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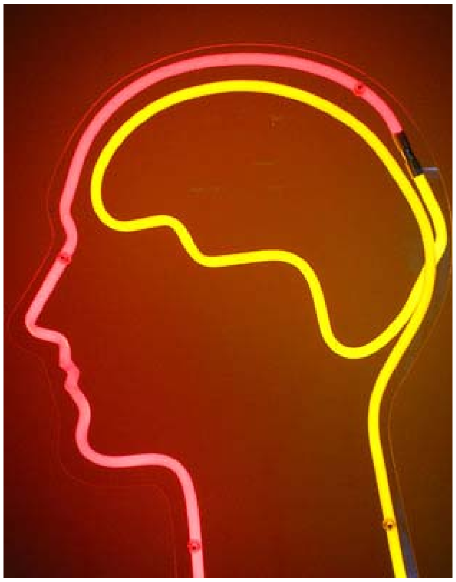
THE TECHNOLOGICAL PROGRESS THAT REVOLUTIONIZED COMPUTING, ELECTRONICS, AND ROBOTICS IN THE 20TH CENTURY WILL TRANSFORM OUR BODIES AND ENHANCE OUR BRAINS IN THE 21ST.

The Expanding Mind
BIG IDEA BY **PETE ESTEP** / MAY 17, 2010

Scarcely a decade has passed since scientists painstakingly sequenced the first bacterial genome, yet today automated human genome sequencing is becoming routine, heralding a new era of medicine. Replacement tissues and even organs can now be grown from a patient's own cells and used without risk of immune rejection. Genetic therapies for a plethora of debilitating conditions are on the horizon; brain and body imaging technologies allow early discovery of potentially harmful pathologies. But as these developments have unfolded, another area of research has simultaneously matured to rival them in its dramatic potential to help people. It's called neuroengineering.

My colleagues and I have expected these events for years, but we are still awed by the results; some things are so powerful that, even if you know they are coming, they remain breathtaking when they actually arrive. Watching a person move a robotic limb or control the functions of a computer, *through thought alone*, we have little choice but to stare in amazement. These breakthroughs were made possible by prototype brain-computer interfaces (BCIs), which allow direct communication between the brain and external devices.



Credit: Dierk Schaefe

Prototype BCIs now facilitate basic motor control of prosthetic limbs and hands, computer keyboards and cursors, and even some features of computer games; new sensory BCI can restore damaged hearing to acceptable levels, and to a limited degree, speech and vision. Though much work remains to be done, many who have witnessed these recent successes are confident that similar but more sophisticated BCI technologies will eventually become routine and widespread.

As these neuroengineering capabilities have emerged, powerful computers, digital storage devices, software, and networking technologies have also relentlessly improved, and these dual progressions now offer a remarkable synergy. Although our minds are quite good at certain things, they absorb, process, store, recall, and share many types of information very slowly and inaccurately. In contrast, computers and digital storage devices excel at these tasks, but our eyes and fingers combined with current computer interface (touchscreens, keyboards, mice, and monitors) still provide extremely inefficient exchange of information. Consequently, vital question lie before us: Should demonstrations of sensory and motor BCI technologies give us reason to expect we could use computers in an analogous manner, to extend cognitive functions, such as learning and memory, in a way that seems as natural as using our own minds? Can we move beyond sensorimotor BCI to create cognitive BCI?

Envision far more efficient learning, allowing the rapid accumulation of or access to knowledge it now takes years to learn. Picture a memory that behaves exactly as you'd like, even in middle age and beyond, where recollections normally begin to lose their edge. Imagine simply remembering all the important information you'd like to recall.

These speculative excursions where we are relieved from our modern state of information overload and forgetfulness allow us a glimpse, a taste of what sophisticated cognitive
BCI might enable. From our current vantage point, such spectacular developments are not on the immediate horizon. Indeed, some eminent neuroscientists have suggested we'll need to understand far more about higher brain functions, and perhaps consciousness itself, to even consider tackling cognitive BCI. But there are sound, compelling reasons to believe the task may not be quite so daunting.

First, sensory and motor functions are thought by many leading researchers to be very similar mechanistically and physiologically to cognitive functions, which is unsurprising since they both may share evolutionary origins in basic motor functions. In the words of Rodolfo Llinás, one of the founders of modern neuroscience, "that which we call thinking is the evolutionary internalization of movement" and "it would be a strange brain if it used different global strategies for motion and cognition." Another reason is that sensory and motor functions are dependent upon cognitive functions such as learning, storage, and recall of relevant memories; sensorimotor BCI technologies have been demonstrated despite our ignorance of the underlying mechanism(s) of how these memories are learned, stored, and recalled.

