CUTTING-EDGE BRAIN TECHNOLOGIES CAN ERASE TRAUMATIC MEMORIES AND READ PEOPLE'S THOUGHTS. THEY COULD ALSO BECOME THE 21ST CENTURY'S MOST DANGEROUS WEAPONS.

# MIND FIELD

BY TIM REQUARTH

*ILLUSTRATIONS BY* JIMMY TURRELL

**ON AN OTHERWISE** routine July day, inside a laboratory at Duke University, two rhesus monkeys sat in separate rooms, each watching a computer screen that featured an image of a virtual arm in two-dimensional space. The monkeys' task was to guide the arm from the center of the screen to a target, and when they did so successfully, the researchers rewarded them with sips of juice.

But there was a twist. The monkeys were not provided with joysticks or any other devices that could manipulate the arm. Rather, they were relying on electrodes implanted in portions of their brains that influence movement. The electrodes were able to capture and transmit neural activity through a wired connection to the computers.

Making things even more interesting, the primates shared control over the digital limb. In one experiment, for example, one monkey could direct only horizontal actions, while the other guided just vertical motions. Yet the monkeys began to learn by association that a particular way of thinking resulted in the movement of the limb. After grasping this pattern of cause and effect, they kept up the behavior—joint thinking, essentially—that led the arm to the target and earned them juice.

Neuroscientist Miguel Nicolelis, who led the research, published earlier this year, has a name for this remarkable collaboration: a "brainet." Ultimately, Nicolelis hopes that brain-to-brain cooperation could be used to hasten rehabilitation in people who have neurological damage—more precisely, that a healthy person's brain could work interactively with that of a stroke patient, who would then relearn more quickly how to speak or move a paralyzed body part.

His work is the latest in a long string of recent advances in neurotechnologies: the interfaces applied to neurons, the algorithms used to decode or stimulate those neurons, and brain maps that produce a better overall understanding of the organ's complex circuits governing cognition, emotion, and action. From a medical perspective, a great deal stands to be gained from all this, including more dexterous prosthetic limbs that can convey sensation to their wearers, new insights into diseases like Parkinson's, and even treatments for depression and a variety of other psychiatric disorders. That's why, around the world, major research efforts are underway to advance the field.

But there is a potentially dark side to these innovations. Neurotechnologies are

"dual-use" tools, which means that in addition to being employed in medical problem-solving, they could also be applied (or misapplied) for military purposes.

The same brain-scanning machines meant to diagnose Alzheimer's disease or autism could potentially read someone's private thoughts. Computer systems attached to brain tissue that allow paralyzed patients to control robotic appendages with thought alone could also be used by a state to direct bionic soldiers or pilot aircraft. And devices designed to aid a deteriorating mind could alternatively be used to implant new memories, or to extinguish existing ones, in allies and enemies alike.

Consider Nicolelis's brainet idea. Taken to its logical extreme, says bioethicist Jonathan Moreno, a professor at the University of Pennsylvania, merging brain signals from two or more people could create the ultimate superwarrior. "What if you could get the intellectual expertise of, say, Henry Kissinger, who knows all about the history of diplomacy and politics, and then you get all the knowledge of somebody that knows about military strategy, and then you get all the knowledge of a DARPA engineer, and so on," he says, referring to the U.S. Defense Advanced Research Projects Agency. "You could put them all together." Such a brainet would create near-military omniscience in high-stakes decisions, with political and human ramifications.

To be clear, such ideas are still firmly in the realm of science fiction. But it's only a matter of time, some experts say, before they could become realities. Neurotechnologies are swiftly progressing, meaning that eventual breakout capabilities and commercialization are inevitable, and governments are already getting in on the action. DARPA, which executes groundbreaking scientific research and development for the U.S. Defense Department, has invested heavily in brain technologies. In 2014, for example, the agency started developing implants that detect and suppress urges. The stated aim is to treat veterans suffering from conditions such as addiction and depression. It's conceivable, however, that this kind of technology could also be used as a weapon—or that proliferation could allow it to land in the wrong hands. "It's not a question of *if* non-state actors will use some form of neuroscientific techniques or technologies," says James Giordano, a neuroethicist at Georgetown University Medical Center, "but when, and which ones they'll use."

