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Action Potentials

Neurotechnology, Brain-Computer Interfaces, and Implications for Germany's and Europe's Foreign & Security Policy

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Executive Summary

Neurotechnology comprises a range of devices, some implantable into the human body and others applied externally, that sense and stimulate activity in the brain and the adjacent central nervous system. So far, such devices have mainly been developed for medical purposes, for example, to restore movement and speech after severe strokes or to alleviate mental health conditions. However, the field is evolving rapidly and has the potential to revolutionize how humans perceive the world, process information, and interact with each other, as well as with computers, artificial intelligence (AI) systems or robots. Ultimately, brain-computer interfaces (BCIs) that establish a direct link between the brain and machines might become a platform technology comparable to smartphones today.

Against the backdrop of intense global competition over technology leadership, this report examines how advances in neurotechnology matter for Germany's and Europe's foreign and security policy.

It highlights the expanding range of real-world use cases and the likelihood that progress will further accelerate in the future, with innovation and adoption poised to enter a mutually reinforcing dynamic once a certain tipping point is reached.

The analysis further considers regional variation in the global neurotechnology ecosystem. It stresses how the United States and China are pushing ahead, each combining strategic state intervention and private entrepreneurship in distinctive ways. Meanwhile, Europe is strong in academic research but lags in the translation to practical use and commercialization.

Based on these assessments, the report proposes 10 recommendations for Germany's and Europe's foreign and security policy, structured along three widely agreed-upon policy aims. While these recommendations cover a range of complex issues, one consistent thread is that focusing on the regulation and governance of neurotechnology both domestically and globally is important, but it is not enough. Foreign and security policy also has an important role to play in fostering responsible innovation and adoption, both to realize the major opportunities provided by this technology and to build and sustain influence over global developments.

1. Enhancing Defense and Deterrence

Neurotechnology has obvious potential for military use on the battlefield and beyond. Military actors are deeply involved in the regional neurotechnology ecosystems in the US and China, targeting enhanced performance, brain-machine integration and even potential offensive applications. In contrast, despite the widely acknowledged need to better defend the continent against acute security threats, Europe's engagement with these novel possibilities remains timid and reactive.

Europe and Germany should:

- Work towards becoming leaders in the responsible military use of neurotechnology through investment in a dual-use backbone, applied research for military applications, and deepened engagement with international partners (especially via NATO).
- Develop an independent perspective on how to effectively prevent leakage of dual-use knowledge and technologies to potential adversaries and engage

with the US discussion on export controls to maintain tight links between the innovation systems across the Atlantic.

- Initiate a global process toward ethically grounded norms on the military use of neurotechnology.

2. Fostering Resilience Against Dependencies and Cyber Threats

Neurotech and BCIs will likely become relevant in many areas of the economy and society. While the benefits could be significant, this also means that dependencies and chokepoints in global supply chains require attention and that devices may become targets for hostile interference. Building a strong European neurotech industry is key to addressing these concerns.

Europe and Germany should:

- Mobilize European public funding to support translational neurotech research, commercialization, and trusted solutions for critical domains.
- Establish a regular monitoring of the global neurotech ecosystem for emerging dependencies and chokepoints, as well as for signs of unfair competition.
- Clarify how existing European Union regulations apply to neurotech and review their design and implementation to reduce obstacles to research and commercialization while fostering cyber and data security in a targeted way.
- Actively invest in responsibly making anonymized neural data available for innovation in Europe.
- Promote cybersecurity-enhancing solutions in processes toward global technical standards.

3. Pursuing Shared Benefits for Society

Neurotechnology can support major advances in public health and productivity, as well as spurring innovation in adjacent fields. At the same time, its spread and adoption should be accompanied by inclusive political dialogue to avoid exacerbating social inequality and political conflict over profound ethical questions.

Europe and Germany should:

- Foster the exchange of expertise and good practices among policymakers and agencies working on neurotech, both within the EU and with like-minded countries.
- Continue actively engaging in processes toward global ethical standards and raise awareness of key issues also domestically.

These recommendations sketch a path for Germany and the EU to deal with a technology field that has not yet received widespread attention but is likely to acquire critical importance. Now is the time to act to strategically position the continent in the global ecosystem and help shape a trajectory for neurotechnology that benefits society and advances German and European security interests.

INTRODUCTION

Fast-moving technologies are reshaping economies, societies, and politics worldwide. In recent years, artificial intelligence (AI) and its enabling hardware have taken center stage not just in debates about how to govern novel technological possibilities and risks, but also in discussions about the exercise of power and influence among states. A key example of this has been the United States' expansive adoption of export controls and related measures to rein in advances by potential adversaries, chiefly China.[1] Against this backdrop, other emerging technologies that are advancing equally quickly (often in conjunction with progress in AI) also warrant urgent attention.

Neurotechnology may profoundly change how humans perceive the world, process information and interact with each other as well as with computers, AI systems, or robots.

One of them is neurotechnology: devices that interface directly with the human brain and neural system to detect and interpret signals or to influence its inner workings. Currently, these technologies are mainly used for medical purposes, for instance, to provide people living with paralysis with alternative ways to communicate or to treat mental health conditions such as depression. But they clearly also lend themselves to non-medical use and may, in the not-too-distant future, profoundly change how humans perceive the world, process information, and interact with each other as well as with computers, AI systems or robots. Potential applications are apparent in a range of areas, from wellness and leisure to education and work, as well as in the military domain. While emerging neurotechnology poses questions that are, in some regards, similar to those arising from other novel technologies, its immediate bearing on issues of consciousness, autonomy, identity, and the human experience at the most fundamental level makes the field uniquely fascinating and sensitive.

The reception of neurotechnology in public discourse has often been marked by either oblivion or hyperbole. While most people are unaware of the impressive advances of the field, evangelism by Elon Musk — co-founder of neurotech company Neuralink — and other tech leaders, as well as science-fictional depictions (for example, in the TV show *Black Mirror*), have captured the imagination of influential audiences. Especially in the US and China, governments have also recognized the strategic relevance of the field and actively sought to foster innovation, including for military purposes. A small but dedicated global expert community has, meanwhile, been working towards norms regarding the ethical development and use of neurotechnology.

A systematic perspective on the foreign and security policy implications of neurotech from a German and European vantage point, however, has so far been missing. This report seeks to close this gap. It proceeds in three parts:

First, it explains what neurotechnology encompasses and how the field is evolving. While progress to date offers some indications of the future innovation and adoption pathway, there are clear reasons to expect this pathway to be strongly non-linear. While it seems largely futile to speculate about the precise timing of a future take-off of neurotechnology, it is possible to establish a set of developments that should serve as relatively early indicators and therefore merit close monitoring.

Second, it considers the global neurotech ecosystem and regional variation within it, critical in a context where emerging technologies are frequently viewed in competitive terms and through the lens of influence, dependencies and vulnerabilities. It highlights Germany's and Europe's strong position in academic research, but lagging translation of research into practical use compared to the US and China.

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[1] Florian Klumpp and Jakob Hensing, *"As Large of a Lead as Possible"? Taking Stock of the Biden Administration's Agenda on Critical and Emerging Technologies* (Global Public Policy Institute, 2024); Ansgar Baums and Nicholas Butts, *Tech Cold War: The Geopolitics of Technology* (Lynne Rienner Publishers, Inc, 2025).

Third, this report discusses why and how neurotech matters for three widely accepted goals of German and European foreign and security policy. First, given its obvious military potential, policymakers not only need to find ways to defend against novel threats but should also seek to turn Europe into a leader in responsible military use of neurotechnology and should leverage these technologies to help meet the continent's acute security challenges. Second, they need to address vulnerabilities that may arise from dependencies and chokepoints in the global ecosystem, as well as from the proliferation of neurotechnology as a form of decentralized critical infrastructure. Finally, they should contribute in the international realm to creating conditions under which neurotechnology can unfold its potential to advance societal prosperity, while adequately managing attendant risks and safeguarding individual rights and democratic control over technology.

> Focusing on the appropriate regulation and governance of neurotechnology is important, but not sufficient.

Building on this analysis, the report identifies potential lines of action for European and German policymakers in each of these areas. One of its central messages is that focusing on the appropriate regulation and governance of neurotechnology and contributing to international and global efforts in this regard is important, but not sufficient. In addition, Germany and Europe need to use all available levers — including those in the realm of foreign and security policy — to responsibly foster innovation and adoption of the technology. This is not only vital to seize the opportunities that neurotech offers at home, but also to effectively exert influence on the technology's global trajectory.

NEUROTECHNOLOGY: METHODS, USE CASES, OUTLOOK

Structuring the Technology Field

Neurotechnology can be defined in functional terms as methods and devices that "enable activity in the nervous system to be measured or modulated by creating interfaces that establish artificial connections within the body or to the outside world."[2] This study mainly deals with technologies that focus on the brain, though the latter is inextricably connected to the spinal cord as well as to the peripheral nervous system. Although it encompasses a diverse range of approaches, the field can be structured along two basic dimensions.

First, technologies differ in terms of their primary function. Some mainly serve to sense or monitor neural activity, for example, in the form of electroencephalography (EEG), which detects the minuscule fluctuations in voltage associated with any activity in the electrochemical system that is the brain. These recordings can either be used to inform behavioral adjustments and interventions or to realize further, more technologically complex use cases such as controlling a computer or physical device. Others aim to stimulate or influence processes in the brain, as in the case of transcranial magnetic stimulation (TMS) that uses an electromagnetic coil applied to the skull. In many practical applications, technologies covering both functions are combined, increasingly in the form of closed-loop systems that adjust stimulation based on ongoing neural feedback.

The second dimension concerns the mode of application, that is, whether a system is planted into the body or applied externally.[3] Some non-invasive methods have been known for decades, while invasive techniques have mostly been developed more recently on account of their complexity and associated risk (an important exception is deep-brain stimulation/DBS, which was developed in the 1980s with a focus on tremor patients). Today, the choice between a non-implantable and implantable approach for any given use case still entails a key trade-off: Implantable devices typically provide better local and temporal resolution (both for sensing and for stimulation) and are less susceptible to displacement and other interference, allowing for more stable long-term use than their non-implantable counterparts. However, they also require surgery, pose a greater risk of causing physical damage to the brain, and are typically much more costly.[4]

As detailed in the overview of relevant technologies on p.16-17, researchers and entrepreneurs are trying to address this trade-off from both angles. On the one hand, they develop implantable devices that are less intrusive and require only minimal and routine surgery, for instance through miniaturized designs, stent electrodes that are inserted into the jugular vein rather than directly into the cortex, or even "biohybrid" designs in which a neural pathway grows into the brain.[5] On the other hand, they seek to improve the sensing and stimulation capabilities offered by non-implantable devices, notably through better signal decoding and interpretation.

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[2] Gerwin Schalk et al., "Translation of Neurotechnologies," *Nature Reviews Bioengineering*, Nature Publishing Group UK London, 2024, 1.

[3] This distinction is often also referred as "invasive"/"non-invasive", but this terminology arguably carries unhelpful connotations.

[4] Schalk et al., "Translation of Neurotechnologies"; Linda J Szymanski et al., "Neuropathological Effects of Chronically Implanted, Intracortical Microelectrodes in a Tetraplegic Patient," *Journal of Neural Engineering* 18, no. 4 (2021): 0460b9.

[5] Thomas J Oxley et al., "Minimally Invasive Endovascular Stent-Electrode Array for High-Fidelity, Chronic Recordings of Cortical Neural Activity," *Nature Biotechnology* 34, no. 3 (2016): 320—27; Nicholas A. Steinmetz et al., "Neuropixels 2.0: A Miniaturized High-Density Probe for Stable, Long-Term Brain Recordings," *Science* 372, no. 6539 (April 16, 2021), https://doi.org/10.1126/science.abf4588; Elissa Welle, "Biohybrid BCI Adds More Neurons to the Brain," *IEEE Spectrum*, February 19, 2025, https://spectrum.ieee.org/brain-computer-interface-2671151260.

Indeed, the capabilities and performance of any advanced neurotech device are driven not just by physical hardware but also by the software used to process, decode and interpret neural signals or to direct stimulation. This applies especially to the subfield of brain-computer interfaces (BCIs), with a BCI being defined as “a system that measures brain activity and converts it in (nearly) real-time into functionally useful outputs to replace, restore, enhance, supplement, and/or improve the natural outputs of the brain, thereby changing the ongoing interactions between the brain and its external or internal environments. It may additionally modify brain activity using targeted delivery of stimuli to create functionally useful inputs to the brain.”[6] The possibility of creating such a direct link between brain and computer that eschews traditional solutions like a keyboard and mouse has unsurprisingly drawn considerable interest in tech circles, with Meta CEO Mark Zuckerberg, for example, referring to a neural interface as the “holy grail” of human-machine interaction.[7]

Connections with Other Fields

Neurotechnology is an inherently interdisciplinary field. Its development has been closely linked to advances in a range of disciplines and technologies, many of which act as enablers or are themselves shaped by progress in neurotechnology.

The most obvious connection is, of course, with neuroscience. Much of what neurotechnology achieves builds directly on foundational research into the structure and functioning of the human brain — though one of the remarkable aspects of the field is what capabilities have already been developed based on mere correlates of neural activity, in the absence of a true understanding of the symbol system by which information is encoded and processed in the brain.[8] At the same time, improved tools for monitoring and interacting with neural activity —such as higher-resolution sensors or adaptive stimulation systems — hold promise for pushing neuroscience forward. The relationship is mutually reinforcing: better insights into the brain support better tools, and better tools, in turn, open up new frontiers for neuroscience.

Another critical intersection is with AI. Machine learning has proven very useful in detecting patterns in neural signals and enabling the kind of real-time control required for BCIs. AI systems can perform various functions for neurotechnology, be it in interpreting noisy, high-dimensional brain data, selecting appropriate stimuli, or supporting shared-control applications where the AI agent executes part of a task based on a user’s intent.[9] AI also plays a role in adapting systems to individual users, helping to tailor neurotech devices to the variability of each brain.

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[6] This is the working definition of the BCI Society, based on extensive input from its members. See https://bcisociety.org/bci-definition.

[7] Harry Baker, “Zuckerberg & Bosworth Talk Neural Interfaces & Virtual Work - Video & Transcript,” UploadVR, June 6, 2021, https://www.uploadvr.com/zuckerberg-bosworth-vr-transcript/.

[8] Surjo R Soekadar et al., “Future Developments in Brain/Neural–Computer Interface Technology,” in *Policy, Identity, and Neurotechnology: The Neuroethics of Brain-Computer Interfaces* (Springer, 2023). For a fascinating account of how the broader state of available technology has historically shaped ideas about the functioning of the brain, see Matthew Cobb, *The Idea of the Brain: The Past and Future of Neuroscience* (Basic Books, 2020).

