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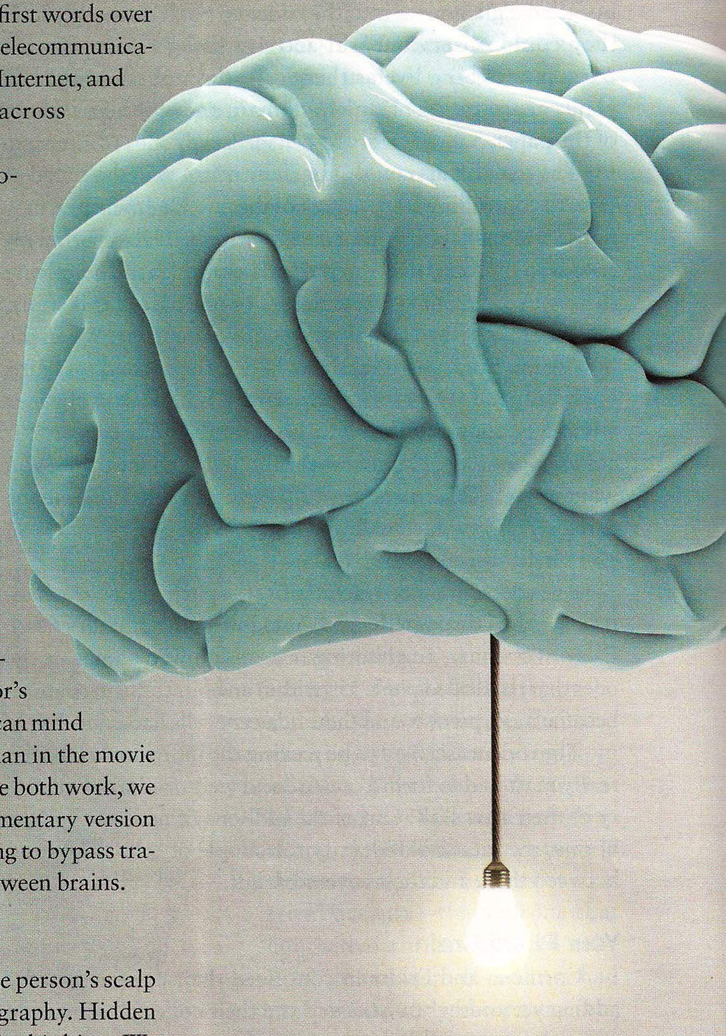
WHEN TWO BRAINS



"Mr. Watson, come here!" Alexander Graham Bell uttered these first words over a telephone 138 years ago. With that statement he ushered in the telecommunications revolution that would ultimately bring us mobile phones, the Internet, and near-instantaneous exchanges of speech, text and video across continents.

Yet speech can be limiting. Some abstract concepts and emotions can be difficult to convey with words. And certain disabilities rob people of their full communicative powers even as their minds remain otherwise intact.

Neural engineers have spent several decades developing ways to overcome such impairments. Technologies known as brain-computer interfaces (BCIs) are now beginning to allow paralyzed individuals to control, say, a computer cursor or a prosthetic limb with their brain signals. BCIs rely on data-processing techniques to extract a person's intention to move and then relay that information to the device he or she wishes to control.

In 2010 one of us (Rao) had a realization: perhaps we could use this same principle to beam thoughts from one human brain to another. Imagine if a teacher could convey a mathematical proof directly to your brain, nonverbally. Or perhaps a medical student could learn a complex surgical skill straight from a mentor's mind. Such ideas have been a staple of science fiction, from the Vulcan mind meld of *Star Trek* to the control of an avatar by a paraplegic human in the movie *Avatar*. In conversations at the University of Washington, where we both work, we realized that we had all the equipment we needed to build a rudimentary version of this technology. Along with other scientists, we are now learning to bypass traditional modes of communication and swap thoughts directly between brains.

