

STANFORD UNIVERSITY

# THE STANFORD EMERGING TECHNOLOGY REVIEW 2025

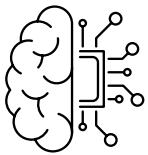
A Report on Ten Key Technologies and Their Policy Implications

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# NEUROSCIENCE

## KEY TAKEAWAYS

- Popular interest in neuroscience vastly exceeds the actual current scientific understanding of the brain, giving rise to overhyped claims in the public domain that revolutionary advances are just around the corner.
- Advances in human genetics and experimental neuroscience, along with computing and neuroscience theory, have led to some progress in several areas, including understanding and treating addiction and neurodegenerative diseases and designing brain-machine interfaces for restoring vision.
- American leadership is essential for establishing and upholding global norms about ethics and human subjects research in neuroscience, but this leadership is slipping with decreased strategic planning and increased foreign investments in the field.

## Overview

Neuroscience is a multidisciplinary field of study that focuses on the components, functions, and dysfunctions of the brain and our nervous system at every level. It reaches from the earliest stages of embryonic development to dysfunctions and degeneration later in life and from the individual molecules that shape the functions of a neuron to the study of the complex system dynamics that are our thoughts and dictate our behaviors.

The human brain consumes 20 to 25 percent of the body's energy even though it constitutes only a small percentage of a human's body weight, a fact that underscores its outsize importance.<sup>1</sup> The power of the human brain is what has allowed us to become the dominant species on Earth without being the fastest, strongest, or biggest.

The brain is unfathomably complex, containing approximately 86 billion neurons<sup>2</sup>—nerve cells that sense the physical world, transmit information to the

brain, process information, and send information from the brain to other parts of the body. A single neuron can make thousands or tens of thousands of connections to other neurons. These connections are called synapses (see figure 6.1).

All of our consciousness and behavior, from the action of stabbing a potato with a fork to contemplating the mysteries of the universe, is underpinned by which neurons connect with one another, the neurotransmitter/receptor pairs involved, the strength of the connections, and the electrical properties of the neurons—as well as by how these various features change over time.

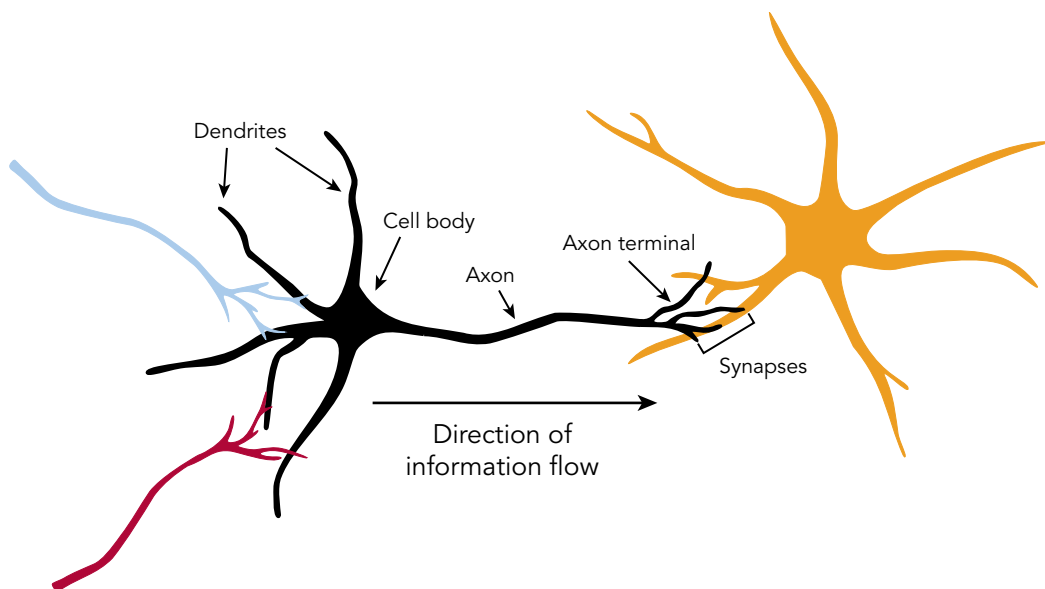
Neurons and synapses function in many ways that are similar to electrical circuits. Indeed, the exploration of the electrical properties of neurons came directly from the same technologies, theories, and equations developed for harnessing electricity. Many pioneering neuroscientists started as electrical engineers and physicists. Just as electrical connectors create a

path for electricity to flow through a circuit, neural circuits can be defined by the parallel and recurrent connections between neurons that occur to compute a specific function, such as deciding to move a limb or identifying an object visually. Neurons can also communicate with each other using hormone-like signaling, which is relatively slow but longer lasting compared to fast-acting electric signals. These types of communications underlie mood and behavior states such as sleep/awake and hunger/satiety.