Of course, similarities between sensorimotor and cognitive functions don't mean that we'll be able to use identical approaches to achieve cognitive BCI, or that the way forward is completely clear. In fact, there is considerable puzzlement among experts on how to proceed, and one reason for this is clear: We possess far less obvious feedback by which we can monitor performance in order to extend and close the "cognitive loop." In sensorimotor BCI loops, feedback is essentially immediate, and highly similar to lost function. Consider as an example a prosthetic limb. A natural limb has nerves that inform the brain of spatial position. Eyes connected to the same brain are able to visually monitor the arm, confirming nerve feelings but also providing a separate sensory channel for feedback surveillance. If the limb is lost and replaced by a prosthesis, nerves will no longer transmit information, but visual feedback will remain allowing the user to control the arm's movement and position. Similarly obvious feedback mechanisms guide the development and use of most other sensorimotor BCIs.

Now, let's consider a third reason to doubt that we must deeply understand higher brain functions or consciousness to achieve cognitive BCI: Although extension and closure of the cognitive loop is difficult to imagine and implement, evolution accomplished this feat through the blind, iterative application of natural selection. Of course, we must do better in many respects. We'd like the development of cognitive BCI to be fast, we'd like the results to be highly optimized and easily improved, and we must avoid creating unnecessary pain and suffering, as often occurs in nature's tinkerings.

While the specific paths scientists and engineers ultimately will take to develop a cognitive BCI are not yet clear, research in this area is progressing rapidly as comprehensively reviewed in a recent article in *Behavioral Brain Research* written by Mijail Serruya and Michael Kahana, both of the University of Pennsylvania. The article is entitled "Techniques and Devices to Restore Cognition," and its survey of new developments in neuroengineering reveals the tremendous potential for cognitive BCI and related technologies.

There are too many important projects to list here, but recent highlights include work by many leading companies, engineers, and scientists. BCI pioneer Philip Kennedy of Neural Signals, Inc. has been working with increasing success to give "locked-in" patients control of an outboard speech synthesizer, a technology that lies at the intersection of sensory, motor, and cognitive BCI. Theodore Berger of USC is leading a project to create an artificial hippocampus, the so-called "librarian of the brain." Ed Boyden and Hugh Herr of MIT have established the MIT Media Lab Center for Human Augmentation, and Dr. Boyden's research team has produced and demonstrated the first optical control device and optically responsive circuit elements for brain engineering. Steve Potter of Georgia Tech has made the first clear demonstration of "synthetic learning" by computer training of living neuronal networks to control robot behavior.

This diversity of highly experimental research contributes to the overall advance toward cognitive BCI, but at least one better established area of biomedicine, functional brain imaging, has also begun to make important contributions. Functional brain imaging is a collection of technologies used to visualize changes in the behaving brain; it expands the repertoire of approaches for using machines to move information into and out of our heads. One very important approach in recent years has been functional Magnetic Resonance Imaging (fMRI), which was used in several landmark studies last year to "read minds." These studies demonstrate a growing ability to infer or predict what is in a person's mind and strongly suggest that reconstructions of sensory experiences, memories, mental imageries, and dreams are within reach.

Even with these and many other recent successes, the neuroengineering community remains relatively small, and funding for important but unconventional research is lacking relative to the field's potential. As a scientist and technologist, I felt dwarfed by the enormity of the technical challenges of artificially extending and closing the cognitive loop. I thought it important to enable and support many researchers and leading technologists working together to solve the problem, rather than attempting to solve it directly myself. So my colleagues and I started the Innerspace Foundation to help fund the world's most talented and visionary researchers, empowering them to produce what we believe will be the most highly leveraged of all humanitarian technologies. The foundation is a hybrid organization that includes aspects of both a typical research funding institution, and a prize-creation and management organization, all designed to reward those who most effectively translate their ideas into functional technologies.

We have adopted this unique organizational structure to accelerate the responsible and ethical development of these uniquely important technologies, because we believe, in the long run, cognitive BCI and related technologies will have a profoundly positive impact. But these developments likely lie on—and a bit beyond—the visible technological horizon, so we also are focused on more near-term and tractable technologies, like basic memory-assist devices, which have the potential to improve the lives of those with serious memory inabilities and disabilities. The Innerspace Foundation intends to be an active participant in funding and guiding the maturation of these and other enabling technologies, and in the conversation to help ensure that they will be developed responsibly for everyone.