People have long been fascinated, and terrified, by the idea of mind control. It may be too early to fear the worst—that brains will soon be vulnerable to government hacking, for instance—but the dual-use potential of neurotechnologies looms. Some ethicists worry that, absent a legal framework to govern these tools, advances in the lab could enter the real world dangerously unencumbered.

For better or for worse, Giordano says, "the brain is the next battlespace."

D

**DRIVEN BY THE DESIRE** to better understand the brain, arguably the most unknowable of human organs, the past 10 years have seen a burst of neurotechnology innovation. In 2005, a team of scientists announced that it had successfully read a human's mind using functional magnetic resonance imaging (fMRI), a technique that measures blood flow triggered by brain activity. A research subject, lying still in a full-body scanner, observed a small screen that projected simple visual stimuli—a random sequence of lines oriented in different directions, some vertical, some horizontal, and some diagonal. Each line's orientation provoked a slightly different flurry of brain functions. Ultimately, just by looking at that activity, the researchers could determine what kind of line the subject was viewing.

It took only six years for this brain-decoding technology to be spectacularly extended—with a touch of Silicon Valley flavor—in a series of experiments at the University of California, Berkeley. In a 2011 study, subjects were asked to watch Hollywood movie trailers inside an fMRI tube; researchers used data drawn from fluxing brain responses to build decoding algorithms unique to

**THE SAME BRAIN-SCANNING MACHINES MEANT TO DIAGNOSE ALZHEIMER'S OR AUTISM COULD POTENTIALLY READ SOMEONE'S PRIVATE THOUGHTS.**

each subject. Then, they recorded neural activity as the subjects watched various new film scenes—for instance, a clip in which Steve Martin walks across a room. With each subject's algorithm, the researchers were later able to reconstruct this very scene based on brain activity alone. The eerie results are not photo-realistic, but impressionistic: a blurry Steve Martin floats across a surreal, shifting background.

Based on these outcomes, Thomas Naselaris, a neuroscientist at the Medical University of South Carolina and a coauthor of the 2011 study, says, "The potential to do something like mind reading is going to be available sooner rather than later." More to the point, "It's going to be possible within our lifetimes."

Expediting this is the rapidly advancing technology behind brain-machine interfaces (BMI)—neural implants and computers that read brain activity and translate it into real actions, or that do the reverse, stimulating neurons to create perceptions or physical movements. The first sophisticated interface made it out of the operating room in 2006, when neuroscientist John Donoghue's team at Brown University implanted a square chip—measuring less than one-fifth of an inch across and holding 100 electrodes—into the brain of then-26-year-old Matthew Nagle, a former high school football star who had been stabbed in the neck and paralyzed below the shoulders. The electrodes were positioned over Nagle's motor cortex, which, among other things, controls arm motions. In a matter of days, Nagle, with his device wired to a computer, could move a cursor and even open email just by thinking about it.

Eight years later, BMIs had grown profoundly more complex, as demonstrated at the 2014 World Cup in Brazil. Juliano Pinto, a 29-year-old with complete paralysis of the lower trunk, donned a mind-controlled robotic exoskeleton—developed by Duke's Nicolelis—to deliver the kickoff at the tournament's opening ceremony in São Paulo. A cap on Pinto's head picked up signals from his brain, indicating his intention to kick. His computer, strapped to his back, received these signals and then spurred the robotic suit to execute the action.

**"THE POTENTIAL TO DO SOMETHING LIKE MIND READING IS GOING TO BE AVAILABLE SOONER RATHER THAN LATER."**

Neurotechnologies go further still, dealing with the complexity of memory. Studies have shown that it might be possible for one person to insert thoughts into another's mind, like a real-life version of the blockbuster film *Inception*. In a 2013 experiment led by Nobel laureate Susumu Tonegawa at the Massachusetts Institute of Technology, researchers implanted what they called a "false memory" in a mouse. While observing the rodent's brain activity, the researchers placed the animal in a container, and watched as the mouse became acquainted with its surroundings. The team was able to pick out the precise network of cells among millions that were stimulated in the mouse's hippocampus while it formed a memory of the space. The next day, the researchers put the animal in a new container it had never seen before, and delivered an electric shock while simultaneously activating the neurons the mouse had used to remember the first box. The association was formed: When they put the mouse back in the first container, it froze in fear, even though it had never experienced a shock there. Just two years after Tonegawa's discovery, a team at the Scripps Research Institute administered mice a compound that could remove a specific memory while leaving others intact. This kind of erasing technology could be used to treat post-traumatic stress, eliminating a painful thought and thus improving someone's quality of life.