Complete understanding of what each neuron is doing at any given time is currently impossible. Even for a mouse brain, which is much simpler than a human brain, it is still a tremendous effort to characterize individual brain regions despite the availability of powerful techniques that allow us to identify activity in individual neurons or to noninvasively tag cells to respond to light signals.

Over the past several years, however, it has become clear that individual neurons are almost never

**FIGURE 6.1** Structure of a neuron



responsible for any given behavior or computation; instead, they act in parallel, duplicating some functions and combining to determine thoughts and actions. This neural redundancy makes it easier to infer what is going on in the brain more broadly.

A particular brain region can be considered like a magnificent one-thousand-person choir. Just sampling 1 percent of the singers can provide a pretty good idea of the music the overall choir is producing at any given time. Researchers already have the ability to record from thousands of neurons at a time. This provides useful insight into how a brain functions, even if we don't understand in detail what the other 99 percent of its neurons are doing.

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## Key Developments

This chapter focuses on three research areas in neuroscience that show major promise for concrete applications: brain-machine interfaces (neuroengineering), degeneration and aging (neurohealth), and the science of addiction (neurodiscovery).

### ***Neuroengineering and the Development of Brain-Machine Interfaces***

A brain-machine interface is a device that maps neural impulses from the brain and translates these signals to computers. The potential applications for mature brain-machine interface technologies are wide-ranging: The augmentation of vision, other senses, and physical mobility; direct mind-to-computer interfacing; and computer-assisted memory recall and cognition are all within the theoretical realms of possibility. However, headlines about mind-reading chip implants are exaggerated and still more the realm of science fiction. Even with tremendous interest and rapid progress in neuroscience and engineering, the necessary theoretical understanding of how neurocircuits work is still limited to only a few areas of the brain. What's more, the

technical problems of safely implanting electrodes have not been solved.

Perhaps the most encouraging example of a brain-machine interface is the recent development of an artificial retina. The retina is the part of the eye that converts light into corresponding electrical signals sent to the brain. People who have certain incurable retinal diseases are blind because the light-detecting cells in their retinas do not work. To restore sight, the Stanford artificial retina project aims to take video images and use electrodes implanted in the eye to simulate the electronic signals in a pattern that a functional retina would normally produce.<sup>3</sup>

The project involves recording spontaneous neural activity to identify cell types and their normal signals, understanding how electrodes activate cells, and stimulating retinal ganglion cells—which collect visual information from photoreceptors in retinas—to represent an image so that this information can be transmitted by the optic nerve to the brain. Solving these technical problems calls for deep knowledge of relevant surgical techniques as well as significant engineering know-how in multiple areas—including translating the scientific understanding of the stimulation algorithm used into practical applications, making experimental recordings, and fabricating and packaging the electrode into the device.

The artificial retina project is the most mature brain-machine interface to date in terms of its ability to “read” and “write” information. The retina, a part of the central nervous system, is well suited as an experimental environment, as its stimuli (light) is experimentally controllable and can be captured by a digital camera. It is the best-understood neural circuit and the theory of its function has developed to the point where much of retinal processing can be modeled. Compared to complex cognitive processes like learning and memory—where even the inputs aren't fully understood—the task of reconstructing vision is more achievable, albeit still challenging.

Other brain-machine interfaces are currently being developed, though they are less mature or less ambitious than the artificial retina project. Some of these decode brain activity without controlling a neural signal. For instance, one interface can translate brain activity in areas controlling motor functions into signals that can then be sent to an artificial prosthetic limb. Here, feeding high-dimensional patterns of recorded neural activity into an artificial intelligence (AI) algorithm can make it possible to control an artificial limb without requiring direct control of neural functions—a form of control that remains beyond our current scientific understanding.

