ear. Perhaps the most successful example of these is the cochlear implant. Sounds registered by a microphone are transformed into electrical impulses that directly stimulate the auditory nerve, which transmits signals from the ear to the brain. The implant thereby bypasses damaged parts of

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To be optimally effective, a sensory prosthesis implanted in the brain would need to integrate incoming sensory information with ongoing brain activity.



the ear itself, enabling some profoundly deaf people to recognize sounds in the environment and to hear and understand speech.

Another brain-input device currently in the testing stage could be the first successful attempt at creating artificial “eyes” for the blind. One such device, developed by researchers at Second Sight Medical Products in Sylmar, Calif., transmits images captured by a video camera to electrodes implanted in the retina at the back of the eye. The Second Sight implant has enabled blind subjects to perceive simple patterns and to distinguish among the light configurations emitted by different objects. In addition, bladder stimulators, such as the Finetech-Brindley system developed by Giles Brindley of the Medical Research Council in London, can help restore some bladder function to paralyzed people by supplying appropriate signals to the neurons that control the release of urine.

Many such peripheral devices, however, do not work in those whose eyes, ears or other organs have become disconnected from their brain through injury or disease. To overcome such problems, scientists have been working since the 1960s on write-in prostheses that could be implanted into the brain regions responsible for senses such as sight, hearing and touch. Thus, a brain implant for hearing might stimulate the auditory cortex, located behind the ears at the brain’s surface, to elicit the perception of sound; to create sight, an implant might excite the visual cortex, located at the rear surface of the brain.

Such methods have provided only the most primitive sensations to date. Electrical probes in the auditory cortex, for instance, enable patients to hear little more than rustling or crackling sounds. And electrically stimulating the visual cortex can cause a patient to see spots of light called phosphenes. But no such device has produced apprehension of the edges and contours that define objects and scenes or the nuances of a conversation or song.

The technology used in such devices, which is not yet fully developed, is only partly to blame for these limitations. The problem is more fundamental. In contrast to peripheral nerves, the sensory cortex does not passively register sensory information the way a camera or audio recorder does. Rather perceptual brain regions are active on their own at all times, functioning, in all probability, to reinterpret incoming sensory data by matching them against related pieces of knowledge, an individual’s past experiences and the brain’s own expectations. That is, knowledge of the structure and meaning of words helps listeners interpret speech, whereas experience with the visual world helps people make sense of changes in a scene’s lighting or perspective. To integrate such information into a perception, the sensory regions exchange data with other parts of the brain that govern higher thought processes. A sensory prosthesis implanted in the brain therefore has to integrate incoming information with ongoing brain activity.

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## Soundless Hearing

Along with physiologists and physicians, we are currently studying the fundamental principles of such a dialogue in Mongolian gerbils (*Meriones unguiculatus*), whose hearing is similar to that of humans at low frequencies. Scientists can also easily teach these gerbils behaviors that indicate what they are sensing. For example, they can be taught to jump from one compartment of a box over a hurdle and into a second

change with the stimulated regions of the cortex. To automate this synchrony, a write-in cerebral prosthesis would also have to read and interpret existing auditory brain signals and use them to calibrate its own activity.

These promising early results prompt the question: Do brain prostheses pose ethical or moral dilemmas that, say, artificial hands or eyes do not? When scientists or doctors decide to tinker directly with the brain, a person may feel that

# Do brain prostheses pose ethical or moral dilemmas that, say, artificial hands or eyes do not?

compartment whenever they hear a specific cue, such as a low tone or a fast rhythm, and otherwise to stay put. In one experiment, we taught the gerbils to jump only on hearing two tones of ascending pitch. (They stood still if the higher note came first.) The rodents also learned a more complex sensory task: leaping only when they heard the same tone played repeatedly at shorter and shorter intervals.

After teaching the gerbils such tricks, we deafened them by experimentally damaging their inner ears. We then implanted prototypes of a two-electrode neuroprosthesis into their auditory cortex. One electrode stimulated a cortical region that processes high frequencies, and the other excited an area that represents low frequencies. With this device alone, these otherwise deaf gerbils could differentiate between high- and low-frequency tones and also detected changes in interval. Additionally, the animals could perceive combination patterns in which we altered both the location and the timing of the stimulation. The rodents learned to do these tasks just as well as gerbils that did not receive the brain implant but that heard the same sound patterns the normal way: through their ears.

Those experiments demonstrated that an auditory cortex implant can produce meaningful perception on its own. Our implant works better, however, if it is precisely synchronized with ongoing neural activity in the auditory cortex. The gerbils learned to tease apart the different sound patterns faster and more accurately when we stimulated that brain region during certain split-second phases of brain activity, as detected by an array of 18 recording electrodes, in comparison to other time points. This finding suggests that the prosthesis is dependent on information ex-

he or she is being altered in a profound, even spiritual way. In principle, a sensory prosthesis in the brain does fundamentally transform a person, because such a device alters an individual's perception of the world. On the other hand, so do many ordinary events of daily life. People are constantly experiencing new things, learning and changing. In doing so, everybody's sense of self is continually evolving.

And yet the deeper scientists penetrate into the mind, the greater the risk of crossing a line between replacing biological hardware and altering an individual's sense of self. As interactive neuroprostheses mature, their developers will need to consider the social and ethical ramifications of their advances. If they manage to do so, we forecast a bright future for synthetic supplements to the brain. **M**

## (Further Reading)

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