[9] David Haslacher et al., “AI for Brain-Computer Interfaces,” in *Brains and Machines: Towards a Unified Ethics of AI and Neuroscience*, ed. Marcello Ienca and Georg Starke, vol. 7, *Developments in Neuroethics and Bioethics* (Academic Press, 2024), https://www.sciencedirect.com/science/article/pii/S2589295924000031; Soekadar et al., “Future Developments in Brain/Neural–Computer Interface Technology.”

Conversely, improving the understanding of the human neural system is also a critical frontier in advancing AI research and applications.[10] This is most obvious in neuromorphic computing, where chips and algorithm designs are explicitly inspired by the brain, borrowing features such as asynchronous signal processing or structural adaptability (learning in the form of ongoing hardware adjustments) to achieve greater computing power and reduce energy consumption.

Improving the understanding of the human neural system is also a critical frontier in advancing AI research and applications.

An important challenge to the use of AI in neurotech, though, is its heavy dependence on the availability of suitable training data. To date, neural datasets, especially from healthy individuals, remain limited and fragmented. Much of the data that is available stems from clinical settings and specific patient populations, offering limited variation across gender, age and socioeconomic background, leading to concerns about generalizability.[11] As discussed below, several initiatives are seeking to remedy this situation, and broader policy and regulation will have an important role to play.

Progress in microelectronics and semiconductor technology also remains important for innovations in neurotechnology. Characteristics such as device size, flexibility, biocompatibility, and power efficiency significantly affect the viability of designs, especially for implantable systems. Innovations that reduce heat or improve long-term stability directly echnologically feasible.[12]

Advanced materials and nanotechnology similarly play an important role in neurotechnological advancements, as the degradation of materials is a constraint on the longevity and safety of implantable devices. Nanoparticles are being explored for use in brain mapping and neural monitoring. Nanowires may significantly enhance the performance of neural probes, improving both resolution and compatibility with the surrounding organic tissue. Manufacturing techniques that enable smaller, more intricate structures will be essential for integrating these advances into real-world systems.[13]

In the longer term, quantum technology may prove relevant to the field as well. For example, quantum computing could offer new ways of simulating neural networks or optimizing the performance of AI systems that interpret brain data, while quantum sensors may enable more precise measurements of neural activity.[14]

Finally, and with more immediate prospects, some of the more experimental approaches to building devices for practical use combine neurotechnology with augmented and virtual reality. In these setups, BCIs may allow users to control or experience digital content more directly, blending virtual elements into sensory perception or enabling new modes of interaction. As discussed in the section on practical use cases below, the offerings available so far have only begun to explore the possibilities in this regard, but already offer a glimpse into the kinds of hybrid realities that neurotechnology could eventually bring about.

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[10] Tom Macpherson et al., "Natural and Artificial Intelligence: A Brief Introduction to the Interplay between AI and Neuroscience Research," *Neural Networks* 144 (2021): 603–13.

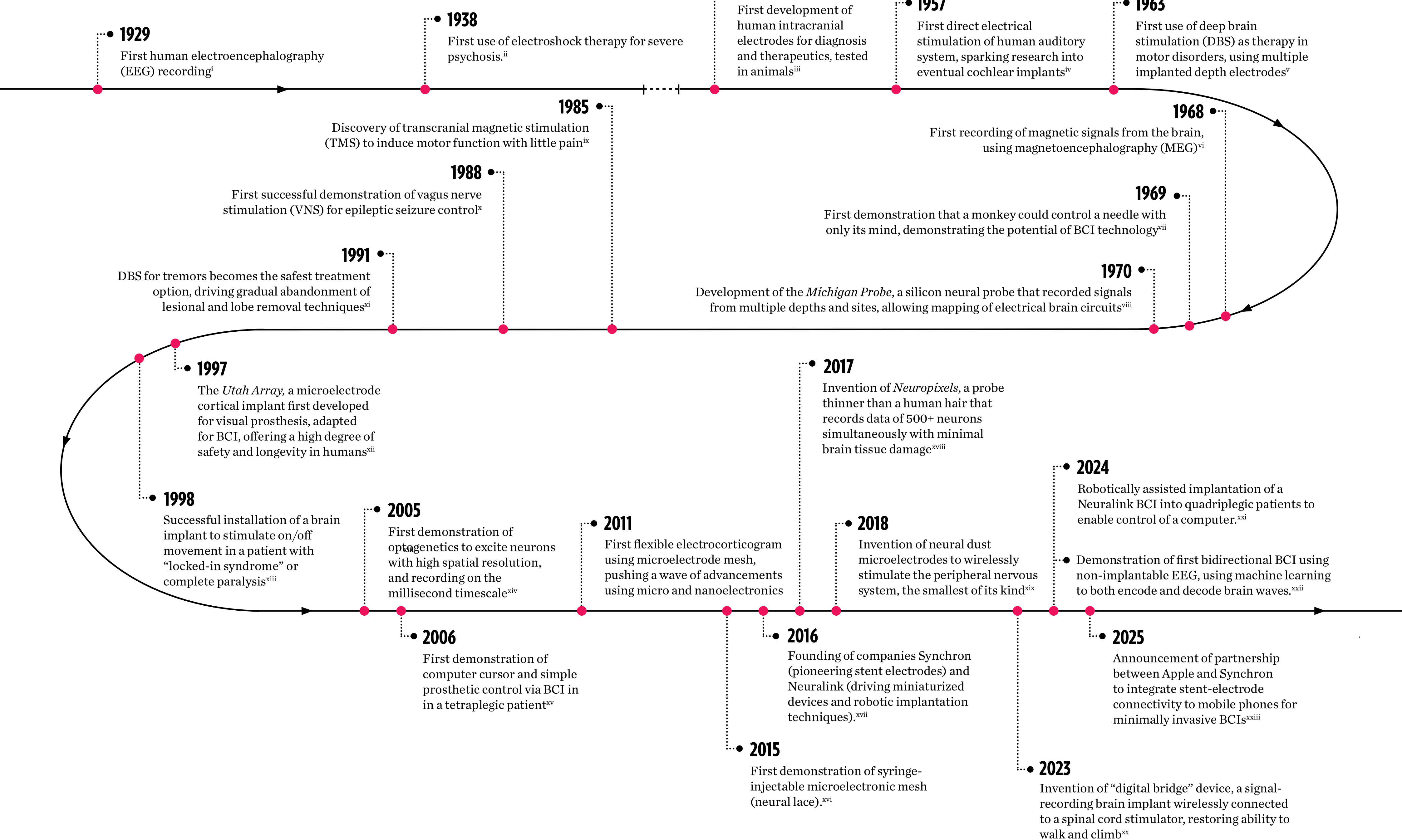
[11] Esther Landhuis, "Neuroscience: Big Brain, Big Data," *Nature* 541, no. 7638 (2017): 559–61, https://doi.org/10.1038/541559a.

[12] Eve McGlynn et al., "The Future of Neuroscience: Flexible and Wireless Implantable Neural Electronics," *Advanced Science* 8, no. 10 (2021)

[13] Jia Liu et al., "Syringe-Injectable Electronics," *Nature Nanotechnology* 10, no. 7 (2015): 629–36, https://doi.org/10.1038/nnano.2015.115; Xiao Yang et al., "Nanotechnology Enables Novel Modalities for Neuromodulation," *Advanced Materials* 33, no. 52 (2021)

[14] Kun Liao et al., "Exploring the Intersection of Brain–Computer Interfaces and Quantum Sensing: A Review of Research Progress and Future Trends," *Advanced Quantum Technologies* 7, no. 1 (2024): 2300185

Figure 1: Timeline of Key Neurotech Developments



1929 First human electroencephalography (EEG) recording[i]

1938 First use of electroshock therapy for severe psychosis.[ii]

1952 First development of human intracranial electrodes for diagnosis and therapeutics, tested in animals[iii]

1957 First direct electrical stimulation of human auditory system, sparking research into eventual cochlear implants[iv]

1963 First use of deep brain stimulation (DBS) as therapy in motor disorders, using multiple implanted depth electrodes[v]

1968 First recording of magnetic signals from the brain, using magnetoencephalography (MEG)[vi]

1969 First demonstration that a monkey could control a needle with only its mind, demonstrating the potential of BCI technology[vii]

1970 Development of the *Michigan Probe*, a silicon neural probe that recorded signals from multiple depths and sites, allowing mapping of electrical brain circuits[viii]

1985 Discovery of transcranial magnetic stimulation (TMS) to induce motor function with little pain[ix]

1988 First successful demonstration of vagus nerve stimulation (VNS) for epileptic seizure control[x]

1991 DBS for tremors becomes the safest treatment option, driving gradual abandonment of lesional and lobe removal techniques[xi]

1997 The *Utah Array,* a microelectrode cortical implant first developed for visual prosthesis, adapted for BCI, offering a high degree of safety and longevity in humans[xii]

1998 Successful installation of a brain implant to stimulate on/off movement in a patient with “locked-in syndrome” or complete paralysis[xiii]

2005 First demonstration of optogenetics to excite neurons with high spatial resolution, and recording on the millisecond timescale[xiv]

2006 First demonstration of computer cursor and simple prosthetic control via BCI in in a tetraplegic patient[xv]

2011 First flexible electrocorticogram using microelectrode mesh, pushing a wave of advancements using micro and nanoelectronics

2015 First demonstration of syringe-injectable microelectronic mesh (neural lace).[xvi]

2016 Founding of companies Synchron (pioneering stent electrodes) and Neuralink (driving miniaturized devices and robotic implantation techniques).[xvii]

2017 Invention of *Neuropixels*, a probe thinner than a human hair that records data of 500+ neurons simultaneously with minimal brain tissue damage[xviii]

2018 Invention of neural dust microelectrodes to wirelessly stimulate the peripheral nervous system, the smallest of its kind[xix]

2023 Invention of “digital bridge” device, a signal-recording brain implant wirelessly connected to a spinal cord stimulator, restoring ability to walk and climb[xx]

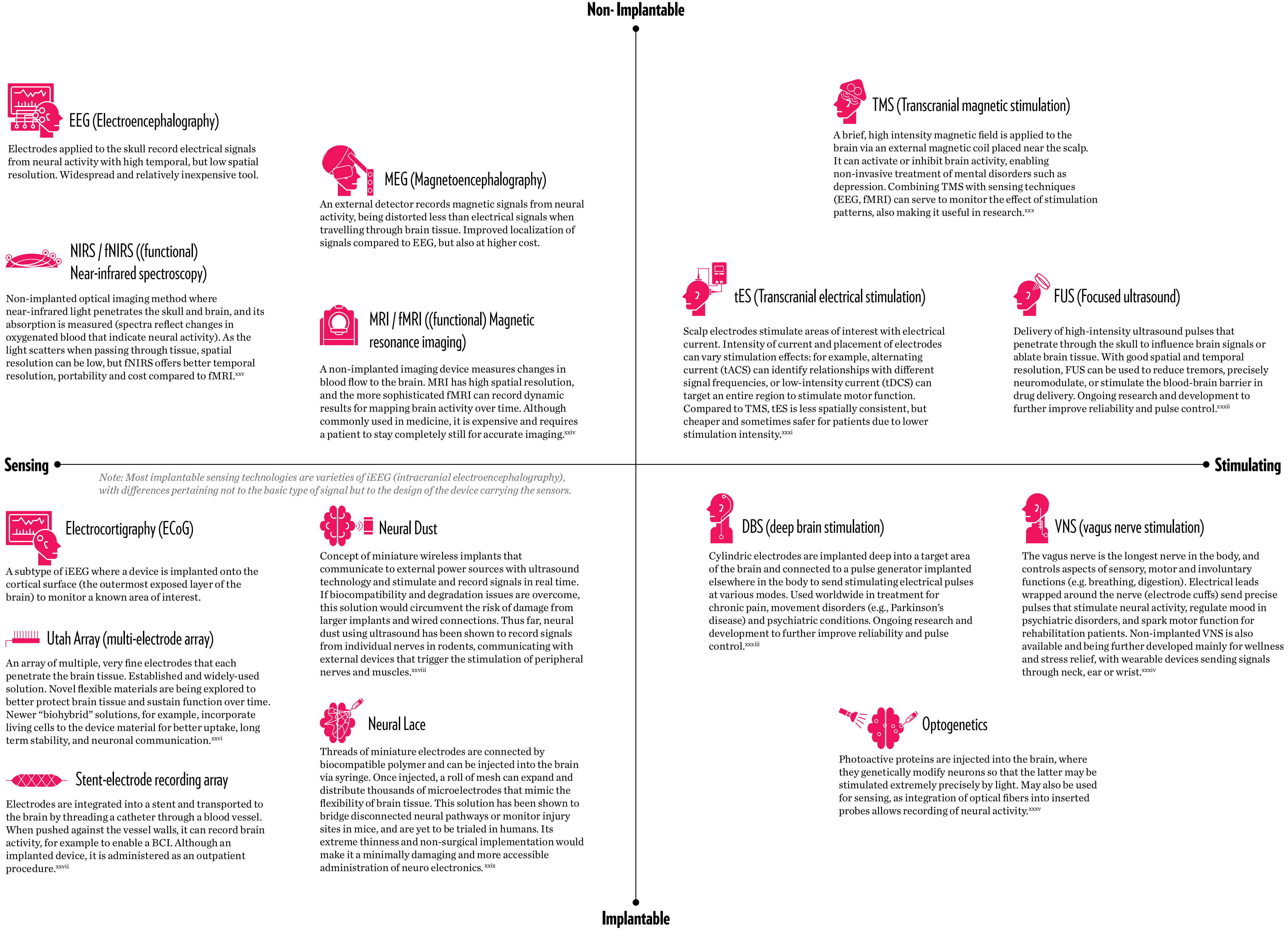
2024 Robotically assisted implantation of a Neuralink BCI into quadriplegic patients to enable control of a computer.[xxi]

Demonstration of first bidirectional BCI using non-implantable EEG, using machine learning to both encode and decode brain waves.[xxii]

2025 Announcement of partnership between Apple and Synchron to integrate stent-electrode connectivity to mobile phones for minimally invasive BCIs[xxiii]

This visualization generally draws strongly on Royal Society, *iHuman: Blurring Lines between Mind and Machine* (London: The Royal Society, 2019), 24–25.; The full list of references for this visual can be found at the end of the report.

Figure 2: Overview of Key Neurotechnologies



EEG (Electroencephalography)

Electrodes applied to the skull record electrical signals from neural activity with high temporal, but low spatial resolution. Widespread and relatively inexpensive tool.