These demonstrations hint at the prospect of other brain-machine interfaces in the future, such as computer-assisted memory recall, even if the full suite of potential applications is still unclear. The scope and feasibility of these applications will be determined by advances in neuroscientific theory and in technical solutions to engineering problems

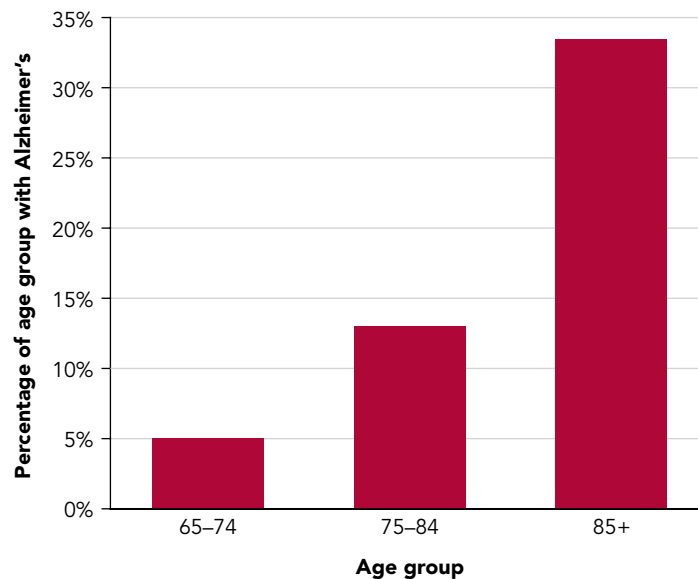
such as how to safely and accurately insert probes into deep-layer tissues.

### Neurohealth and Neurodegeneration

Neurodegeneration is a major challenge as humans live longer. Alzheimer's disease is of particular concern. In the United States alone, the annual cost of treating it is projected to grow from \$305 billion today to \$1 trillion by 2050.<sup>4</sup> Diseases like Alzheimer's and Parkinson's surge in frequency with age—while just 5 percent of 65- to 74-year-olds have Alzheimer's, this rises to 33 percent for those over 85 (see figure 6.2).<sup>5</sup> As modern medicine and society enable longer lifespans, the human body and brain remain maladapted to maintaining nervous system function for decades past childbearing age.

Alzheimer's disease is characterized by the accumulation of two different proteins—amyloid beta and tau—into toxic aggregates. Amyloid beta accumulates

**FIGURE 6.2** Alzheimer's disease surges in frequency with age



Source: Data from "2023 Alzheimer's Disease Facts and Figures," *Alzheimer's & Dementia* 19, no. 4 (April 2023): 1598-1695

outside of neurons, induces cellular stress, and in turn may cause tau to build up inside the neurons. As the brain regions where tau accumulates are those most cognitively impacted, a reasonable consensus exists that tau is the more direct cause of the neural death responsible for dementia.

However, despite what is known about neurodegenerative diseases such as Alzheimer's, little progress has been made in producing effective treatments that slow disease progression. For example, tau remains harder to target therapeutically, and the recently approved drugs target amyloid beta. While these amyloid drugs are very effective in eliminating the amyloid plaques from patient brains, their effectiveness in improving patients' cognitive abilities remains questionable.

Another form of neurodegeneration results from traumatic brain injury (TBI), which can manifest itself in a range of complex symptoms and pathologies.<sup>6</sup> Traumatic impact to brain systems can affect cognitive and behavioral functions in ways that lead to long-term and severe psychiatric conditions requiring specialized care. This is particularly evident in the current surge of athletic and military brain injuries that exhibit predominantly psychiatric symptoms. A person's past medical and psychiatric records, as well as any coexisting conditions, play a vital role in diagnosis and treatment. TBI offers insights into other neuropsychiatric disorders and can pave the way for innovative concepts in neurodegenerative disease.

### **Neurodiscovery and the Science of Addiction**

Researchers are working to understand the neural basis of addiction and of chronic pain while working with psychiatrists and policymakers to address the opioid epidemic.<sup>7</sup> Estimates of the economic costs of that epidemic range from \$100 billion to \$1 trillion a year when the loss of potential lifetime earnings of overdose victims is included.<sup>8</sup> Additional economic losses occur due to depletion of the labor

force and the billions spent on the criminal justice system and healthcare related to addiction.<sup>9</sup> Beyond economics, there are the significant emotional costs that impact individuals experiencing addiction, as well as their families and friends. Death also takes its toll: The number of opioid deaths in the United States has risen from 21,000 in 2010 to 111,000 in 2022,<sup>10</sup> which places deaths from opioid overdoses on the same level as those caused by diabetes and Alzheimer's.<sup>11</sup> Overdose deaths fell by 3 percent in 2023 compared with the prior year,<sup>12</sup> but it is not clear yet whether the downtick is merely a pause in growth or a fundamental turning point.