It's likely this research momentum will continue, because the mind-science revolution is being bankrolled lavishly. In 2013, the United States launched the BRAIN Initiative (Brain Research through Advancing Innovative Neurotechnologies), with hundreds of millions already earmarked for studies within the first three years; future funding has not yet been determined. (The National Institutes of Health (NIH), one of the five federal agencies involved in the project, has requested $4.5 billion, spread over a 12-year period, for its part alone.) For its part, the European Union has devoted an estimated $1.34 billion to its 10-year Human Brain Project, which began in 2013. Both programs are designed to build innovative

tools that will map the brain's structure and eavesdrop on the electrical activity of its billions of neurons. In 2014, Japan launched a similar initiative, known as Brain/MINDS (Mapping by Integrated Neurotechnologies for Disease Studies). And even Paul Allen, Microsoft's co-founder, is throwing hundreds of millions of dollars into his own Allen Institute for Brain Science, a large-scale effort to create brain atlases and unravel how vision works.

To be sure, as incredible as recent inventions are, most of today's neurotechnologies are inchoate. They do not function for very long inside the brain, can only read or stimulate a limited number of neurons, or require a wired connection. "Mind-reading" machines, for example, rely on expensive equipment available only in lab or hospital settings to produce even their crude results. Yet the commitment from researchers and funders alike to neuroscience's future means devices will likely become only more sophisticated, ubiquitous, and accessible with every passing year.

Each new technology will bring creative possibilities for its application. Ethicists warn, however, that among these uses is weaponization.

It does not appear that, to date, any brain tools have been employed as weapons, which is not to say their battlefield values aren't currently being considered: Earlier this year, for example, a quadriplegic woman flew an F-35 fighter-jet simulator using only her thoughts and a brain implant whose development was funded by DARPA. It seems the possibility of weaponization might not lie in some distant future—and there is ample precedent for the rapid transition of technology from basic science to disruptive, global menace. After all, just 13 years elapsed between the discovery of the neutron and the atomic blasts in the skies over Hiroshima and Nagasaki.

**MIND MANIPULATION BY** governments would be safely in the domain of conspiracy theorists and fictional thrillers if world powers didn't have such a checkered past with neuroscience. In one bizarre set of experiments conducted between 1981 and 1990, Soviet scientists built equipment designed to disturb the functioning of neurons in the body and brain by exposing people to various levels of high-frequency electromagnetic radiation. (The results of this research are still unknown.) Over many decades, the Soviet Union spent more than $1 billion on such mind-control schemes.

Perhaps the most notorious examples of U.S. abuses of neuroscience occurred from the 1950s into the 1960s, when Washington pursued a wide-ranging research program to find ways of monitoring and influencing human thoughts. CIA investigations, code-named MK-Ultra, promoted "research and development of chemical, biological, and radiological materials capable of employment in clandestine operations to control human behavior," according to a 1963 CIA inspector general's report. Some 80 institutions, including 44 colleges and universities, were involved, but they were often funded under the veil of other scientific goals, leaving participants unaware they were carrying out Langley's bidding. The program's most infamous aspects involved dosing individuals—some unwittingly—with LSD. One Kentucky man was administered the drug for 174 consecutive days. Equally harrowing, however, were the MKUltra projects that focused on mechanisms of extrasensory perception and electronic manipulation of subjects' brains, as well as attempts to gather, interpret, and influence the thoughts of others through hypnosis or psychotherapy.