NIRS / fNIRS ((functional)
Near-infrared spectroscopy)

Non-implanted optical imaging method where near-infrared light penetrates the skull and brain, and its absorption is measured (spectra reflect changes in oxygenated blood that indicate neural activity). As the light scatters when passing through tissue, spatial resolution can be low, but fNIRS offers better temporal resolution, portability and cost compared to fMRI.[xxv]

MEG (Magnetoencephalography)

An external detector records magnetic signals from neural activity, being distorted less than electrical signals when travelling through brain tissue. Improved localization of signals compared to EEG, but also at higher cost.

MRI / fMRI ((functional) Magnetic resonance imaging)

A non-implanted imaging device measures changes in blood flow to the brain. MRI has high spatial resolution, and the more sophisticated fMRI can record dynamic results for mapping brain activity over time. Although commonly used in medicine, it is expensive and requires a patient to stay completely still for accurate imaging.[xxiv]

TMS (Transcranial magnetic stimulation)

A brief, high intensity magnetic field is applied to the brain via an external magnetic coil placed near the scalp. It can activate or inhibit brain activity, enabling non-invasive treatment of mental disorders such as depression. Combining TMS with sensing techniques (EEG, fMRI) can serve to monitor the effect of stimulation patterns, also making it useful in research.[xxx]

tES (Transcranial electrical stimulation)

Scalp electrodes stimulate areas of interest with electrical current. Intensity of current and placement of electrodes can vary stimulation effects: for example, alternating current (tACS) can identify relationships with different signal frequencies, or low-intensity current (tDCS) can target an entire region to stimulate motor function. Compared to TMS, tES is less spatially consistent, but cheaper and sometimes safer for patients due to lower stimulation intensity.[xxxi]

FUS (Focused ultrasound)

Delivery of high-intensity ultrasound pulses that penetrate through the skull to influence brain signals or ablate brain tissue. With good spatial and temporal resolution, FUS can be used to reduce tremors, precisely neuromodulate, or stimulate the blood-brain barrier in drug delivery. Ongoing research and development to further improve reliability and pulse control.[xxxii]

Note: Most implantable sensing technologies are varieties of iEEG (intracranial electroencephalography), with differences pertaining not to the basic type of signal but to the design of the device carrying the sensors.

Electrocortigraphy (ECoG)

A subtype of iEEG where a device is implanted onto the cortical surface (the outermost exposed layer of the brain) to monitor a known area of interest.

Utah Array (multi-electrode array)

An array of multiple, very fine electrodes that each penetrate the brain tissue. Established and widely-used solution. Novel flexible materials are being explored to better protect brain tissue and sustain function over time. Newer “biohybrid” solutions, for example, incorporate living cells to the device material for better uptake, long term stability, and neuronal communication.[xxvi]

Stent-electrode recording array

Electrodes are integrated into a stent and transported to the brain by threading a catheter through a blood vessel. When pushed against the vessel walls, it can record brain activity, for example to enable a BCI. Although an implanted device, it is administered as an outpatient procedure.[xxvii]

Neural Dust

Concept of miniature wireless implants that communicate to external power sources with ultrasound technology and stimulate and record signals in real time. If biocompatibility and degradation issues are overcome, this solution would circumvent the risk of damage from larger implants and wired connections. Thus far, neural dust using ultrasound has been shown to record signals from individual nerves in rodents, communicating with external devices that trigger the stimulation of peripheral nerves and muscles.[xxviii]

Neural Lace

Threads of miniature electrodes are connected by biocompatible polymer and can be injected into the brain via syringe. Once injected, a roll of mesh can expand and distribute thousands of microelectrodes that mimic the flexibility of brain tissue. This solution has been shown to bridge disconnected neural pathways or monitor injury sites in mice, and are yet to be trialed in humans. Its extreme thinness and non-surgical implementation would make it a minimally damaging and more accessible administration of neuro electronics.[xxix]

DBS (deep brain stimulation)

Cylindric electrodes are implanted deep into a target area of the brain and connected to a pulse generator implanted elsewhere in the body to send stimulating electrical pulses at various modes. Used worldwide in treatment for chronic pain, movement disorders (e.g., Parkinson’s disease) and psychiatric conditions. Ongoing research and development to further improve reliability and pulse control.[xxxiii]

VNS (vagus nerve stimulation)

The vagus nerve is the longest nerve in the body, and controls aspects of sensory, motor and involuntary functions (e.g. breathing, digestion). Electrical leads wrapped around the nerve (electrode cuffs) send precise pulses that stimulate neural activity, regulate mood in psychiatric disorders, and spark motor function for rehabilitation patients. Non-implanted VNS is also available and being further developed mainly for wellness and stress relief, with wearable devices sending signals through neck, ear or wrist.[xxxiv]

Optogenetics

Photoactive proteins are injected into the brain, where they genetically modify neurons so that the latter may be stimulated extremely precisely by light. May also be used for sensing, as integration of optical fibers into inserted probes allows recording of neural activity.[xxxv]

Technological Outlook and Expansion of Use Cases

Some of the technologies discussed in the previous sections are already routinely used in practice, mostly for medical purposes. For some medical challenges, such as controlling artificial limbs or restoring communication for people with paralysis, existing neurotechnology enables solutions that are superior to any available alternative.[15] Such medical use cases, as well as the treatment of mental health conditions, hold considerable potential for societal benefit and commercial opportunity in their own right. A 2024 Morgan Stanley analysis focusing mainly on relief for upper and lower limb impairment estimated the early and intermediate market potential for medical BCIs to be around $400 billion in the US alone (though it ought to be noted that this report is discussed critically in the neurotech community).[16]

The early and intermediate market potential for medical BCIs is estimated to be around $400 billion in the US alone.

Beyond medical applications, though, researchers and entrepreneurs are continuously exploring ways to expand the use of neurotechnology to other societal domains. Any attempt at mapping this space is likely to underestimate the creativity of future innovators, but an overview of applications for which devices are already being tested, developed or at least discussed in theory demonstrates the extraordinary potential of the field. For example, future neurotech devices may not only allow humans to monitor their brain activity and mental state and to employ targeted stimulation to improve well-being and cognitive capabilities, but also to interact with computers and robots in highly intuitive ways. This could take the form of conscious device control by thought alone or machines adjusting to their operators' mental state and intentions, further aided by virtual and augmented reality tools. Interactions with AI models, currently still highly constrained by chatbot designs, could develop into a much more organic experience that ultimately fuses human and machine intelligence.

Table 1 delineates a set of abstract neurotech applications and concrete medical and non-medical use cases — from the relatively familiar to the seemingly science-fictional — along with a rough indication of their current level of progress.[17]

This overview highlights the transformative potential of neurotechnology and the remarkable advances already recorded, but it also underlines that many of the most promising applications are still at the research device stage. To date, uptake for practical use cases at scale has been limited, especially outside the medical domain.

There is a palpable sense of caution and sometimes frustration among some in the field who feel that past expectations of neurotech innovation have proven too optimistic and that this

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[15] Parmy Olson, "Brain Tech Is Here and Not as Creepy as You Think," *Bloomberg.Com*, November 1, 2024, https://www.bloomberg.com/opinion/articles/2024-11-01/brain-tech-is-here-and-not-as-creepy-as-you-think.; Francis R Willett et al., "A High-Performance Speech Neuroprosthesis," *Nature* 620, no. 7976 (2023): 1031–36; Kallum L Titchmarsh et al., *Brain Computer Interface Primer: The Next Big MedTech Opportunity?* (Morgan Stanley, 2024).

[16] Yasmin Khorram, "Inside a $400 Billion Bet on the Brain-Computer Interface Revolution," *Yahoo! Finance*, November 18, 2024, https://finance.yahoo.com/news/inside-a-400-billion-bet-on-the-brain-computer-interface-revolution-150057794.html?guccounter=1.

[17] Inevitably, such a mapping is non-exhaustive and employs concepts that would merit more careful discussion, for example regarding the distinction and interplay between mood and cognition. It is also shaped and limited by the state of the underlying brain science: For example, given open questions about the nature of consciousness and the way "thought" is fundamentally formed and encoded in the brain, it is unclear whether "thought recording" could be envisaged outside the framework of natural language. Finally, while it is often reasonably clear what type and level of technical functionality will be required to realize a given use case, it is not possible to determine which specific technologies will ultimately prove most suitable to deliver it, given that many relevant options are still at an emergent stage or yet to be invented.

Table 1: Neurotech Applications – Use Cases and Progress

Abstract Application	Medical Use Cases	Non-Medical Use Cases	Level of Progress
Sensing brain activity to inform behavioral adjustments, interventions, or decisions	Diagnose mental disorders and neurodegenerative diseases Provide diagnostic support for treatment Prepare and monitor surgical procedures	Inform cognitive or behavioral adjustments, e.g., for conscious relaxation (neurofeedback)[xxxvi] Monitor mental state (focus, alertness, fatigue, etc.), e.g., in high-risk work settings[xxxvii] Test an individual's recognition of a specific piece of information (e.g., for law enforcement)[xxxviii] Biometric identification (based on individually unique patterns of brain activity)	Medical use cases supported by mature and evolving technologies Attempts at marketing professional and consumer devices (e.g., headbands, helmets and headphones with EEG), but still with limited functions and uptake
Connecting the brain to virtual/augmented reality applications	Support treatment and rehabilitation processes	Enhanced neurofeedback Support professional or everyday task execution (e.g., real-time provision of relevant information) Recreational use (e.g., gaming, immersive experiences)	Marketing of initial professional and consumer products, e.g., to enhance neurofeedback[xxxix] Various experimental studies on more sophisticated setups
Augmentative and alternative communication	Restore ability to speak and write (e.g., for ALS patients)	Low Reduce effort and increase speed of writing (brain-to text) "Silent talk" (brain-to-brain communication)	Fluid speech with minimal latency realized using implantable research device[xl] Progress in speed and error-rate for brain-to-text using stationary non-implantable devices (magnetoencephalography or MEG)[xli] Basic experimental proofs of concept for brain-to-brain communication (e.g., collaboration in a Tetris-like game)[xlii]
Controlling digital and physical devices	Control artificial limbs Control exoskeletons for rehabilitation Enable control of computers (e.g., for ALS patients)	Reduce effort of operating computers Control vehicles, robots, drones, exoskeletons, etc. Enable machines to adjust to the condition of human operator[xliii] Dynamically tailor content (e.g., music) to mental state	Mature and further evolving solutions for neuroprosthetics (often relying at least partly on sensing in the peripheral rather than central nervous system)[xliv] Various successful experiments on operating computers (e.g., controlling cursors and avatars in games) and controlling vehicles and devices, with implantable devices required for any sophisticated control[xlv]
Influencing sensory reception	Restore sensory functions (e.g., hearing, vision, touch)	Enhance sensory functions (e.g., vision) for specific tasks Reduce pain and other undesired sensations	Cochlear implants are an established solution to restore hearing Successful experiments on rudimentary vision restoration through neuroprosthetics since 1990s; several devices at clinical trial stage[xlvi]

Influencing mood & emotions	Treat mental disorders	Lift mood Generate pleasant sensations Suppress undesired emotions and memories Support sleep and recovery	Established therapeutic procedures mainly using transcranial magnetic stimulation (TMS) Various other implantable and non-implantable devices at clinical trial stage Attempts at marketing consumer devices, notably using transcranial direct current stimulation, (tDCS)[xlvii]
Influencing cognitive processes (incl. motor cognition)	Prevent and treat conditions such as tremors, depression, Alzheimer's	Enhance attention, concentration, memory, etc. Increase speed and quality of decision-making Increase dexterity	Established therapeutic procedures mainly using deep brain stimulation (DBS) Early non-medical use in professional sports Limited dedicated effort toward consumer devices, but part of broader vision of brain-computer interfaces (BCIs) for broad popular use
Integration of brain functions with external information processing capacity, storage and AI systems	Alternative path to maintain or restore cognitive capabilities in cases of neurodegenerative diseases	Integrate human and AI Enable knowledge or skill acquisition, circumventing conventional learning Store knowledge for later retrieval Ultimately, severance of dependence of conscious existence on mortal body (transhumanist vision)[xlviii]	Significant experimental advances in recent years [xlix] Ambitious visions being articulated by industry players Full mapping of brain of a fruit fly, but mapping of human brain many orders of magnitude more complex[l]

harms public perception and discussion.[18] Sensationalist reporting aside, an otherwise rather cautious EU-funded foresight exercise in 2015, for example, suggested that before 2025, we may already see significant user adoption of non-implantable brain state monitoring.[19] Still, while experts' expectations on specific innovation and adoption pathways and timelines vary,[20] most people with knowledge of the field expect such non-medical use to eventually become widespread. A 2019 assessment by Britain's Royal Society concluded that it is "probable by 2040" for neural interfaces to "become widely used for gaming, fitness and well-being," including, for example, "hands-free control of computers, typing or entering data sing the brain alone."[21]

Crucially, innovation and adoption of neurotechnology are shaped not just by advances in the lab, but by the broader environment in which these processes take place. They are generated by the interplay of multiple actors that together determine what gets funded and developed, what gets offered and adopted, and at what pace. Relevant stakeholders include researchers, entrepreneurs, public funders, private investors, innovation agencies, regulators, policymakers, more broadly and — importantly — early adopters (currently mostly in clinical and research settings). The roles of these various players can be complementary but also in tension, particularly where incentives or risk appetites diverge.

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[18] See, for example, https://www.linkedin.com/pulse/3-brain-tech-myths-what-bcis-can-cant-do-zander-labs-tczze/?trackingId=IHQvOnqCSceAB2J1I03xvw%3D%3D.

[19] BNCI Horizon 2020, *Horizon 2020 Roadmap: The Future in Brain/Neural-Computer Interaction* (Verlag der Technischen Universität Graz, 2015), https://bnci-horizon-2020.eu/images/bncih2020/Roadmap_BNCI_Horizon_2020.pdf.

[20] Soekadar et al., "Future Developments in Brain/Neural–Computer Interface Technology."

[21] Royal Society, *iHuman: Blurring Lines between Mind and Machine* (The Royal Society, 2019), 58–59.

While much work remains to be done on foundational research, the field's central challenge on the path to widespread adoption is arguably the "valley of death" facing actors who seek to translate research findings into real-world applications. Although familiar from other technological fields, this challenge of funding activities during the phase between proof of concept and substantial adoption is particularly pronounced in neurotech. This is because development cycles, at least for implantable systems, easily exceed 10-15 years, and considerable uncertainty surrounds future policy as well as the fundamental question of societal acceptance. The result is that promising innovations often stall before reaching users, due not to technical failure, but to the absence of sustained support along the full innovation cycle.[22] As discussed in the next section, public funding and policy have a critical role to play in addressing this issue and have done so in different geographies to varying extents — shaping in turn, the extent to which private funding has been mobilized for commercialization efforts.