Many of the most impactful changes for dealing with the societal problems arising from addiction come from public policy interventions and societal shifts, such as raising taxes on tobacco or changing physicians' prescribing practices for addictive substances such as opioids (see figure 6.3). Nevertheless, neuroscience has a potentially important role to play in addressing addiction. For example, a nonaddictive painkiller drug as effective as current-generation opioids could be transformative.<sup>13</sup>

**FIGURE 6.3** Opioids prescribed by physicians



Source: iStock.com / Johnrob

Another approach is to leverage neuroscience to identify and target brain states that reinforce addiction or make it more likely. Consider the problem of relapse in tackling addiction. Scientists have found that the brain mechanisms leading to an initial opioid addiction differ significantly from those that trigger a relapse. It turns out that opioid receptors are found in neural circuits related to the desire for social interaction. Stanford neuroscientists have recently identified a circuit that is responsible for the onset of aversion to social interactions during recovery.<sup>14</sup> Such an aversion is a significant challenge to recovery because social interactions are often key to helping an individual cope with the vulnerabilities associated with the recovery process. The finding suggests it may be possible to develop drugs that inhibit social aversion during withdrawal, thereby assisting patients in seeking help or companionship from friends, families, recovery programs, and doctors.

Depression is also a major driver of addiction and a barrier to recovery. It involves a loss of the ability to feel good, which addictive drugs temporarily counteract by activating the brain's reward centers. However, over the long term, these drugs can also dull emotions, making normal experiences less rewarding and worsening patients' overall mood. Addiction also impairs executive control, makes normal life seem unsatisfactory, and creates a belief that drug use is essential for survival. Addressing any factor that contributes to depression-driven addiction can help facilitate the recovery process.

One nonpharmaceutical intervention for depression is Stanford neuromodulation therapy (SNT).<sup>15</sup> SNT employs transcranial magnetic stimulation (TMS)—the use of magnetic fields to stimulate specific brain regions—on regions involved in executive functioning and emotional regulation, particularly the left dorsolateral prefrontal cortex, which is responsible for functions such as problem-solving and self-control.<sup>16</sup> This approach aims to strengthen connections between brain areas to better regulate negative emotions. Initial trials have shown promising results, with nearly 80 percent of participants

experiencing lasting remission.<sup>17</sup> SNT improves upon traditional TMS by using individualized brain scans and condensing treatment into five days. If these remission rates hold, it could represent a significant step forward in treating depression.

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## Over the Horizon

### *Progress and Prospects in Neuroscience*

The pace of neuroscientific discovery is slow and limited by the biological nature and complexity of the nervous system. Year-over-year advances tend to be incremental. Researchers use simple model organisms like fruit flies with short generation times to study fundamental questions inexpensively. But the closer research gets toward human application, the more complex, time-consuming, and expensive it becomes. For instance, because neurodegeneration is a slow, progressive disease where day-to-day worsening is minimal, clinical trials often take many years.

Most of the economic impacts of neuroscience in some way connect to the healthcare industry and its search for treatments for neurodegenerative disorders (such as Alzheimer's and Parkinson's disease), neuropsychiatric disorders (addiction, depression, and schizophrenia), and neural prosthesis (brain-machine interfaces to restore limb function and speech).

It is important to keep in mind that the brain's complexity often prevents researchers from understanding fully why even effective treatments for neurological conditions actually work. For example, we know that drugs called selective serotonin reuptake inhibitors block the reabsorption of serotonin into neurons, but neuroscientists do not have a clear explanation for why this helps treat depression. New neurological therapies may work, but because we don't have a good understanding of exactly why they do so, fine-tuning and improving them often comes down to simple trial and error. Luckily for medical science, an in-depth understanding of how

a particular treatment works may not always be necessary for therapeutic intervention.