Today, there is no evidence that the United States is similarly abusing neurotechnology for national security purposes. The armed forces, though, remain deeply committed to advancing the field. In 2011, according to figures tabulated by Margaret Kosal, a professor at the Georgia Institute of Technology, the Army set aside $55 million, the Navy $34 million, and the Air Force $24 million to pursue neuroscience research. (The U.S. military, it should be noted, is the primary funder of various scientific fields, including engineering and computer science.) In 2014, the Intelligence Advanced Research Projects

**Jan Scheuermann, who has quadriplegia, brings a chocolate bar to her mouth using a robot arm she is guiding with her thoughts. She later flew an F-35 fighter-jet simulator.**

COURTESY OF UPMC

Activity, or IARPA, a research organization that develops cutting-edge technology for U.S. intelligence agencies, pledged $12 million to design performance-enhancing techniques, including electrical stimulation of the brain for "optimizing human adaptive reasoning"—that is, for making the analysts smarter.

The real energy, however, is emanating from DARPA, an agency of international intrigue and envy. It funds about 250 projects at any given time, recruiting and leading teams of experts from academia and industry to work on ambitious, highly defined assignments. DARPA's knack for funding visionary projects that remake the world—the Internet, GPS, and the stealth fighter, just to name a few—is unparalleled. In 2011, DARPA, which has a modest (by defense standards) annual budget of $3 billion, slated $240 million for neuroscience research alone. It has also already committed some $225 million to the first few years of the BRAIN Initiative, only $50 million less than the project's top funder, the NIH, during that same period.

With DARPA's game-changing model and international cachet, perhaps it was only a matter of time before other world powers began emulating it. This January, India announced that it would reshape its Defence Research & Development Organisation along the lines of DARPA. Last year, Russia's military announced its $100 million support of the newly minted Foundation for Advanced Research. In 2013, Japan made public the creation of an agency with "DARPA of the United States in mind," in the words of Science and Technology Minister Ichita Yamamoto. (It has been dubbed "JARPA" by some observers.) The European Defence Agency was established in 2001, answering the call for a "European DARPA." And there are even efforts to export the DARPA model to corporations, such as Google.

What role neuroscience will play at these research centers has yet to be determined. However, given recent progress in brain technologies, DARPA's interest in it, and the new hubs' desire to follow the Pentagon's lead, it's likely the field will get at least some—if not substantially more—attention. Robert McCreight, a former U.S. State Department official who specialized in arms control, among other security issues, for over two decades, says this "competitive environment" could feed into a sort of neurological space race, a contest to control and commoditize neurons. The subsequent risk is that research will be channeled toward weaponization—toward making the brain a tool for fighting wars more effectively.

It isn't hard to imagine what this might look like. Today, a head cap equipped with electrodes gathers from the scalp someone's electroencephalographic (EEG) brain signals relevant only to an intended purpose, like kicking a ball; tomorrow, EEG-capturing electrodes could surreptitiously collect weaponry access codes. Likewise, a BMI could become a data siphon—used, say, to hack into an enemy spy's thoughts. Arguably more frightening, if terrorists, hackers, or other criminals were to acquire such neurotechnologies, they could use the tools to engineer single-minded assassins or steal personal information, such as passwords or credit card numbers.

Troublingly, little seems to be preventing these scenarios from materializing. Very few international agreements or even national laws effectively protect personal privacy, and none pertain directly to brain technologies. When it comes to dual use and weaponization, far fewer barriers exist, exposing the human brain as a vast, lawless territory.

N

**NEUROSCIENCE FALLS INTO** a sort of chasm in international law. A neuroweapon that co-opts a brain is "not biological. It's not chemical. It's electronic," says Marie Chevrier, a professor of public policy at Rutgers University. That's a critical distinction, because the two existing U.N. treaties—the Biological Weapons Convention (BWC) and Chemical Weapons Convention (CWC)—that in theory could be used to limit abuses of brain technologies contain no provisions for electronic arms. Indeed, the documents weren't written in such a way as to cover all emerging trends, which means certain weapons can be regulated only *after* they exist.