Where neurotech companies have managed to establish themselves, they mostly have yet to achieve profitability and their funding has typically far exceeded their revenue: a 2025 analysis of 273 dedicated global neurotech companies conducted by the Center for Future Generations found that the average ratio of aggregate funding to revenue to date is 13:1 for edical neurotech companies and 6:1 for firms focusing on non-medical products.[23]

While the obstacles to the successful commercialization of neurotechnology are formidable, innovation and adoption of emerging technologies are typically interdependent and likely to enter a mutually reinforcing dynamic once a certain threshold is crossed. In part, this is due to sociological aspects of innovation diffusion in general, where a critical mass of early adopters is often key for promoting knowledge and acceptability of novel technologies among broader audience and precipitating a seemingly sudden surge of adoption.[24] Moreover, once technological advances have enabled initial use cases that appeal to consumers, their uptake of the technology creates a more compelling investment proposition and helps fuel further innovation, for example by generating data that can be used for further research and development (R&D).

Innovation and adoption of emerging technologies are typically interdependent and likely to enter a mutually reinforcing dynamic once a certain threshold is crossed.

Given that the question of societal acceptance and trust is particularly critical in the case of neurotechnology and that the scarcity of capital and data have been key impediments to faster advances, both of these aspects are likely to prove particularly pronounced in this field (leaving aside the more radical argument that cognitive enhancements through neurotechnology may themselves help unlock future innovation). The future innovation and adoption trajectory should therefore be expected to take a distinctly non-linear shape, comparable to the "ChatGPT moment" for AI in the last years. While it seems futile to predict the precise timing at which an acceleration may take hold, one or multiple of the following developments should be observable at a relatively early point and accordingly merit close monitoring:

- **Development of a non-implantable device with much better sensing or stimulation capability.** This would greatly expand the set of possible use cases that can be realized without surgery, creating a pathway toward broad adoption with a much lower threshold.

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[22] See, for example, the discussion of this issue on the website of BrainMind, an organization dedicated to galvanizing the brain science ecosystem: https://brainmind.org/about.

[23] Laura Bernáez Timón and Virginia Mahieu, *Consumer Neurotech Market Atlas: How the Sector Is Making Moves into the Mainstream* (Center for Future Generations, 2025).

[24] This topic is the subject of an expansive literature, see for example Everett M. Rogers, *Diffusion of Innovations*, 5th ed (Free Press, 2003); Paul A. Geroski, "Models of Technology Diffusion," *Research Policy* 29, nos. 4–5 (2000): 603–25, https://doi.org/10.1016/S0048-7333(99)00092-X.

- **Successful clinical trial of a safe, minimally invasive and ideally reversible implantable solution.** This could take the form of minimally invasive surgery to insert sensors into the brain itself, but also an alternative, non-surgical approach, such as the injection of miniaturized components.
- **Substantial improvements in decoding and interpretation of available brain data.** This would likely be accomplished through more powerful machine learning algorithms and the use of more and better training data, and serve as a force multiplier, especially for non-implantable, but also implantable devices.
- **Surge of commercial investment and first successful exits from neurotech start-ups.** This would further galvanize investor interest in the field and create a group of potential angel investors with first-hand expertise and experience to be passed on to other entrepreneurs.
- **A lifestyle or fashion trend involving a neurotech device.** This could increase the social acceptability and desirability, especially of wearables, as well as boosting the generation of consumer data to support further technological development.

At the same time, the inherent sensitivity of neurotechnology also means that it is prone to lasting damage from negative events. For example, even a single case of a botched implantation or a cybersecurity incident could durably undermine trust in these technologies and reinforce regulatory risk-aversion. However, it seems likely that such a development would only temporarily set back the innovation and adoption trajectory rather than derail it altogether.

REGIONAL VARIATION AND COMPETITION IN THE NEUROTECHNOLOGY ECOSYSTEM

For some purposes, it makes sense to think of the myriad stakeholders noted in the previous section — from researchers to users, entrepreneurs to policymakers — worldwide as constituting a global neurotechnology ecosystem underpinning an overall technological trajectory. This lens is helpful, for instance, when looking at global efforts to develop ethical norms as well as technical standards around neurotechnology. As discussed in further detail in the next chapter, these efforts are taking place both under the auspices of established organizations such as UNESCO and the International Organization for Standardization (ISO) and in the form of voluntary bottom-up initiatives such as the Implantable Brain Computer Interface Collaborative Community (iBCI-CC) or those hosted by the Institute of Electrical and Electronics Engineers (IEEE).

At the same time, though, regional differences within the global ecosystem matter greatly. In recent years, competition among states over leadership across emerging technologies has become explicit and prominent. Power and security considerations increasingly shape national approaches, including decisions about funding, industrial policy and regulation.

Neurotechnology is no exception to this development, and indeed, it is particularly pertinent to the field due to the centrality of public initiatives in overcoming the key challenges in innovation and translation noted above. In many countries, national or regional "brain projects" have, over the past decade, provided a framework for coordinated action and funding, focusing on the research stage but often with a strong emphasis on practical relevance. In parallel, states have directly supported or initiated further translational efforts through dedicated innovation agencies as well as military and other security-oriented institutions. Serious attempts at commercialization of neurotechnology to date have almost invariably benefited from these schemes and remained closely intertwined with publicly funded academic research, not least due to the critical importance of clinical trials for medical devices.

The US dominates already at the stage of academic research and of patent applications; however, Europe is not so far behind.

As the following sections discuss more systematically, the interplay of stakeholders in the neurotech ecosystem differs significantly across regions and has correspondingly yielded varying results. As a collection of indicators from different sources along the research-to-adoption funnel indicates, the US dominates already at the stages of academic research and patent applications related to neurotechnology; however, Europe is not so far behind if considered collectively rather than as individual countries. Within Europe, Germany plays a leading role in research, and even more so in translation into patents.

At the stage of commercialization — operationalized here in terms of the volume of new funding deals for neurotech ventures in 2024, as well as the number of dedicated consumer neurotech companies and the size of their workforce as of 2025 — the US lead, even over Europe as a whole, is drastic. In China, quantitative transparency, especially regarding translation and commercialization, is patchier, but both the quantity and quality of publications and anecdotal evidence on the efforts of key research groups and firms point to major advances at all stages of the funnel in recent years. This is particularly remarkable given the low baseline from which efforts, especially on implantable neurotechnology in China, started not too long ago.

In the US, much of the progress in neurotech has followed a well-established pattern: public funding for basic research lays the foundation for entrepreneurial ventures that drive commercialization. Start-ups and scale-ups attract private investment, enabled by largely permissive regulation. In China, the push has even been more systematically state-driven: Over the past decade, the government (at national as well as provincial and municipal levels) has explicitly prioritized neurotechnology as a strategic domain and has invested accordingly — often in conjunction with broader military-civil fusion efforts. Still, private ventures aligning themselves with these state-led efforts have also played an important role.

Table 2: Neurotech Leadership Metrics Along the Research-to-Commercialization Funnel

Country	Number of high-impact neuroscience publications, 2000-2021[li]	Number of English-language neuroscience patent applications, 2000-2020[lii]	Reported new funding deals for neurotech companies, 2024 (US$ millions)[liii]	Number of dedicated consumer neurotech companies, 2025[liv]	Number of employees in dedicated consumer neurotech sector, 2025[lv]
United States	16,000	4,900	1,530	117	6,211
China	2,000	1,200	N/A	8	303
Germany	2,800	700	21	9	211
France	1,600	500	16	10	141
Netherlands	1,200	>100	168	7	217
Italy	1,600	100	48	3	42
United Kingdom	3,600	200	149	22	3,348[lvi]
Australia	1,200	>100	60	3	156
Canada	1,600	200	21	14	333
Japan	1,600	700	0	1	87
South Korea	<500	1,100	18	3	54

Europe, meanwhile, faces clear challenges in translating a strong research base into commercial success. The region has been central to key scientific advances. It is also home to some small but reasonably successful neurotech companies, mainly pursuing non-implantable approaches. However, a risk-averse regulatory environment and a persistent shortage of capital willing to fund uncertain, long-term neurotech ventures have been among the key factors making the transition from lab to market significantly more difficult than in the US and China. This has led to a situation in which none of the largest and best funded neurotechnology players globally are located on the continent.

United States

Strategic Initiatives and Public Funding

Neurotechnology has been a strategic priority in the US for over a decade, in both civilian and military contexts. In 2013, the US government launched the BRAIN (Brain Research through Advancing Innovative Neurotechnologies) Initiative hosted by the National Institute of Health (NIH). The program reached a peak annual budget of nearly $700 million in 2023, supporting both basic and translational research in close collaboration with academia.[25]

Beyond the BRAIN Initiative, the US national security apparatus has shown sustained interest in the field and constituted a further source of public funding. Most notably, the Defense Advanced Research Projects Agency (DARPA), the independent R&D agency within the Department of Defense, has since the early 2000s, organized and funded

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[25] https://braininitiative.nih.gov/funding/understanding-brain-initiative-budget

multiple substantial programs (each in the range of $50-$100 million). These have focused on enablers of battlefield applications as well as on issues such as recovery after traumatic brain injury[26] and explored wearable, implantable, and even injectable neural interfaces, the latter as part of a particularly innovative program titled “N3” (Next-Generation Nonsurgical neurotechnology).[27] DARPA projects were directly instrumental to innovations such as the stent electrode; one commentator notes that “almost every advance or major technology in the field can be traced back to DARPA funding to the researchers.”[28]

The US national security apparatus has shown sustained interest in the field and constituted an important source of public funding.

The Intelligence Advanced Research Projects Activity (IARPA) has also supported neurotech research through programs such as “SHARP” (Strengthening Human Adaptive Reasoning and Problem Solving), which sought to explore combinations of various interventions to further enhance the cognitive performance of already high-performing individuals in information-rich environments.[29] Since the US government first defined a National Strategy for Critical and Emerging Technologies in 2020, “Human-Machine Interfaces” (and BCIs as a subfield) have been included in its list of focus areas, highlighting the field’s perceived relevance to national security interests.[30]

Private Investment and Enterprise

Building upon and complementing this substantial state support, private capital has played an increasingly important role in the US neurotech ecosystem in recent years. A large share of the approximately $1.5 billion in funding deals compiled for 2024 by Naveen Rao’s *Neurotech Futures* is accounted for by smaller, early-stage venture funding, but there have also been a growing number of standout deals, such as Blackrock Neurotech’s $200 million in funding from crypto platform provider Tether.[31] This deal is also indicative of the somewhat idiosyncratic investor landscape that has emerged, especially for implantable neurotech; actors that have not traditionally been interested in medical technologies are being attracted by the technology’s wider transformative potential. Besides further investors with a crypto background,[32] Neuralink co-founder Elon Musk played an important role in drawing other tech players into the field. The company’s latest funding round of $650 million in June 2025 featured several well-known venture capitalists (VCs) and investment managers such as Sequoia Capital and ARK Invest, as well as Peter Thiel’s Founders Fund.[33]

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[26] https://www.darpa.mil/research/programs/restoring-active-memory

[27] https://www.darpa.mil/research/programs/next-generation-nonsurgical-neurotechnology

[28] Pooja Rao, *How DARPA Drives Brain Machine Interface Research*, November 22, 2020, https://www.from-the-interface.com/DARPA-funding-BCI-research/; Robbin A Miranda et al., “DARPA-Funded Efforts in the Development of Novel Brain–Computer Interface Technologies,” *Journal of Neuroscience Methods* 244 (2015): 52–67.

[29] https://www.iarpa.gov/research-programs/sharp

[30] The White House, *National Strategy for Critical and Emerging Technologies* (2020), https://trumpwhitehouse.archives.gov/wp-content/uploads/2020/10/National-Strategy-for-CET.pdf; Fast-Track Action Subcommittee on Critical and Emerging Technologies, *Critical and Emerging Technologies List Update* (2024), https://bidenwhitehouse.archives.gov/wp-content/uploads/2024/02/Critical-and-Emerging-Technologies-List-2024-Update.pdf.

[31] Naveen Rao, “What $200 Million In Crypto Cash Means For Blackrock Neurotech,” *Forbes*, April 30, 2024, https://www.forbes.com/sites/naveenrao/2024/04/30/what-200-million-in-crypto-cash-means-for-blackrock-neurotech/; Rao, “2024 Neurotech Funding Snapshot.”

[32] Ashlee Vance, “How a Winning Bet on Crypto Could Transform Brain and Longevity Science,” *Bloomberg*, November 11, 2024, https://www.bloomberg.com/news/articles/2024-11-11/crypto-millionaire-fuels-push-to-transform-brain-research.

[33] Neuralink, “Neuralink Raises $650 Million Series E,” Press Release, June 2, 2025, https://neuralink.com/blog/neuralink-raises-650m-series-e/.

The commercial neurotechnology sector in the US comprises a mix of specialized start-ups and large tech firms. Several dedicated neurotech firms stand out for their technical ambition and progress. For example, Neuralink, Blackrock Neurotech, Synchron, Paradromics, Precision Neuroscience, and Science Corp. all focus on different varieties of minimally invasive implantable devices and are currently either at the stage of clinical trial or intend to enter it soon. In parallel, firms such as Neurable, OpenBCI and Muse (technically named InteraXon Inc.) are active in the non-implantable space, with products ranging from research equipment and dedicated neuroheadsets to established wearables such as headphones integrating neurotechnology.

Large players have recognized the importance of neurotech and are all active in R&D.

At the same time, large players such as Meta, Apple, Microsoft, and IBM have recognized neurotech's importance and are all active in R&D, partly in collaboration with specialized neurotech firms. For example, Meta has invested substantially in R&D on brain-to-text, acquired CTRL-Labs (the developer of a wristband offering BCI-like functions based on signals from the peripheral nervous system),[34] and established a business unit "Reality Labs" that is exploring the use of neural interfaces in AR environments.[35] Apple has filed patents for EEG-equipped earbuds,[36] and established a partnership with Synchron regarding the use of stentrode technology for controlling digital devices[37]

Regulation and Policy

The regulatory and policy landscape for neurotech in the US is widely considered to be permissive. One factor driving this perception is that companies targeting broader consumer markets are typically able to market their devices as "general wellness" products, avoiding medical device approval through the Food and Drug Administration (FDA) altogether. In such cases, only the Federal Trade Commission (FTC) rules on unfair and deceptive marketing apply.[38]

Another reason is the dialogic approach espoused by the FDA for those cases where medical device approval is required, providing developers with transparent conditions and permitting iterative adjustments.[39] While the FDA has not issued formal product classifications for all relevant technologies (with transcranial direct current stimulation or tDCS as the most notable case in which such a classification is lacking), it has treated non-implantable devices using EEG, stationary magnetoencephalography (MEG) and functional near-infrared spectroscopy (fNIRS) as Class II. This is an intermediate category in which manufacturers have to demonstrate substantial equivalence to already approved products, rather than conducting full pre-market studies, as would be required for a novel and potentially risker

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[34] Nick Statt, "Facebook Acquires Neural Interface Startup CTRL-Labs for Its Mind-Reading Wristband," *The Verge*, September 24, 2019, https://www.theverge.com/2019/9/23/20881032/facebook-ctrl-labs-acquisition-neural-interface-armband-ar-vr-deal.