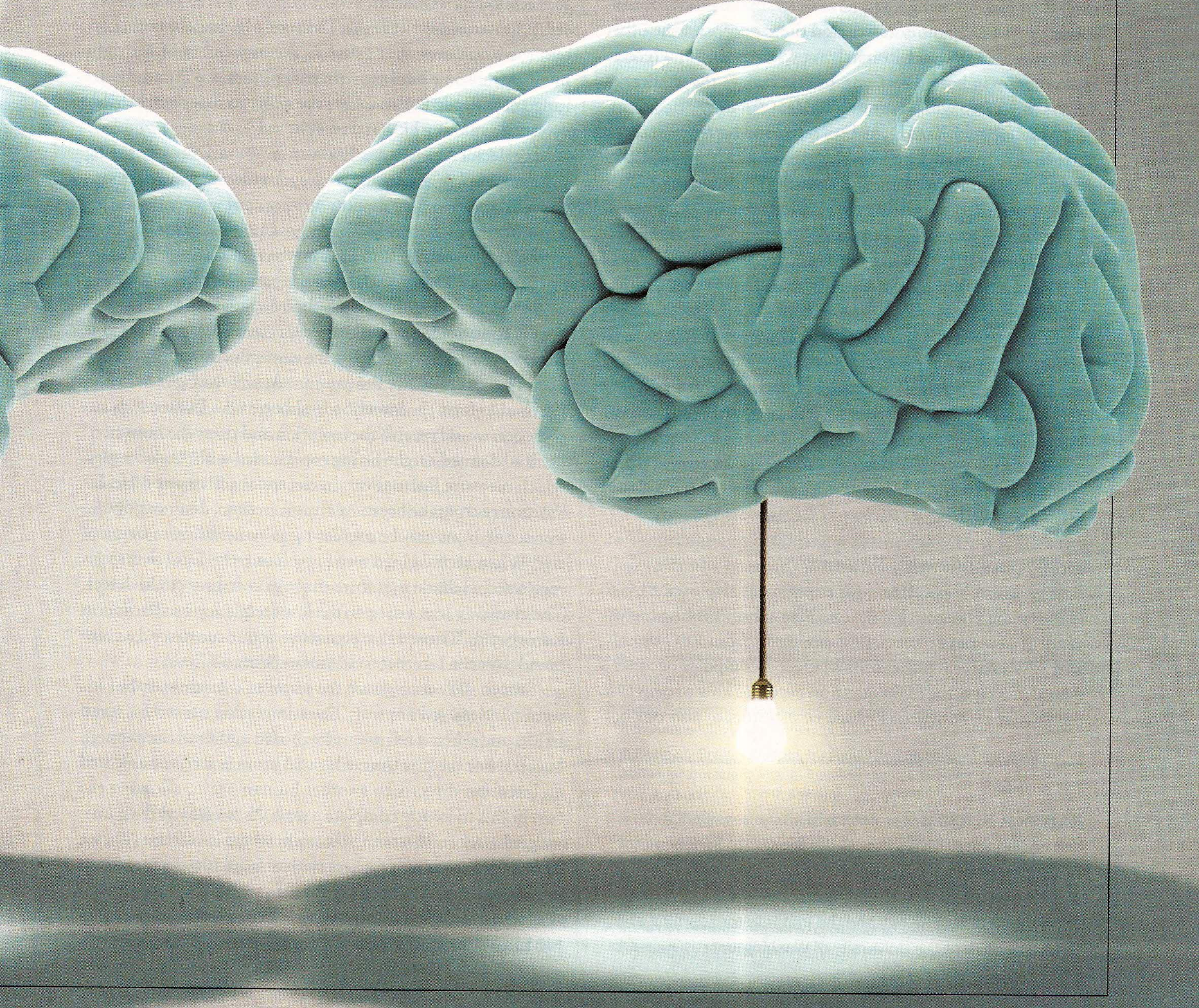
Mind Melds Made Real

The gist of our strategy was to use electrodes arranged on one person's scalp to pick up brain waves, a technique known as electroencephalography. Hidden in that neural hubbub are signals that indicate what a person is thinking. We would focus on extracting one such pattern and then send it over the Internet to a second person. The signal would dictate how to electrically stimulate the recipient's brain. Because neurons communicate electrically, we can strategically influence their messaging by applying electric current or a magnetic field, among

CONNECT

The dawn of human brain-to-brain communication has arrived

By Rajesh P. N. Rao and Andrea Stocco



FAST FACTS
CONNECTED BRAINS

1. Two humans have transmitted thoughts directly between their brains in a recent experiment.
2. Scientists used electroencephalography to decode the neural chatter in a sender's brain and transcranial magnetic stimulation to induce neurons to fire in a recipient's brain.
3. Direct brain-to-brain communication may one day offer a fundamentally different way for people to share and transfer knowledge.

other tricks. In short, we would use one person's brain data to produce a specific pattern of neural activity in another individual.