Chevrier argues that because neuroweapons would affect the brain, a biological system, the BWC, which prohibits the use of harmful or deadly biological organisms, or their toxins, could be modified to include them. She isn't alone: Many ethicists are pushing for the closer involvement of neuroscientists during the convention's regular reviews, when member states decide upon changes to the treaty. What the process lacks currently, Chevrier says, is a scientific board. (At a meeting pertaining to the treaty this August, one of the key proposals on the table was the creation of such an entity, which would include neuroscientists; the outcome was not known as of press time.) Technical input could spur state parties into action. "Politicians don't have an understanding of how dangerous the threat could be," Chevrier argues.

Even with a board, however, the glacial pace of U.N. bureaucracy would likely prove a problem. BWC review conferences, where states report on new technologies that could be adapted into biological weapons, happen only every five years—all but ensuring that changes to the treaty are considered well after the latest scientific advances. "The general tendency is always that science and technology take ardent strides, and ethics and politics creep up behind," says Giordano, the neuroethicist at Georgetown's Medical Center. "They tend to be more reactive, not proactive." (Ethicists already have a name for this lag: the Collingridge dilemma, named for David Collingridge, who in his 1980 book, *The Social Control of Technology*, argued that it is difficult to predict the potential impact of a new technology and thus impossible to enact policy to stay ahead of it.)

But Moreno, the University of Pennsylvania bioethicist, says this isn't an excuse for inaction. Ethics experts have a duty to ensure that scientific developments and the potential threats they pose are explained fully to policymakers. Moreno argues that the NIH should establish a permanent neuroethics research program. The United Kingdom's Royal Society took a step in that direction five years ago, when it convened a steering group of neuroscientists and ethicists. Since then, the group has published four reports on neuroscience advances, including one on conflict and national security implications. That document calls for neuroscience to be a focal topic at BWC review meetings and urges bodies, such as the World Medical Association, to conduct studies on the potential weaponization of any technologies that affect the nervous system, including those, such as BMIs, not explicitly covered by international law.

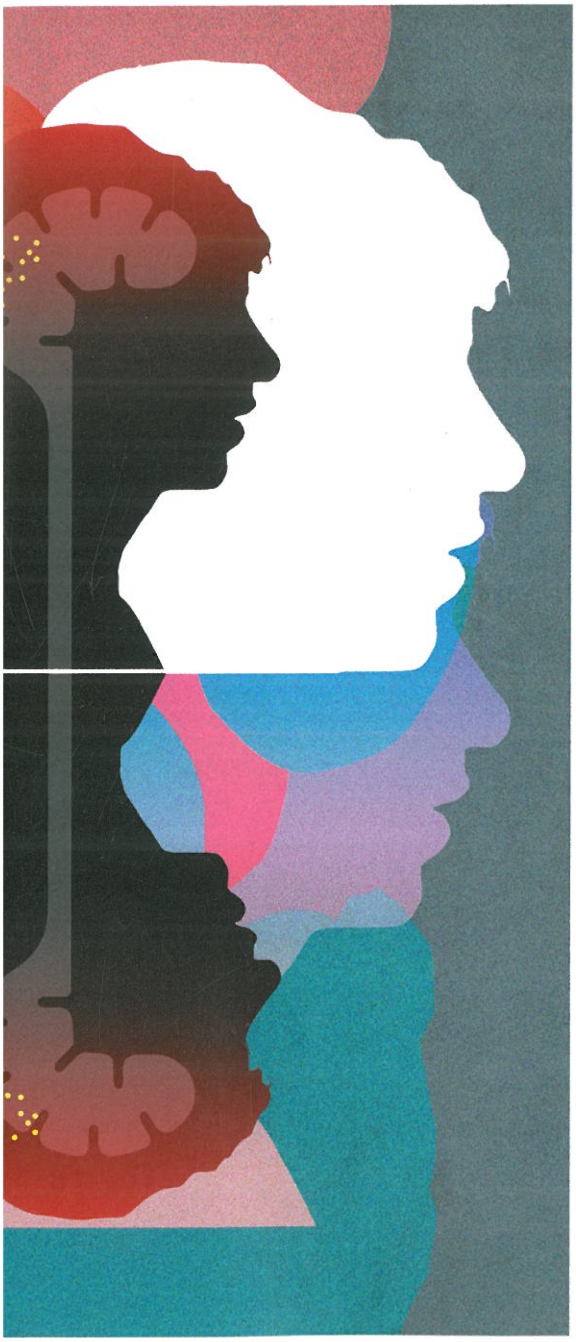
Neuroethics, however, is a relatively new field. In fact, its name wasn't properly coined until 2002. Since then, it has grown substantially—spawning the Program in Neuroethics at Stanford University, the Oxford Centre for Neuroethics, and the European Neuroscience and Society Network, among other programs—and has attracted funding from the MacArthur Foundation and the Dana Foundation. Nevertheless, these institutions' influence is still nascent. "They defined the workspace," says Giordano. "Now it's a question of going to work."