[35] https://tech.facebook.com/reality-labs/

[36] Erdrin Azemi et al., Biosignal Sensing Device Using Dynamic Selection of Electrodes, Patent US20230225659A1, filed January 9, 2023, and issued July 20, 2023, https://patentimages.storage.googleapis.com/e2/4d/92/a20ceacf02d9db/US20230225659A1.pdf.

[37] BusinessWire, *Synchron To Achieve First Native Brain-Computer Interface Integration with iPhone, iPad and Apple Vision Pro*, May 13, 2025, https://www.businesswire.com/news/home/20250513927084/en/Synchron-To-Achieve-First-Native-Brain-Computer-Interface-Integration-with-iPhone-iPad-and-Apple-Vision-Pro.

[38] Farahany, *The Battle for Your Brain*, 102–3.

[39] This assessment was consistent in several interviews with neurotechnology researchers and company executives, May-June 2025.

Class III device. The FDA also issued specific guidance for BCIs in 2021[40] and has enabled fast-tracking of applications in this area through its Breakthrough Devices Program. In combination with a health system where it is common for wealthy patients to cover innovative but expensive treatments out of pocket via private insurance, this contributes to a comparatively attractive early market for medical neurotechnology — though some warn about the longer-term challenge of broadening adoption in a health system that does not prioritize a uniformly high standard of care.[41]

A further factor contributing to the advancement of commercial neurotech in the US is the lack of comprehensive federal privacy and data protection legislation that could hinder the processing of neural data (beyond certain boundaries for health data established by the 1996 Health Insurance Portability and Accountability Act). This has granted neurotech companies considerable leeway to collect and process neural data from users. However, the recent adoption of state-level laws in Colorado and California targeting neural data privacy highlights policymakers' growing concern about this situation.[42] In the absence of clearer federal regulation, the result could be a patchwork of state-level rules that may render navigation for neurotech companies more challenging in the future.

Another significant source of uncertainty about the future of the US neurotech ecosystem is the cuts in research funding pursued by the Trump administration; the BRAIN initiative saw its funding cut by 20 percent on top of a 40 percent reduction already in the previous year.[43] These cuts could undermine the conditions for the academic research still underpinning much of the progress in neurotechnology and prompt leading researchers to consider alternative locations, even though DARPA will likely continue to be a significant source of funding alongside private investors and philanthropists. In parallel, personnel cuts at key institutions such as the FDA bode ill for the speedy processing of approvals, unless regulatory requirements are dropped altogether. Finally, tariffs and technology restrictions could affect the sourcing of components from abroad. To date, however, the US has been the prime global location for neurotechnology development, testing and bringing to market at scale.

China

Strategic Initiatives and Public Funding

China has approached neurotechnology with an increasingly coordinated national strategy, integrating basic research, industrial development and political positioning. Although the country's engagement with neuroscience predates its rise in AI, it is in the combination of these two domains that Chinese policymakers mainly see strategic promise.[44] China's Five-Year Plans have highlighted Brain Science and Brain-Inspired Intelligence as a priority since 2016.

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[40] Food and Drug Administration, *Implanted Brain-Computer Interface (BCI) Devices for Patients with Paralysis or Amputation - Non-Clinical Testing and Clinical Considerations* (Food and Drug Administration, 2021), https://www.fda.gov/media/120362/download.

[41] Interview with Prof. James Giordano, 29 May 2025. See also Ani Satz, "Toward Solving the Health Care Crisis: The Paradoxical Case for Universal Access to High Technology," *Yale Journal of Health Policy, Law, and Ethics* VIII, no. 1 (2008): 93–144.

[42] Jennifer Dickey, *The Rise of Neurotech and the Risks for Our Brain Data* (New America Foundation, 2025), https://www.newamerica.org/future-security/reports/the-rise-of-neurotech-and-the-risks-for-our-brain-data/.

[43] https://braininitiative.nih.gov/funding/understanding-brain-initiative-budget

[44] William C Hannas et al., *China AI-Brain Research: Brain-Inspired AI, Connectomics, Brain-Computer Interfaces* (Center for Security and Emerging Technology (CSET), 2020), https://cset.georgetown.edu/wp-content/uploads/CSET-China-AI-Brain-Research.pdf.

This approach and ambition are reflected in the China Brain Project (CBP), formally launched in 2021 after years of preparatory work.[45] The initiative pursues the dual objective of treating brain disorders and accelerating the development of brain-inspired AI, including through BCIs and neuromorphic computing. Estimates of the CBP's total budget vary widely — from an officially confirmed CNY 3.2 billion (app. $450 million) for the first phase to figures up to CNY 100 billion ($16 billion) quoted in media reporting.[46] However, there is no doubt that the program is backed by strong political will at both the national and local levels. The Chinese Academy of Sciences (CAS), the National Natural Science Foundation (NNSF), and multiple ministries have launched dedicated projects and funding lines.[47] In contrast to the US BRAIN Initiative's strong focus on clinical applications, the CBP places greater emphasis also on non-medical use cases, suggesting a broader push for societal integration.[48]

Although China's engagement with neuroscience predates its rise in AI, it is in the combination of these two domains that policymakers mainly see strategic promise

To name only a few examples, prominent neurotech research hubs in China include the CAS Institute of Automation in Beijing, Tianjin University's "Brain Talker" program (focused on developing a chip geared at separating signal and noise in brain recordings), and the Chinese Institute for Brain Research. The latter was initiated and funded in 2018 by the Beijing municipal government through a "cooperative framework" comprising universities and institutes in the area as well as the PLA Academy of Military Science.[49] Regionally, municipalities such as Shanghai and Beijing have published BCI development plans aiming to support hundreds of firms and reach clinical deployment of invasive BCIs by 2030.[50]

Given that military modernization, including through "military-civil fusion" efforts, has been an openly articulated priority of China's leadership, it also not surprising that the Central Military Commission's Science and Technology Commission has reportedly overseen several "plans, programs, and expert groups of top scientists for priorities that include human-machine fusion intelligence," though these programs are by their nature opaque.[51] In the words of the Commission's Director, "AI will accelerate the process of military transformation, ultimately leading to a profound Revolution in Military Affairs [...] The combination of artificial intelligence and human intelligence can achieve the optimum, and human-machine hybrid intelligence will be the highest form of future intelligence."[52]

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[45] Lin LU et al., "Progress of China's Brain Science Program (中国脑科学计划进展)," Journal of Peking University (Health Sciences) 54, no. 5 (2022): 791–95, https://doi.org/10.19723/j.issn.1671-167X.2022.05.002.

[46] Stephen Chen, "Rare Public Row Erupts over Funding for US$16 Billion China Brain Project," *South China Morning Post*, January 25, 2022, https://www.scmp.com/news/china/science/article/3164585/rare-public-row-erupts-over-funding-us16-billion-china-brain.

[47] Hannas et al., *China AI-Brain Research: Brain-Inspired AI, Connectomics, Brain-Computer Interfaces*.

[48] Margaret Kosal and Joy Putney, "Neurotechnology and International Security: Predicting Commercial and Military Adoption of Brain-Computer Interfaces (BCIs) in the United States and China," *Politics and the Life Sciences* 42, no. 1 (2023): 81–103.

[49] Hannas et al., *China AI-Brain Research: Brain-Inspired AI, Connectomics, Brain-Computer Interfaces*. On the Chinese neurotech research landscape, also see Pooja Rao, "China's Brain-Computer Interface Landscape in 2021: Has the Dragon Woken up to Neurotech?," *From the Interface*, April 17, 2021, https://www.from-the-interface.com/China-BCI-neurotech/; Xu Zhang et al., "Brain Science and Technology: Initiatives in the Shanghai and Yangtze River Delta Region," *Nature Portfolio*, n.d., accessed June 4, 2025, https://www.nature.com/articles/d42473-019-00213-5.

[50] Mandy Zuo, "Shanghai and Beijing Aim to Become Global Players in Brain Computer Interface Industry," *South China Morning Post*, January 12, 2025, https://www.scmp.com/news/china/science/article/3294425/shanghai-and-beijing-aim-become-global-players-brain-computer-interface-industry.

[51] Elsa B. Kania, "Minds at War: China's Pursuit of Military Advantage through Cognitive Science and Biotechnology," *PRISM 3*, no. 8 (2020): 83–101.

[52] Translation of quote from Kania, "Minds at War: China's Pursuit of Military Advantage through Cognitive Science and Biotechnology," 84.

Private Investment and Enterprise

Private investment into neurotechnology in China is less consistently documented than in Western markets but appears to have reached substantial proportions as well. In early 2025, two authors from the China Academy of Information and Communications Technology (CAITC, a state-affiliated research institute) published an analysis suggesting that funding for "China-related" neurotech ventures had accrued to almost $2 billion overall, though it unfortunately does not provide any further breakdown. (For comparison, this report puts the global figure at $10 billion and the US at $5 billion, so it most likely includes public funding).[53] Around the same time, Shanghai-based BCI company StairMed reportedly completed the single largest funding round to date, amounting to CNY 350 million ($48 million).[54]

Investment activity in China spans a range of actors, from generalist tech investors such as HongShan (formerly Sequoia China) to actors with a more explicit focus on health and biotech such as Qiming Venture Partners. Established corporate actors are likewise active in funding BCI-related research, often through university partnerships. For instance, Huawei, Alibaba, Baidu, and Ant Group are all funders of the Brain-Computer Interface and Machine LearningLaboratory at Huazhong University of Science and Technology.[55] Ping An Technology, a subsidiary of the Ping An conglomerate best known for its insurance business, held more than 100 neurotech-related patents as of 2020, making it the second-largest corporate patent holder globally after IBM.[56] Finally, the Tianqiao and Chrissy Chen Institute is a prominent example of a philanthropic initiative in the sector, which first funded an institute at Caltech in the US but has since supported an institute and a "frontier lab" in hanghai.[57] Its founders acquired their wealth through Shanda Group, a China-focused investment firm that has also funded Chinese commercial neurotech ventures such as the BCI company NeuroXess.[58]

According to a report by the CAITC and China's BCI Industrial Alliance, more than 100 neurotech firms operated in China as of 2023, ranging from recent university spinouts to fast-growing commercial enterprises.[59] Notable examples include the already mentioned StairMed and NeuroXess, as well as Xinzhida Neurotechnology, all of which aim to develop fully implantable interfaces. PINS Medical and SceneRay, founded in 2008 and 2009 respectively, have focused on DBS and developed devices that have already been implanted into thousands of patients in China.[60] Meanwhile, mass-market devices such as EEG-enabled headbands are being commercialized by companies like BrainCo and Entertech, the latter reportedly already supplying fatigue-monitoring equipment such as EEG-equipped helmets r use at scale in state-owned utilities.[61]

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[53] Jie ZHOU and Liwei CHENG, "Global Brain Computer Interface Technology and Industry Development Trends (全球脑机接口技术与产业发展态势)," *Information and Communications Technology and Policy* 51, no. 3 (2025): 53–58.

[54] Chen, "Rare Public Row Erupts over Funding for US$16 Billion China Brain Project."

[55] https://lab.bciml.cn/

[56] Hain et al., *Unveiling the Neurotechnology Landscape: Scientific Advancements, Innovations and Major Trends*, 12.

[57] https://www.cheninstitute.org/

[58] https://www.crunchbase.com/organization/neuroxess/company_financials

[59] China Academy of Information and Communications Technology and Brain-Computer Interface Industrial Alliance, "Brain-Computer Interface Technology Development and Application Research Report (2023)" (脑机接 口技术发展与应用研究报告 (2023)) (2023), https://perma.cc/GJ5Q-D5FR.

[60] Michelle Paff et al., "Update on Current Technologies for Deep Brain Stimulation in Parkinson's Disease," *Journal of Movement Dirorders* 13, no. 3 (2020).

[61] Ben Goertzel, "SingularityNET Partners with the Chinese Neurotechnology Firm Entertech," Medium, November 22, 2018, https://medium.com/singularitynet/singularitynet-partners-with-the-chinese-neurotechnology-firm-entertech-58d25f0a5ecc.

Regulation and Policy

The regulatory environment in China has seen some relevant developments in recent years, within a fundamentally state and security-centric framework. Since 2018, medical device approval has been the responsibility of the National Medical Products Administration (NMPA), which issued industry standards for medical devices with BCI technology in February 2025.[62] Shortly after, the National Healthcare Security Administration (NHSA) also published pricing guidelines for BCI-related services, including insertion and removal fees as well as "adaptation fees" for non-invasive BCIs.[63]

In early 2024, the Ministry of Science and Technology (MoST) published dedicated "Ethics Guidelines for Brain-Computer Interface Research," focusing on "restorative" rather than enhancement-oriented applications and accordingly emphasizing issues such as the safety of patients, study participants and testing animals.[64] China is often portrayed as exceptionally permissive when it comes to lab animals; the CBP puts specific emphasis on fostering research monkey "colonies," and most primates used for research in the US are now imported from China.[65]

Especially relevant for broader non-medical use, a Personal Information Protection Law has been in force in China since 2021, covering aspects such as the collection of sensitive personal information, including biometric features, consent and specificity of purpose. However, experts have cautioned that this and related legislation are still geared at granting state authorities extensive leeway in their interpretation and are ultimately subordinate to the goal of "creating a state-led data economy [as] part of a strategy that treats data as a national asset."[66] This approach raises ethical questions, but for the reasons discussed above, it could constitute a significant competitive advantage in the neurotech field.

Importantly, with a view to the possibility that Chinese neurotech devices will be used at scale in other parts of the world, China's government has generally attempted to reassure foreign interlocutors over the last years that it will not request access to any data generated and stored abroad by Chinese firms, notably through its "Global Data Security Initiative."[67] How reliable those assurances will prove in case of a national security contingency, however, remains to be seen. According to the National Intelligence Law, Chinese entities are obligated to share any data with federal authorities when requested for national security reasons.[68]

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[62] Weilan Zhang, "China Approves New Standards for BCI-Enabled Medical Devices to Boost Industry Development," *Global Times*, February 25, 2025, https://www.globaltimes.cn/page/202502/1329053.shtml.

[63] Global Times, "New Pricing Guideline for Brain-Computer Interface Services to Boost Application," *Global Times*, March 12, 2025, https://www.globaltimes.cn/page/202503/1330012.shtml.