### **ALZHEIMER'S DISEASE DETECTION AND TREATMENT**

The potential for early detection prior to the onset of cognitive impairment is higher than it has ever been before. Current-generation diagnostic tools now include the ability to cheaply test for biomarkers from blood plasma paired with more accurate but expensive spinal taps and positron emission topography, or PET, scans for toxic tau and amyloid buildup. While anti-amyloid drugs are controversial for treating even mild cases of Alzheimer's because of their side effects (which include brain swelling and bleeding), a rollout of mass blood-plasma screening, along with confirmation using more expensive tests, might mean these drugs could be applied before clinical symptoms manifest, possibly increasing their effectiveness.

At this point, detection is more advanced than treatments. Antisense oligonucleotides (ASOs) are an up-and-coming class of drugs that may actively slow cognitive decline in patients already exhibiting disease symptoms. An ASO that disrupts the production of additional tau showed positive results in an early clinical trial for safety in early 2023.<sup>18</sup> The sample size was small, but the trial showed cognitive improvements from treatment.<sup>19</sup> Participants are currently being recruited for another clinical trial scheduled to stretch from 2022 to 2030.<sup>20</sup> While this approach suffers from the drawback of the treatment requiring spinal injections, extreme adverse events were mostly limited to side effects of the injections themselves, rather than the brain swelling or bleeding frequently observed with the anti-amyloid antibody drugs.

### **NEUROSCIENCE-BASED PROSTHESES**

Neural redundancy has important ramifications for the development of brain-controlled prostheses. For example, if the goal were to develop an artificial limb controlled by the brain, it would be nearly impossible to monitor every neuron in the motor

cortex. However, if about 80 percent of neural activity can be represented by a small group of neurons, then a single, minimally invasive probe might be sufficient to interpret movement intentions and control an artificial limb. Although the remaining 20 percent of neural activity, which the probe wouldn't capture, would likely still be important for fine-tuning limb movement, a computer could help manage these details once there's a clear understanding of how to interpret movement intentions.

Neural redundancy is also important in neural prostheses for seizure treatment. If a probe can be implanted into an area of the brain prone to seizures, then it might be possible, even without a complete sampling of the neural population, to predict the state of the relevant part of the brain and warn of an imminent seizure. Such a prediction could allow for intervening immediately to disrupt those network dynamics or informing the patient of imminent danger. It wouldn't be necessary to understand the complete set of neural computations to have a sufficiently clear signal for medical intervention.

### **NEUROSCIENCE AND AI**

As understanding of the mathematics of our neural computations increases, these computational models may have direct relevance to AI. In particular, machine learning requires vast training datasets. By contrast, humans can learn languages with a small fraction of the training data that AI models require (for more discussion of this point, please refer to chapter 1 on artificial intelligence). Better understanding the mathematical principles that define how human brains compute may therefore improve AI. The melding of neuroscience theory and AI is a topic of increasing interest under the umbrella of Stanford's Wu Tsai Neurosciences Institute.<sup>21</sup>

### ***Challenges of Innovation and Implementation***

Contrasting the work on artificial retinas and the work on the science of neurodegeneration and addiction illustrates the dual-pronged nature of neuroscience

applications. They have two primary components: a scientific one that focuses on identifying relevant brain circuits and understanding how these function and compute, and a technical engineering one that focuses on how to safely stimulate the relevant brain circuits to create the desired responses.

There is much about the brain's anatomy, physiology, and chemistry that is still not well understood, and addressing the theoretical issues in neuroscience is almost exclusively the purview of academia rather than industry. There are research programs in industry that solve basic biological questions in neuroscience, but these are tied to solving problems with a profit motive—usually the development of new drugs.

Once the basic science has been developed and a research area approaches an economically viable application, industry does a much better job of developing it. Consequently, helping to smooth the friction of moving a project from academia to industry is crucial to overcoming roadblocks in development. Incubators and accelerators can help transition the findings of basic research to application by aiding in high-throughput screening—the use of automated equipment to rapidly test samples—and prototyping. With viable prototypes, new companies can be created or licenses granted to existing companies to produce a final product. Such

activities are critical in facilitating the integration of well-understood scientific theory, technical engineering, and final application.