Also troubling is scientists' lack of knowledge about the dual-use nature of neurotechnologies—namely, the disconnect between research and ethics. Malcolm Dando, a professor of international security at the University of Bradford in England, recalls organizing several seminars for science departments across the United Kingdom in 2005, the year before a BWC review conference, to educate experts on the potential misuses of biological agents and neurological tools. He was shocked to find that "they didn't know very much"; one scientist, for example, denied that a possibly weaponizable microbe he kept in the fridge had any dual-use potential. Dando remembers it as "a dialogue of the deaf." Since then, not much has changed: Lack of awareness, Dando explains, "certainly remains the case" among neuroscientists.

It is encouraging that neuroscience's moral quandaries are being acknowledged in some key places, Dando points out. Barack Obama charged the Presidential Commission for the Study of Bioethical Issues to prepare a report of possible ethical

and legal issues related to the advanced technology of the BRAIN Initiative, and the EU's Human Brain Project established an Ethics and Society Programme to guide the endeavor's governance.

But these efforts may skirt the particular issue of neuroweapons. For instance, the two-volume, 200-page report on the ethical implications of the BRAIN Initiative, released in full this March, does not include the terms "dual use" or "weaponization." Dando says this gap—even in neuroscience literature, where one might expect the topic to thrive—is the rule, not the exception.



**WHEN DUKE'S NICOLELIS** created his first brain-machine interface in 1999—a rat, from thought alone, pressed a lever to receive water—he never imagined the device would be used as a rehabilitative tool for paralyzed people. But now, his patients can kick a soccer ball across a World Cup playing field in a brain-controlled exoskeleton. And the applications of his research are growing. Nicolelis is working to put a noninvasive version of the brainet—EEG caps worn by users—in clinics where physical therapists might be able to utilize their own brain waves to help injured people walk. "The physical therapist lends their brain 90 percent of the time, and the patient 10 percent of the time, and by doing that the patient likely will learn faster," he says.

But Nicolelis admits he worries that as his innovations gain traction, they could be put to other nefarious uses. After a project in the mid-2000s, using BMIs to help veterans gain mobility, he now refuses to accept DARPA money. Nicolelis senses that, in the United States at least, he is in the minority. "I think some neuroscientists, at meetings, are foolish enough to brag about how much they got from DARPA to do research, without even thinking about what DARPA might want out of that," he says.

The thought of BMIs, his life's work, becoming weaponized pains him. "I've been trying for the last 20 years," he says, "to do something that might have intellectual benefit for understanding the brain and eventually have clinical benefit."

The fact is, however, that neuroweapons developing alongside the clinical applications of brain technologies is a foregone conclusion. What kind of weapons these will be, when they will emerge, and in whose hands remain to be seen; people today certainly do not need to fear that their minds are on the brink of being compromised. But though a nightmare scenario in which emerging technologies turn the human brain into a tool—more sensitive than a bomb-sniffing dog, as controllable as a drone, or more vulnerable than an open safe—seems a dystopian fantasy, it's worth asking: Is enough being done to rein in the next generation of lethal weapons before it's too late? ■

**TIM REQUARTH** (*@timrequarth*) is a science journalist based in New York. Jack El-Hai (*@Jack_ElHai*), author of *The Lobotomist: A Maverick Medical Genius and His Tragic Quest to Rid the World of Mental Illness*, contributed to this article.