[64] A translation of this document is available here: Artificial Intelligence Ethics Subcommittee of the National Science and Technology Ethics Commission, *Ethics Guidelines for Brain-Computer Interface Research* (国家科技伦理委员会人工智能伦理分委员会) (2024), https://cset.georgetown.edu/publication/china-bci-ethics/.

[65] Kosal and Putney, "Neurotechnology and International Security: Predicting Commercial and Military Adoption of Brain-Computer Interfaces (BCIs) in the United States and China."

[66] Rebecca Arcesati, "China Activates Data in the National Interest," *Merics Comment*, June 4, 2022, https://merics.org/de/kommentar/china-activates-data-national-interest.

[67] Siladitya Ray, "China Launches Own Global Data Security Initiative, Targets U.S.' 'Clean Network,'" *Forbes*, September 8, 2020, https://www.forbes.com/sites/siladityaray/2020/09/08/china-launches-own-global-data-security-initiative-targets-us-clean-network/.

[68] An English translation of this law is available at https://www.chinalawtranslate.com/national-intelligence-law-of-the-p-r-c-2017/?lang=en

Germany and the European Union

Strategic Initiatives and Public Funding

The European Union's engagement with neurotechnology has so far emphasized support for research and a precautionary approach to regulation, rather than the promotion of practical use. A longstanding commitment to neuroscience and brain health notwithstanding, neurotechnology has remained marginal to European industrial or foreign and security policy agendas. Nonetheless, the EU and several of its member states — Germany in particular —possess a strong academic foundation and can build at least on some individual success stories and promising initiatives in translation and scaling.

> The EU's engagement with neurotechnology has so far emphasized support for research and a precautionary approach to regulation.

Europe's most high-profile coordinated initiative in the field was the Human Brain Project (HBP), which ran from 2013 to 2023, intending to map the human brain and develop computational models of neural function. Over its ten years of existence, the project received 607 million euros in funding, of which more than 400 million euros was provided through EU grants. The rest was mobilized from national programs and other partners. While this fell short of the originally envisioned 1 billion euros goal, it nonetheless enabled substantial research activity and gave rise to the EBRAINS infrastructure, a pan-European research platform offering data, tools and computing capacity for neuroscience and neurotechnology research.[69]

More generally, public funding for academic neurotech research in Europe flows through established channels such as Horizon Europe or the Innovative Health Initiative.[70] Funding agencies from European countries have also joined forces with international partners, such as in the case of ERA-NET NEURON, an initiative bringing together research funding organizations and ministries from 28 countries to advance basic, clinical and translational search.[71]

In parallel, networks such as NeurotechEU — an alliance of eight European universities — have been established to foster academic exchange and talent development in neurotechnology.[72] Germany features prominently within this European landscape. Institutions such as the University of Freiburg, the Technical Universities of Munich and Berlin, and the Max Planck Institute for Brain Research are internationally recognized in the field, and Germany ranked forth globally in neurotech-related patents as of 2020.[73]

In many instances, public research funding has also directly or indirectly supported translational efforts and commercial European neurotech ventures. The clearest but rather atypical example has been a 30 million euro grant via Germany's Cyberagentur, a government-mandated entity focused on breakthrough innovation in cybersecurity, to Zander Labs, a Dutch-German company that develops a non-implantable BCI to monitor users' "passive" mental state and enable "neuroadaptive" human-computer symbiosis

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[69] Gordon Pipa et al., *Human Brain Project: 10 Years Assessment* (European Commission, 2024), https://ec.europa.eu/newsroom/dae/redirection/document/108431.

[70] https://www.ihi.europa.eu/

[71] https://www.neuron-eranet.eu/about/

[72] https://theneurotech.eu/

[73] Hain et al., *Unveiling the Neurotechnology Landscape: Scientific Advancements, Innovations and Major Trends.*

(rather than mainly deliberate user action).[74] Public development banks and funds have also played a role in financing European neurotech firms, including implantable equipment manufacturer CorTec or photonic neurostimulation startup Nuuron. Moreover, companies such as g.tec Medical Engineering or ANT Neuro have built their businesses by providing non-implantable neurotech equipment for — ultimately overwhelmingly publicly funded — research and therapeutic use.

Private Investment and Enterprise

As just noted, commercial neurotech activity in the EU is diverse in scope and character; however, it mostly remains modest in scale and has struggled to attract substantial private investment to the sector. While most of the companies mentioned above draw on some venture capital from smaller funds, the broader diagnosis of Europe's challenges in mobilizing funding for innovative start-ups and scale-ups plays out starkly in neurotech, given the technology-specific challenges discussed above.

Commercial neurotech activity in the EU mostly remains modest in scale and has struggled to attract substantial private investment.

Cases of established European tech companies entering the space, either on their own or as funders, also remain few and far between and focused on the medical field. (A rare exception was a collaboration between SAP and neurotech firm Emotiv to develop Focus UX, a system to monitor cognitive states in professional settings.)[75]

In an interesting step, Dutch company ONWARD Medical, which has initially focused on stimulation technology to improve hand strength and sensation in patients with chronic spinal cord injuries, circumvented the difficulty of finding larger individual financial backers by opting for an initial public offering (IPO) already at an early stage of its development in 2021. This IPO raised 86 million euros; the firm currently has a market capitalization of approximately 200 million euros.[76]

Regulation and Policy

Compared to the US and China, the regulations applying to neurotechnology in the EU are in some important regards more exigent. The Medical Device Regulation (MDR, in force since 2021) provides the primary framework for evaluating neurotech devices intended for medical use. Implementation of the MDR is decentralized across member states and involves various "notified bodies" authorized to assess conformity with applicable requirements. While this decentralized setup has historically been portrayed as more flexible and attuned commercial interests than its centralized US counterpart,[77] neurotechnology stakeholders commonly complain that, in practice, it is more difficult to navigate, especially due to capacity

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[74] Cyberagentur, "Revolution in Neuro-Adaptive Human-Machine Interaction," Press Release, December 15, 2023, https://www.cyberagentur.de/en/press/30-million-euros-largest-research-financing-in-europe-to-cottbuser-startup/.

[75] Nita Farahany, "This Is the Battle for Your Brain at Work," Fast Company, April 1, 2023, https://www.fastcompany.com/90874616/worker-surveillance-brain-productivity.

[76] ONWARD Medical, "ONWARD Raises up to EUR 87 Million (US$ 101 Million) in Successful Initial Public Offering," Press Release, October 20, 2021, https://ir.onwd.com/static-files/e2efc207-fa32-4dab-8093-9e8403f99b63.

[77] Gail A. Van Norman, "Drugs and Devices: Comparison of European and U.S. Approval Processes," *JACC: Basic to Translational Science 1*, no. 5 (2016): 399–412, https://doi.org/10.1016/j.jacbts.2016.06.003.

constraints on the part of notified bodies and their refusal to engage in iterative dialogue on how requirements can be met.[78]

A 2022 implementing regulation expanded the scope of the MDR to cover non-invasive brain stimulation devices used for non-medical purposes and classified repetitive transcranial magnetic stimulation (rTMS) and low-intensity transcranial electrical stimulation (tES) as Class III devices, the highest risk category.[79] This step marked a salient contrast to the permissive approach to such devices taken in the US and elsewhere so far and prompted considerable criticism from researchers, including a "call to action" by the European Society for Brain Stimulation. This article described the risk assessment underpinning the new rule as "based on incorrect statements [...] that contradict the available scientific evidence" and also pointed to a lack of consultation preceding its adoption.[80] Other non-clinical neurotechnologies remain less clearly regulated in terms of device approval, though they fall by default under the General Product Safety Regulation (GPSR), in force since December 2024.

Central to many discussions of the regulation of neurotechnology in the EU is the General Data Protection Regulation (GDPR), its benchmark privacy regulation. The GDPR establishes specific protection for "personal data", referring to "any information relating to an identified or identifiable natural person" as well as for "biometric data" and "data concerning health." While at least raw data, such as EEG recordings, are likely to fall within one or multiple of these categories, some experts have raised concerns about shortcomings in the protection of "mental data" in a broader sense, including inferences obtained from raw neural data through various processing methods.[81] Notwithstanding, while the requirements arising from any of the above classifications hardly impose prohibitive barriers to neurotechnology research and use, there is a widespread perception that EU data privacy requirements are making commercialization more difficult.

The same applies to the EU AI Act, which will be applicable when neurotechnology uses AI systems to process neural signals (which is likely to become the rule rather than the exception for many applications). Besides an outright prohibition of using AI systems for "subliminal manipulation" and several other specific provisions that could conceivably apply to neurotech use cases, the AI Act's risk classification system makes it highly likely that many devices will be considered "high-risk" systems. This will result in requirements regarding conformity assessments, risk management and quality management that companies will need to navigate (for scientific and pre-market research and testing, exceptions may apply).[82]

Policymakers will need to focus on preventing the justifiable focus on safety from stifling societally beneficial innovation in the field.

Beyond hard law, Europe has also seen dedicated efforts to define ethical guardrails for neurotechnology. The European Charter for the Responsible Development of

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[78] Interviews with several neurotechnology researchers and company executives, April-May 2025. Also see Matthias Fink and Bassil Akra, "Comparison of the International Regulations for Medical Devices–USA versus Europe," *Injury* 54 (October 2023): 110908, https://doi.org/10.1016/j.injury.2023.110908.

[79] Christoph Bublitz and Sjors Ligthart, "The New Regulation of Non-Medical Neurotechnologies in the European Union: Overview and Reflection," *Journal of Law and the Biosciences* 11, no. 2 (2024).

[80] Chris Baeken et al., "European Reclassification of Non-Invasive Brain Stimulation as Class III Medical Devices: A Call to Action," *Brain Stimulation* 16, no. 2 (2023): 564–66, https://doi.org/10.1016/j.brs.2023.02.012.

[81] Marcello Ienca and Gianclaudio Malgieri, "Mental Data Protection and the GDPR," *Journal of Law and the Biosciences* 9, no. 1 (2022): lsac006, https://doi.org/10.1093/jlb/lsac006.

[82] Christoph Bublitz et al., "Implications of the Novel EU AI Act for Neurotechnologies," *Neuron* 112, no. 18 (2024): 3013–16, https://doi.org/10.1016/j.neuron.2024.08.011. See also Nora Santalu, "Neurotechnologies under the EU AI Act: Where Law Meets Science," *IAPP News*, May 12, 2025, https://iapp.org/news/a/neurotechnologies-under-the-eu-ai-act-where-law-meets-science.

Neurotechnologies, drafted by the European Brain Council based on a public consultation process, sets out principles for safety, transparency, and individual autonomy.[83]

Overall, the situation in Europe is marked by a developed awareness of the regulatory and ethical challenges arising from neurotechnology. Policymakers, therefore, will need to focus on preventing the justifiable focus on safety from stifling societally beneficial innovation in the field and undermining Europe's ability to effectively exert influence at the global level. Europe currently has no players comparable to the most innovative and well-funded companies in the US and China working on implantable BCIs, which were in some cases even set up by Europeans (e.g., Blackrock Neurotech, which was founded by Marcus Gerhardt and Florian Solzbacher).

Further Regional Dynamics

While the US, China and the EU dominate the global neurotechnology landscape, other geographies are also seeing important, if uneven, developments in research, commercialization and governance.

In the EU's immediate neighborhood, the United Kingdom remains a relevant player, not least due to the substantial integration of its research landscape and regulatory alignment with the EU as well as the US. Its Advanced Research and Invention Agency (ARIA), a recently established high-risk funding agency modeled on DARPA, has explicitly identified neurotech as a strategic focus.[84] In addition to globally recognized research groups at institutions such as Imperial College London and the University of Oxford, UK-based startups secured close to $150 million in funding in 2024 alone, suggesting a dynamic early-stage commercial scene.[85]

Similarly, Switzerland is an important node of research activity, anchored by institutions such as the Wyss Center for Bio and Neuroengineering in Geneva, which is backed by substantial philanthropic funding.[86]

In Asia, South Korea and Japan represent technologically advanced economies with substantial state-led neurotech initiatives. Though a relative latecomer to the field, South Korea now ranks among the top countries globally in neurotech patent applications. The Korea Brain Initiative, launched in 2016, builds on earlier frameworks such as the Brain Research Promotion Act of 1998.[87] Korean neurotech activity is heavily shaped by its broader strengths in AI and semiconductor technology, with companies like Samsung and LG playing

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[83] European Brain Council, *European Charter for the Responsible Development of Neurotechnologies* (European Brain Council, 2025), https://www.braincouncil.eu/wp-content/uploads/2025/04/European-Charter-for-the-Responsible-Development-of-NeuroTechnologies-FINAL.pdf.

[84] https://www.aria.org.uk/opportunity-spaces/scalable-neural-interfaces/precision-neurotechnologies

[85] Rao, "2024 Neurotech Funding Snapshot."

[86] https://wysscenter.ch/about-us/

[87] Sung-Jin Jeong et al., "Korea Brain Initiative: Integration and Control of Brain Functions," *Neuron* 92, no. 3 (2016): 607–11, https://doi.org/10.1016/j.neuron.2016.10.055.

notable roles. Private venture capital activity, however, remains modest, with the public sector and industrial heavyweights accounting for most investment and research output.[88]

Japan's Brain/MINDS program — initially launched in 2014 and renewed in 2024 — has focused primarily on brain mapping and disease research.[89] Established conglomerates like Fujitsu, Hitachi and Sony have also shown interest in the field, but their efforts do not yet appear to have translated into relevant product development.[90]

India, meanwhile, remains more of an emerging presence in neurotech. While its enormous startup fairs feature some early-stage neurotech companies, most of them focus on localized deployment of already available technologies, and Indian sector experts point to the need for deeper technical expertise and capacity to generate truly novel applications.[91] Though this situation may change quickly, neurotech currently remains a niche pursuit within India's broader technology ambitions.

In the Gulf region, Saudi Arabia has emerged as a strategic investor in neurotechnology. In February 2025, the investment arm of the NEOM development project, a flagship of the Saudi Vision 2030 strategy, announced an investment in US-based BCI company Paradromics. The agreement includes establishing a "Brain-Computer Interface Center of Excellence" within NEOM, with the ambition of developing into the "premier center for BCI-based healthcare in the MENA region and beyond."[92]

Finally, while Latin America has played a rather marginal role in terms of global R&D or commercialization to date (similarly to African countries), it has produced some noteworthy governance innovations. In 2021, Chile amended its constitution to include explicit "neurorights," making it the first country in the world to do so. These include provisions on mental privacy, cognitive liberty and equitable access to neurotechnologies that strongly resonated in the broader international conversation about ethical guardrails for brain-related innovation.[93]

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[88] Hain et al., *Unveiling the Neurotechnology Landscape: Scientific Advancements, Innovations and Major Trends*, 61.