### ***Policy, Legal, and Regulatory Issues***

#### **DISCONNECT BETWEEN PUBLIC INTEREST AND CAPABILITY**

The brain is perhaps the least understood, yet most important, organ in the human body. Demand for neuroscience research advances and applications—including understanding brain circuitry, developing new drugs, treating diseases and disorders, and creating brain-machine interfaces—is expected to continue to grow considerably over the coming years. The Society for Neuroscience's annual meeting draws close to thirty thousand attendees.<sup>22</sup>

Science fiction and fantastical headlines fuel beliefs that mind-reading technology, brains controlled by computers, and other dystopias are imminent. In reality, work to comprehend the brain's staggering complexity remains in its early stages. Most advances involve incremental progress, expanding our theoretical foundations rather than producing revolutionary leaps to futuristic applications. This vast gap between public expectations and scientific reality creates an environment ripe for exploitation. Impatience for solutions to pressing

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medical problems like dementia and mental illness leave many open to dubious proclamations or pseudoscience.

### **DRUG POLICY AND NEUROSCIENCE RESEARCH**

The Controlled Substances Act governs US policy regarding regulation of the manufacture, importation, possession, use, and distribution of certain substances. Substances on Schedule 1 are drugs or other substances with a high potential for abuse and not currently accepted for medical use in the United States. No research exceptions are provided for Schedule 1 substances such as cannabis or MDMA (often known as Ecstasy or Molly), which have potential for medical use that might be realized through research. In May 2024, the Biden administration proposed to reassign marijuana to Schedule 3, a schedule with fewer restrictions.<sup>23</sup> Placing drugs on Schedule 1 sharply constrains researchers because it becomes difficult to obtain these potentially helpful substances for study. This constraint also denies the public the benefits that might flow from such research—such as better medical treatments—and potentially harms the public if, for example, individual states choose to legalize certain drugs without adequate research into their safety, addictiveness, and public health impacts.

### **THE IMPACT OF COGNITIVE AND BEHAVIORAL NEUROSCIENCE ON LAW**

Cognitive and behavioral neuroscience, which studies the biological basis of thoughts and actions, has broad implications for public policy. For example, a basic aspect of criminal law is the nature and extent of an individual's responsibility for a criminal act. Under a 2005 US Supreme Court ruling, minors under eighteen years of age cannot be subject to the death penalty for crimes they committed because adolescent brains are not fully developed, putting minors at higher risk of impulsive, irrational thoughts and behaviors.<sup>24</sup>

### **THOUGHT IMPLANTS**

The possibility that information can be implanted directly into a person's consciousness is an interesting

future research problem as the nature of brain-machine interfaces becomes more ambitious over the coming decades. As government is still figuring out how to regulate internet forums that influence what people believe and how they feel—a problem that has existed for three decades—regulation will likely not come fast enough to guide even the later-stage promises made about brain-machine interfaces. Establishing proper cultural norms at the outset and careful consideration of technologies is warranted.

### **FUNDING CUTS TO TRANSFORMATIVE NEUROSCIENCE**

Over the past decade, much of the work outlined in this chapter was funded by the Brain Research Through Advancing Innovative Neurotechnologies (BRAIN) Initiative. Starting in 2014, this aimed to be the equivalent of the Human Genome Project for the human brain. Research from the BRAIN Initiative has helped neuroscience generate advances that specifically aid in translating science to medicine. In 2024, however, the initiative's budget was cut by 40 percent, from \$680 million to \$402 million. The decline was due to a combination of reduced funding from the National Institutes of Health (NIH) and through the 21st Century Cures Act. Funding through that act is expected to fall by an additional \$81 million in 2025.<sup>25</sup> Without additional financial support through the NIH, neuroscience research in the United States and the country's ability to tackle some of the most societally impactful diseases will decline.

### **FOREIGN COLLABORATION**

Human expertise will continue to be the primary driver of future advances in neuroscience, and success will continue to depend on the United States being the best place for international scientists to train, conduct research, and use their own expertise to teach the next generation of scientists. Against this backdrop, the apparent targeting of US scientists with personal and professional links to China raises concerns,<sup>26</sup> and the United States only loses if these scientists leave and move their labs to China.

## ETHICAL FRAMEWORKS

Neuroscience research naturally raises many ethical concerns that merit careful, ongoing discussion and monitoring. Chief among these is research on human subjects, which is governed by several existing frameworks and regulations that guide neuroscience studies in American academia today. Ethical guidelines for scientific research are usually national, not international. Some countries might allow particular types of brain research and drugs, while others might not; for example, a nation might permit experimentation on prisoners or on ethnic minorities. Managing differences in state research regimes will be critical to harnessing the power of international collaboration.

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