By the time we finally tried out our design, two other teams of neuroscientists had also transmitted signals directly between brains, though not between two humans. The experiments so far, including ours, have been simple proofs of concept: one participant is designated the sender, and the other subject is the receiver. Ultimately we want to send and receive information in both directions, but we believe the challenges of that next step will be surmountable.

Miguel Nicolelis of Duke University and his team were the first to demonstrate brain-to-brain messaging. In early 2013 they published an experiment in which simple communiqués were transmitted between two rats on different continents. Later that year another experiment was published that involved humans as the senders. In it, six people wearing an EEG headset were each paired with an anesthetized rat. Seung-Schik Yoo of Harvard Medical School and his collaborators made use of an emerging technique that delivers highly focused ultrasonic energy through the skull to specific regions of the brain. When a participant decided to move the rat's tail, that person's corresponding brain activity triggered an ultrasonic pulse that entered the rodent's brain. The 350-kilohertz burst of acoustic pressure was aimed at the rat's motor cortex, which controls movement. About two seconds later the rodent's tail lifted and then fell.

Firing Cannons with Neurons

Similar to Yoo's effort, our experiment also used EEG to identify the control signal. The Rao laboratory has many years of experience extracting intentions from EEG signals, so it was a natural place to start. Once a computer decodes a neural message, the main question becomes how to deliver it. Somewhat serendipitously, one of us (Stocco) and our colleague Chantel Prat were investigating transcranial magnetic stimulation (TMS), a technology approved by the Food and Drug Administration for the treatment of major depression. This method relies on pulses of a magnetic field to induce neurons in a specific area of the recipient's brain to fire.

To deliver the pulses, you place an insulated metal coil next to a person's head. When electricity discharges into the coil, a magnetic field forms around the neurons in the area near the coil. When the electricity stops running, the magnetic field disappears. The sudden rise and fall of the magnetic field induces a tiny electric current in the neurons that had been engulfed by that field, making them more likely to fire. When they do, a chain of connected neurons also activates.

Depending on how you position the coil and configure the magnetic field, you can also induce involuntary movements. We realized we could use this generally unwanted aspect of the technology to generate crude motions in a recipient. In our setup, Stocco would sit with a TMS coil over his left motor cortex, the brain area that controls the movement of his right hand. After some fiddling with parameters, we found the arrangement needed to stimulate the neurons that control Stocco's wrist, making his hand twitch.

We decided to test our brain-to-brain interface by seeing if we could play a simple two-player video game. After students in our labs spent months writing computer code and integrating the technologies, on August 12 of last year we finally tried out our setup. Rao took on the role of the sender of information, and Stocco assumed the part of the receiver.

In the game, a pirate ship is shooting rockets at a city. The goal is to fire a cannon to intercept each rocket. Rao alone could see the screen displaying the game. But only Stocco could press the button to fire the cannon. At just the right moment, Rao had to form the intention to shoot, and a few seconds later Stocco would receive the intention and press the button.

Rao donned a tight-fitting cap studded with 32 electrodes, which measure fluctuations in electrical activity at different locations across the head. At any given time, distinct populations of neurons may be oscillating at many different frequencies. When he imagined moving a hand, the EEG electrodes registered a telltale signature that our software could detect. The giveaway was a drop in the low-frequency oscillations in Rao's brain. We used that signature as our cue to send a command over the Internet to stimulate Stocco's brain.

Stocco did not register the impulse consciously, but his right hand moved anyway. The stimulation caused his hand to lift, and when it fell it hit a keyboard and fired the cannon. Success! For the first time, a human brain had communicated an intention directly to another human brain, allowing the two brains to jointly complete a task. As we played the game, we got better and better, to the point where in our last run, we intercepted the pirate rockets with almost 100 percent accuracy. Rao learned how to imagine moving his hand in a consistent manner, giving the computer a chance to make sense of his EEG brain data. Stocco found that he did not know his