[89] Hideyuki Okano et al., "Brain/MINDS: A Japanese National Brain Project for Marmoset Neuroscience," *Neuron* 92, no. 3 (2016): 582–90.

[90] Hain et al., *Unveiling the Neurotechnology Landscape: Scientific Advancements, Innovations and Major Trends*, 61.

[91] Background conversations with Indian neuroscientists and neurotech entrepreneurs, Delhi, April 2025, as well ab observations at Startup Mahakumbh, Delhi, 3-5 April 2025.

[92] Paradromics, "NEOM Investment Fund Partners with Paradromics to Drive Innovation in Neurotechnology Healthcare," Press Release, February 12, 2025, https://www.paradromics.com/news/neom-investment-fund-partners-with-paradromics-to-drive-innovation-in-neurotechnology-healthcare.

[93] Sergio Ruiz et al., "Neurorights in the Constitution: From Neurotechnology to Ethics and Politics," *Philosophical Transactions of the Royal Society B: Biological Sciences* 379, no. 1915 (2024): 20230098, https://doi.org/10.1098/rstb.2023.0098.

RELEVANCE AND PRIORITIES FOR GERMANY'S AND EUROPE'S FOREIGN AND SECURITY POLICY

The previous chapters have established that neurotechnology is a dynamic field with transformative potential for the economy and society, whose trajectory is likely to further accelerate in the foreseeable future. They have also shown that there is considerable variation between regional neurotech ecosystems, with the US and China pushing ahead. This chapter systematically draws out why and how this matters for German and European foreign and security policy and identifies avenues for policy action.

The analysis is guided by three widely endorsed overarching policy aims:

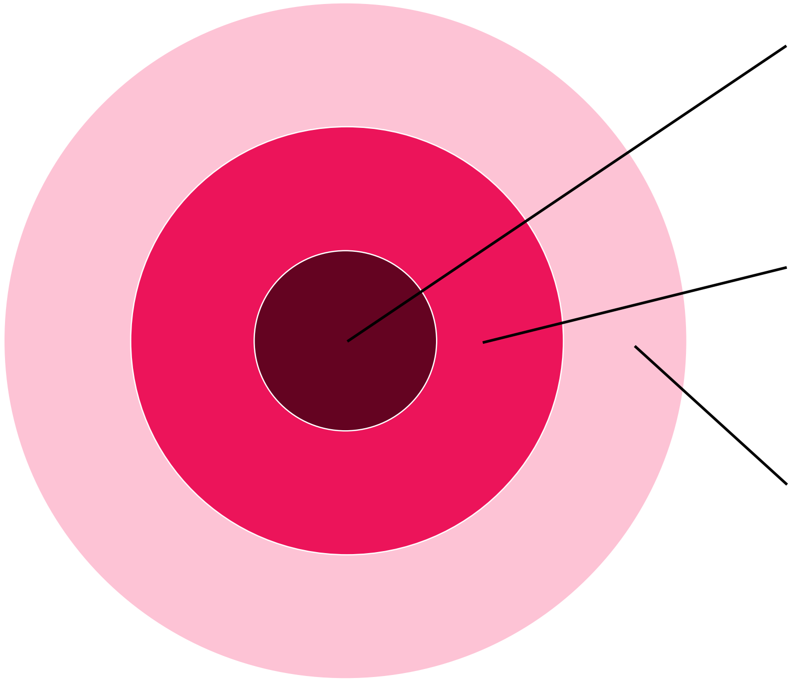
First is the imperative to **enhance defense and deterrence** capabilities. The potential military use cases of neurotechnology on the battlefield and beyond are obvious, as is the involvement of military actors in the American and Chinese ecosystems. Germany and Europe should not only develop safeguards against emerging threats, but also seize the opportunity that neurotechnology may offer for better protecting the continent's security in a hostile global environment.

Second, **fostering resilience against dependencies and cyber threats** will require an engagement with emerging chokepoints and risks of coercion in a fast-moving ecosystem, as well as with neurotechnology's possible future role as a form of decentralized critical infrastructure that is vulnerable to surveillance and interference.

Third, foreign and security policy has a role to play in **pursuing shared benefits for society**, interfacing with many areas of domestic policymaking. In this regard, neurotechnology holds both great promise — for improved healthcare, productivity gains, and the sector's economic potential in its own right — but also challenges, for example, the amplification of social inequality or political dislocations over profound ethical questions. For a liberal democracy, safeguarding human rights and maintaining meaningful political choice over the use of technology are key considerations that will also inform positions in the international realm.

The following sections explore each of these dimensions and conclude with a set of recommendations for German and European policymakers.

Figure 3: Policy Aims Guiding this Analysis



1. **Enhancing Defense and Deterrence**
    - Military use cases on battlefield and beyond
    - Clear role of military actors in neurotech ecosystems in US and China
2. **Fostering Resilience Against Dependencies and Cyber Threats**
    - Risk of strategic dependencies and economic coercion
    - Neurotech as future critical infrastructure: sensitive data, surveillance and interference concerns
3. **Pursuing Shared Benefits for Society**
    - Potential for major gains in productivity as well as health and well-being
    - Risk of socio-political dislocations (value conflicts, social inequality, etc.)

Enhancing Defense and Deterrence

The prominent involvement of military actors in the American and Chinese neurotechnology ecosystems discussed above makes clear the field's role as an important enabler of future advantage on the battlefield and beyond. As Germany and Europe support Ukraine in countering Russia's large-scale aggression and confront the need to restore their defense and deterrence capabilities, neurotechnology is emerging as more than just a potential source of threats to be averted. Europe should also actively pursue the novel opportunities that the field presents, within the boundaries of a robust ethical framework.

Neurotechnology's military relevance is perhaps clearest in its ability to enhance human performance and reshape human-machine interfaces.

Neurotechnology's military relevance is perhaps clearest in its ability to enhance human performance and reshape human-machine interfaces. Concrete use cases include improving resilience against physical and cognitive stress, enhancing decision-making under pressure, enabling more intuitive control of advanced weapons systems or vehicles, and augmenting the learning curve for complex tasks. Mood and alertness modulation, improved sensory perception, and more seamless control of prosthetics, exoskeletons, or robotic assets are all being actively investigated, alongside more futuristic ideas such as "silent" brain-to-brain communication between soldiers equipped with BCIs. Some of these innovations are being framed within broader efforts to increase "cognitive superiority" or develop integrated human-machine combat teams, interfacing with developments in autonomous weapons systems.[94] Importantly, the military advantages that could be obtained from superior neurotech in this vein are not limited to the battlefield, but also include areas such as strategy, tactical planning and logistics.

Beyond the enhancement of a warring party's own capabilities, an outright use of neurotechnology as a weapon is also conceivable. The fundamental approaches used to achieve brain stimulation could be used to interfere with, degrade or deceive the cognitive capacities of adversaries.[95] Reports since 2016 from more than 130 US officials around the globe about a mysterious combination of symptoms, including the perception of a loud sound and pressure, vibration and pain in their heads, triggered speculation about whether a "directed energy weapon" could be the source of these ailments. (This was named "Havana syndrome" after a first cluster of cases had occurred in that location.) A series of investigations and assessments has still not yielded a consensus on the origin of these "anomalous health incidents." While some experts argue that directed energy weapons may only be at an early stage of development and will likely prove impractical anyway, others suggest that Russia has been working towards them and that China may already possess relevant capabilities.[96] Media also reported that a prototype of a microwave weapon had been built for the US Marine Corps as early as 2004.[97]

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[94] Nicholas Wright et al., eds., *Human, Machine, War: How the Mind-Tech Nexus Will Win Future Wars* (Air University Press, 2025).

[95] Joseph DeFranco et al., "Redefining Neuroweapons: Emerging Capabilities in Neuroscience and Neurotechnology," *PRISM* 8, no. 3 (2019): 48–63.

[96] Farahany, *The Battle for Your Brain*, 183–85.

[97] Julian Borger, "Microwave Weapons That Could Cause Havana Syndrome Exist, Experts Say," *The Guardian*,

More widespread use of neurotechnology devices in the military will further amplify such weaponization concerns, given that the devices people use for other purposes may themselves turn into a potential vector of attack. Related to broader cybersecurity concerns further discussed below, the proliferation of neurotechnology both among warfighters and the broader public would drastically widen the toolkit for psychological operations and information warfare. Finally, it is easy to imagine the use of neurotechnology in the context of coercive interrogations or espionage.

In stark contrast to the US, there is very limited investment in actual R&D of neurotechnology for military use in Germany and Europe.

European engagement with the military dimension of neurotechnology has so far mainly taken place through NATO. NATO's Science and Technology Organization has hosted a substantial research effort on possibilities and challenges for neuroenhancement in military personnel, with contributing researchers from five member states (Canada, Germany, the Netherlands, the UK, and the US).[98] Its Allied Command Transformation also manages a broader program on "Cognitive Warfare," described as activities that "affect attitudes and behaviours, by influencing, protecting, or disrupting individual, group, or pulation level cognition, to gain an advantage over an adversary."[99] In 2024, the organization published its Biotechnology and Human Enhancement Technologies Strategy, in which neurotechnology featured, though the strategy is significantly more substantial on other biotechnology topics.[100] These activities provide a solid foundation for future efforts, but political commitment will be required to uphold momentum and ensure that findings and ideas from such exercises result in tangible action.

Within the German military specifically, engagement with neurotech-related questions has so far largely been the preserve of the explicitly future-oriented Office for Defence Planning. Already in 2013, the Office published an overview of approaches to human enhancement, including a brief discussion of TMS, silent speech and invasive neurotechnology.[101] In 2020, it followed up with a detailed discussion of human augmentation, developed in bilateral collaboration with the UK Ministry of Defence. This assessment noted that invasive and non-invasive brain interfaces both had "high transformative potential" and posed "significant policy considerations," yielding an overall classification as technologies warranting efforts to "understand and be prepared to seize opportunities."[102]

In addition, the German Institute for Defence and Strategic Studies (GIDS), a collaboration of the Bundeswehr's leadership academy and the Helmut Schmidt University of the Armed Forces in Hamburg, has contributed analytically

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June 2, 2021, https://www.theguardian.com/science/2021/jun/02/microwave-weapons-havana-syndrome-experts.

[98] Jan BF van Erp et al., *Neuroenhancement in Military Personnel: Conceptual and Methodological Promises and Challenges* (NATO Science & Technology Organisation (STO), 2024).

[99] https://www.act.nato.int/activities/cognitive-warfare/

[100] https://www.nato.int/cps/en/natohq/official_texts_224669.htm

[101] Planungsamt der Bundeswehr, *Human Enhancement: Eine Neue Herausforderung Für Streitkräfte?* (Planungsamt der Bundeswehr, Dezernat Zukunftsanalyse, 2013), https://www.bundeswehr.de/resource/blob/140504/d757cfdc2b1a467fb7d88544075da1d9/ft-he-data.pdf.

[102] UK Ministry of Defence in partnership with the Bundeswehr Office for Defence Planning, *Human Augmentation – The Dawn of a New Paradigm* (UK Ministry of Defence, 2020), https://www.bundeswehr.de/resource/blob/5017656/fdc7f1c529ddfb014d4e321e8b666a2d/sip-data.pdf.

to a Multinational Capability Development Campaign effort on Human Performance Optimization and Enhancement.[103] However, in stark contrast to the openly communicated, large-scale projects funded by DARPA in the US, there is, at best, very limited investment in actual R&D of neurotechnology for military use in Germany and Europe.

The EU's Human Brain Project, from its vantage point as a major civilian research effort, acknowledged early on the relevance of its work for the "political, security, intelligence and military domain." Its opinion on "responsible dual use" published in 2018 focused mainly on clarifying criteria for determining whether a research project or program was "of concern," but notably also included a set of political recommendations, such as a call for the European Commission to address "the tension between the policy of 'Open Innovation, Open Science, Open to the World' and the need to regulate and restrict dual use research of concern."[104]

Already in 2021, the US initiated a review of possible export controls on BCI technology.

This latter recommendation points to the difficulty of drawing any clear line between civilian and military neurotech. Much of the underlying research — such as efforts to improve neural signal processing or develop miniaturized implants — applies equally to therapeutic, consumer and military contexts. There is no singular defining feature that distinguishes a military device from a civilian one, making regulation based on end use inherently difficult to design and enforce. Still, it is clearly in Germany's and Europe's interest to ensure that advances made by their research groups and industry players do not support the military agendas of potential adversaries.

In this context, it is noteworthy that already in 2021, the US, via the Bureau of Industry and Security (BIS) at the Department of Commerce, initiated a review of possible export controls on BCI technology and a corresponding stakeholder consultation process. In the same year, it also blacklisted 12 Chinese institutes and firms allegedly working on "biotechnology processes to support Chinese military end uses," including "purported brain-control weaponry."[105] The BIS consultation process has so far entailed a stakeholder conference in early 2023 and has not yet resulted in concrete measures, but clearly warrants close monitoring and engagement.

Finally, while the current political context renders multilateral processes around arms control or norms of conduct in warfare challenging, it bears noting that policymakers at this level have so far engaged very little with the military potential of neurotech.[106] The most prominent effort to develop global ethical norms for the field — a UNESCO-led process toward a recommendation on the ethical use of neurotechnology — has largely steered clear of the issue. A first, expert-led draft included a clause stating that "neurotechnology should not be used for purposes such as non-consensual interrogation in law enforcement, criminal and civil justice [or] development or deployment of weapons targeted at the nervous system."[107] However, it appears unlikely that this clause will make it into the final version, and it is debatable whether such a categorical statement would do justice to the complex ethical questions surrounding the use of any technology in the specific context of war (that is,

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[103] Multinational Capability Development Campaign, *Human Performance Optimization and Enhancement* (2021), https://gids-hamburg.de/wp-content/uploads/2021/04/2021-03-22_MCDC_HPEO_Project_Report_final-1.pdf.

[104] Christine Aicardi et al., *Opinion on "Responsible Dual Use": Political, Security, Intelligence and Military Research of Concern in Neuroscience and Neurotechnology* (Human Brain Project, 2018), 18, https://zenodo.org/records/4588601.

[105] Conor Finnegan and Luke Barr, "US Accuses Chinese Tech Firms, Research Institutes of Weaponizing Biotechnology, Creating 'Brain-Control Weaponry,'" *Abc News*, December 16, 2021, https://abcnews.go.com/Politics/us-accuses-chinese-tech-firms-research-institutes-weaponizing/story?id=81793798.

[106] Filippa Lentzos and Isobel Butorac, "Neurotechnology Overview: Why We Need a Treaty to Regulate Weapons Controlled by ... Thinking," *Bulletin of the Atomic Scientists*, April 28, 2020, https://thebulletin.org/2020/04/neurotechnology-overview-why-we-need-a-treaty-to-regulate-weapons-controlled-by-thinking/.