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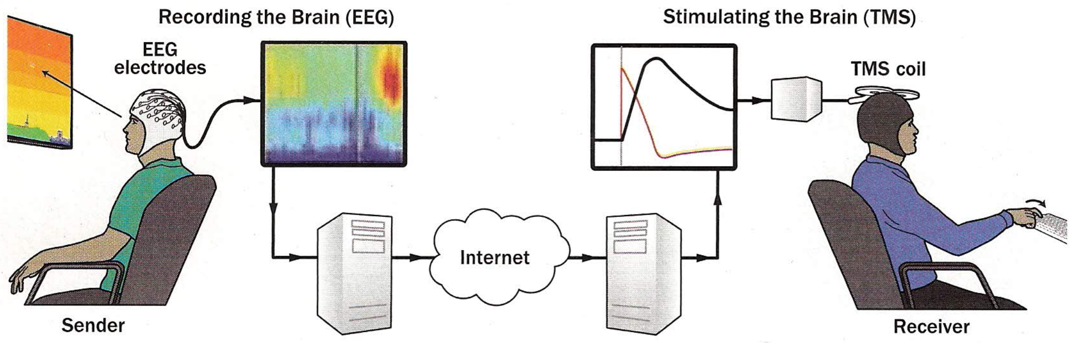
To play a computer game with brain waves alone, one person imagines making a move. An EEG cap registers that neural activity. A computer triggers stimulation of a second player's motor cortex, which causes one hand to lift and hit a key.



wrist was moving until he felt or saw his hand in motion.

We have now replicated our findings with several other pairs of humans. Not every trial went perfectly in these experiments, but in all cases, whenever an intention was correctly detected by the EEG system, the information was communicated directly to the receiver's brain using TMS. Throughout the experiment, both subjects were conscious of each other's roles and willingly cooperated to solve a mutually agreed-on task. When a pirate rocket gets hit, the sender knows that his or her partner's brain enacted a movement in response to the sender's own brain activity. We believe this conscious cooperation between subjects is the ultimate goal of true brain-to-brain communication, something that may be hard to achieve with animal studies.

One weakness of our pilot study is that the receiver is passive, essentially lending a hand to the sender's brain. Our next set of experiments will explore targeting other brain regions to produce a conscious thought. For example, we believe we can send visual, as opposed to motor, information from one brain to another—imagine a recipient suddenly seeing the color green and knowing that the hue means he or she should perform a certain action. Indeed, in August one group of scientists used the same technologies as we did to send a crude visual message from one human to another.

Such simple experiments might seem a long way from the complex thought sharing of a Vulcan mind meld, but we believe it is important to begin with a good understanding of how sensory and motor information can be shared. We know much more about how the brain represents sensory and motor signals than about how it encodes complex ideas, such as how to solve differential equations or which city is the capital of Latvia. In addition, many scientists now believe that sensory and motor information are the building blocks of more complex knowledge. We can only venture into transferring bigger concepts after we have mastered simpler forms.

What the Future Holds

We envision several scenarios in which such technology might one day be used. People undergoing rehabilitation, for example, could receive direct guidance from a therapist to speed up their recovery. Those who are paralyzed and unable to speak could use it to communicate their thoughts and feelings directly to loved ones. As brain-to-brain technologies develop, people may adopt them to solve the challenges facing humanity by literally putting their heads together.

Enhancing the brain's abilities with technology is itself not new, of course. We have augmented our physical abilities using automobiles and airplanes, our memories using books and the Internet, and our analytic and communicative abilities using computers and smartphones. Brain-to-brain communication might amplify the social side of our nature—our core tendency to share thoughts with one another.

If scientists and engineers eventually achieve true brain-to-brain communication, the ethical implications will be enormous. All technologies, from the humble kitchen knife to sophisticated genetic engineering, can be used to do good or abused to cause harm. Brain-to-brain communication is no exception. Many a science-fiction plot has benefited from larger than life villains abusing brain implants for nefarious purposes. Security and privacy, already of paramount importance in today's world of highly connected devices, will also be critical factors in any future era of linked-up brains. Neurosecurity researchers will need to minimize the risks of brain-to-brain technology by developing highly secure communications protocols, and policy makers will need to pass laws to minimize any possibility of abuse.

Ultimately we must ask ourselves: Do the benefits of brain-to-brain communication outweigh its risks? How will it shape the evolution of humans? Will it transform society for the better? As our little experiment demonstrates, we need to begin debating these questions now. M

FURTHER READING

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- **A Brain-to-Brain Interface for Real-Time Sharing of Sensorimotor Information.** Miguel Pais-Vieira et al. in *Scientific Reports,* Vol. 3, Article No. 1319; February 28, 2013.
- **A Direct Brain-to-Brain Interface in Humans.** Rajesh P. N. Rao et al. University of Washington Computer Science and Engineering Technical Report No. UW-CSE-14-07-01; July 2014. **http://homes.cs.washington.edu/~rao/brain2brain**

From Our Archives

- **Mind out of Body.** Miguel A. L. Nicolelis; *Scientific American,* February 2011.