[107] UNESCO, *First Draft of the Recommendation on the Ethics of Neurotechnology*, SHS/BIO/AHEG-Neuro/2024/2 (UNESCO, 2024), https://unesdoc.unesco.org/ark:/48223/pf0000391444.

questions of *ius in bello*).[108] While the possibility of using neurotechnology in this way rightly raises apprehensions, it is hardly obvious that killing an enemy fighter would be the more defensible option if those are the two available courses of action.

Similarly, a resolution adopted by the UN Human Rights Council in early 2025 that requested that its advisory committee draft "a set of recommended guidelines for applying the existing human rights framework to the conception, design, development, and deployment of neurotechnologies" did name the prohibition of torture and cruel, inhuman or degrading treatment or punishments among the norms challenged by developments in this field.[109] Still, this process seems unlikely to trigger a substantive international negotiation of norms around the future use of neurotechnology in war, given that the latter would fall primarily into the remit of international humanitarian law rather than human rights law.

Rather than closing their eyes to neurotechnology's military potential, Germany and Europe should aim to become leaders in its responsible military use.

In sum, for German and European foreign and security policy, the military applications of neurotech raise difficult questions, but also important opportunities. There is a tendency in the region to categorically reject research with potential military uses, most starkly expressed in the "civilian clauses" adopted by many German universities with recourse to their academic independence. However, neurotechnology is one of the areas where this approach is not only difficult to implement in practice, but also blatantly out of step with the realities of a global technology ecosystem in which military actors are obviously and deeply involved. Moreover, it is difficult to square with the acute security threats facing the European continent, which should make any possible contribution of emerging technologies to defense and deterrence capabilities an urgent priority (without prejudice to the right of any individual researcher or institution to reject involvement in military endeavors). Rather than closing their eyes to neurotechnology's military potential, Germany and Europe should aim to become leaders in its responsible military use, while simultaneously advancing ethical priorities at home and abroad.

Recommendations for German and European Policymakers:

- **Work towards becoming a leader in the responsible military use of neurotechnology through investment in a dual-use backbone, applied research for military applications, and deepened engagement with international partners (especially via NATO).** This should build on existing efforts such as NATO's Biotechnology and Human Enhancement Technologies Strategy and the analytical work conducted at the Bundeswehr Office for Defence Planning. Compared to this previous engagement with the topic, though, the emphasis should shift from merely monitoring and assessing technology development to active investment in advancing practical applications. This should ideally take place in collaboration with leading European research groups and industry players and in a fashion that consciously leverages the dual-use character of backbone infrastructure and components for military as well as civilian advantage. In addition, the focus on neurotechnology within ongoing technology assessments such as the NATO STO's Science & Technology Trends should be strengthened.

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[108] James Giordano, "Accessing the Brain to Affect the Mind: Neuroethics of the Mind-Tech Nexus in Military Context," in *Human, Machine, War: How the Mind-Tech Nexus Will Win Future Wars*, ed. Nicholas Wright et al. (Air University Press, 2025).

[109] UN Document A/HRC/RES/58/6, 2 April 2025

Findings from these exercises should also be brought into public discourse more actively, to foster a more informed and differentiated debate about the military applications of neurotech.

- **Develop an independent perspective on how to effectively prevent leakage of dual-use knowledge and technologies to potential adversaries and engage with the US discussion on export controls to maintain tight links between the innovation systems across the Atlantic.** R&D conducted in Europe already frequently has dual-use relevance in practice, and will do so even more acutely if deliberate efforts towards military use are intensified. It is clearly in Europe's interest to avert the leakage of such knowledge and technology to potential adversaries. Given its strong position in academic research, the ongoing discussion on how to improve research security while safeguarding academic freedom is of particular relevance.[110] Initiatives in this vein should actively engage research groups working on sensitive aspects of neurotechnology, where a fundamental awareness of the technology's dual-use potential already exists but may not always result in effective measures to mitigate risks. Once Europe has achieved greater progress towards practical applications, export controls may become a relevant instrument as well — though the more immediate concern should be to actively engage with the US discussion to maintain closely integrated R&D ecosystems across the Atlantic.
- **Initiate a global process toward ethically grounded norms on the military use of neurotechnology.** This should build upon broader ongoing efforts on the ethical development and use of neurotech such as the UNECSO-led process, but focus specifically on a differentiated discussion on appropriate boundaries for the use of neurotech under the exceptional circumstances of war, also in comparison to other technologies and weapons. While it would be naïve to excessively rely on the impact of such processes in shaping actors' behavior, they can help anchor mutual expectations and logics of appropriateness."[111]

Fostering Resilience Against Dependencies and Cyber Threats

Given neurotechnology's wide range of use cases, and especially the advantages offered by BCIs over existing platforms for human-machine interaction, policymakers should reckon with a scenario of widespread adoption across various areas of economic and social life.

While such a proliferation of neurotechnology could unlock significant benefits, it would also give rise to two potential vulnerabilities short of military aggression that are familiar from other vital economic sectors and forms of critical infrastructure: First, the dynamic development of the neurotechnology industry will likely give rise to dependencies and chokepoints in global supply chains. If the sector becomes economically significant in its own right, or an important enabler of other parts of the economy, those could be leveraged for political influence and coercion. Second, neurotech devices could become targets of cyberattacks, exposing sensitive data and enabling various forms of espionage, sabotage and other hostile interference.

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[110] See, for example, *Wissenschaftsrat, Wissenschaft Und Sicherheit in Zeiten Weltpolitischer Umbrüche: Positionspapier* (Wissenschaftsrat, 2025), https://www.wissenschaftsrat.de/download/2025/2485-25.html.

[111] James G. March and Johan P. Olsen, "Institutional Perspectives on Political Institutions," *Governance* 9, no. 3 (1996): 247–64, https://doi.org/10.1111/j.1468-0491.1996.tb00242.x.

While these concerns need to be addressed from several angles, building a strong European neurotech industry is clearly a central and indispensable element. It is, therefore, critical that other measures (especially in the realm of regulation) are aligned with this goal, mitigating threats in a targeted fashion without stifling innovation and adoption altogether.

In general terms, ensuring that Europe's research excellence translates into a vibrant neurotech industry will primarily be a matter of innovation and industrial policy, with health policy also playing an important role. The contribution of foreign policy is less obvious; however, steps in the European context will often need to be taken at the EU level rather than within member states. Much of the analysis laid out in Mario Draghi's 2024 report on the future of European competitiveness — for example, regarding the importance of mobilizing venture capital by changing investment rules for insurers and pension funds — strongly applies to the neurotech sector.[112] Moreover, collaboration across the EU will be critical with regard to mobilizing funding for research and commercialization efforts.

From the vantage point of security policy, a specific concern is the use of neurotechnology in sensitive domains, for example, in law enforcement or public services. In such settings, an attacker who manages to obtain confidential data or manipulate the functioning of devices may cause large-scale and lasting damage. As recent policy debates on other forms of decentralized critical infrastructure (such as connected vehicles) have shown, it will not always be possible to achieve the desired level of security through technical safeguards alone, given the impossibility of checking every single piece of hardware or constantly monitoring evolving codebases. Rather, the question of fundamental trust in suppliers ultimately plays a key role. Beyond promoting a European neurotech industry in general, it therefore seems advisable to specifically support the development of homegrown solutions for such sensitive domains. Germany's Cyberagentur articulated a rationale along those lines in the tender that resulted in its funding of Zander Labs' "passive BCI" project with 30 million euros. The tender aimed "to make human-machine interactions beneficial and safe for the citizens of the Federal Republic of Germany at an early stage in terms of cybersecurity."[113] While such schemes, of course, need to be monitored very closely for the efficiency and effectiveness of their spending, this general direction appears sensible.

More generally, strategic dependencies and chokepoints may arise in any complex supply chain, and neurotechnology is unlikely to prove an exception. As the sector is still at an emerging stage and it remains to be seen which specific technologies and designs will prove successful, it is not yet possible to pinpoint specific areas of concern beyond basic materials that are critical for microelectronics. However, that should not be an argument for inaction, but rather a call to establish transparency around the evolving input needs and supplier landscapes within the sector and for governments to build relations with industry stakeholders that will make it easier to track technology and market dynamics in the future. This approach would be consistent with the direction sketched out in the EU economic security strategy and could also be supported through measures under an EU biotech act expected in 2026. Importantly, managing interdependence requires not only a focus on vulnerabilities and dependencies, but also building and sustaining strengths, ideally to the point of "strategic indispensability" that can be used as leverage against adversarial action.[114]

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[112] Mario Draghi, *The Future of European Competitiveness* (Brussels: European Commission, 2024), https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en; see also Apostolos Thomadakis, "Closing the Gaping Hole in the Capital Market for EU Start-Ups – the Role of Pension Funds," *ECMI Commentary*, no. 90 (August 2024), https://cdn.ceps.eu/wp-content/uploads/2024/08/No-90-Closing-the-gaping-hole-in-the-capital-market-for-EU-start-ups-%E2%80%93-the-role-of-pension-funds.pdf.

[113] Cyberagentur, "Revolution in Neuro-Adaptive Human-Machine Interaction."

[114] Tim Rühlig and Digital Power China, *Reverse Dependency: Making Europe's Digital Technological Strengths Indispensable to China* (Digital Power China, 2024), https://dgap.org/system/files/article_pdfs/DPC%20-%20GESAMT_Final.pdf.

Currently, European firms (including German ones) play an important role globally in some neurotech areas, such as wearable EEG or Electrocorticography (ECoG) arrays. However, they may find themselves vulnerable to surging competition, especially from China, as has been observed across various other industries over the past decade. There is a case to be made that the existing market for these technologies is still far below its potential and that any business activity globally that contributes to greater vibrancy will help all players in the sector; European executives also tend to be confident about the quality and technological edge of their products.[115] Still, policymakers should monitor the evolving situation closely for signs of emerging unfair competition, which could range from outright subsidies to artificially low input costs, to formal or de facto closure of target markets. Given that the European Commission decided in June 2025 to exclude Chinese firms from large public purchases of medical devices on account of legal and administrative obstacles facing European firms on the Chinese market, there should be no lack of awareness of this potential challenge.[116]

The question of regulation of neurotechnology in Europe, meanwhile, requires a differentiated discussion in the context of economic and technology security. Fundamentally, Europe's pursuit of a more precautionary approach to various technological fields than adopted elsewhere is a political choice that must be negotiated democratically among a wide range of stakeholders. From a security perspective, regulation can also help mitigate certain threats, notably regarding data security and cyber vulnerabilities. For example, it could be argued that tightly restricting the collection, storage, pooling, and sharing of data generated by neurotech devices in the first place is the most straightforward way to limit the vulnerabilities that could arise from data theft or leakage. Such an approach is also sometimes advocated from a data protection and privacy perspective, notably due to concerns that future technologies could enable attribution of supposedly anonymized raw neural data (such as an EEG recording) to a specific person.[117]

However, policy must also account for how critical data is for innovation in the field as well as for enabling many neurotech use cases in the first place. Rules that excessively constrain data collection and processing or raise prohibitive compliance costs therefore risk stifling technology development and adoption altogether, which would neither be conducive to strengthening Germany's and Europe's security, nor appropriately account for the technology's potential for societal benefit. While policymakers should avoid a false categorical juxtaposition of regulation and innovation, they also need to shed overly optimistic assumptions about Europe's ability to shape global developments as a "regulatory superpower" and face trade-offs that do exist in this area.

As noted in the previous chapter, the legal framework on data protection in the EU, most importantly in the form of the GDPR, is already comparatively sophisticated and demanding. The same applies to the regulation of neurotech as medical devices and to the use of AI. Other relevant frameworks, such as the Network and Information Security (NIS2) Directive, while not containing any specific reference to neurotechnology, are likely to impose additional layers of requirements once devices see adoption at scale.[118] The priority in this regard

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[115] Conversations with several neurotechnology company executives, February-June 2025.

[116] European Commission, "Commission Restricts Chinese Participation in Medical Devices Procurement," Press Release, June 20, 2025, https://ec.europa.eu/commission/presscorner/detail/en/ip_25_1569.

[117] Anita S. Jwa et al., "Demystifying the Likelihood of Reidentification in Neuroimaging Data: A Technical and Regulatory Analysis," *Imaging Neuroscience* 2 (March 2024): 1–18, https://doi.org/10.1162/imag_a_00111; Arleen Salles et al., *Towards Inclusive EU Governance of Neurotechnologies* (2024), 24, https://cfg.eu/wp-content/uploads/Towards-Inclusive-EU-Governance-of-Neurotechnologies-Full-Report.pdf.

[118] Tim Van Canneyt and Nikhil Shah, "The NIS 2 Directive – Implications for the Healthcare Sector and Manufacturers of

should therefore not be on establishing additional or stricter rules, but rather on clarifying how existing rules apply to neurotechnology and neural data, which is a source of uncertainty among stakeholders.

The regulatory focus should be on clarifying how existing rules apply to neurotechnology and neural data.

On this basis, specific remaining gaps may then be addressed in a targeted fashion. Concretely, commentators have drawn attention to the need to better define and explicitly cover inferences generated from neural data, such as statements about the mood or mental state of an individual at a given time (rather than just the raw EEG data underpinning this analysis). Others have argued in favor of outright prohibition of specific forms of harmful use.[119] Though not a classical foreign and security policy issue, an effort to address these concerns would take place in large part at the EU level and should include a security policy angle in addition to perspectives focusing on individual rights and autonomy, consumer protections, etc.[120]

Finally, though not a substitute for cultivating trusted providers, technical norms can either facilitate or hinder efforts to address cybersecurity and data issues around neurotechnology in practice. As noted earlier, various actors and organizations such as ISO, IEEE and iBCI-CC are already hosting discussions around interoperability, safety and related technical issues. In these contexts, Germany and Europe should seize the opportunity to embed security-enhancing design choices into relevant standards early on. Currently, working groups in these formats are largely staffed by volunteers with limited time and resources. Incentivizing the participation of further German and European experts and supporting coordinated action toward aligned key objectives would require relatively modest investment and offer potentially significant benefits.[121]

Recommendations for German and European Policymakers:

- **Mobilize European public funding to support translational neurotech research, commercialization, and trusted solutions for critical domains.** Especially against a backdrop of major cuts in public funding in the US, Germany and Europe can build on their existing research strengths and bolster their position in the global neurotech industry. Given the pronounced problem of a lengthy "valley of death," particularly in implantable neurotech, developing financing models that enable public engagement in start-ups and scale-ups while ensuring that the state participates financially in those ventures that do prove successful will be an important element. Such schemes should complement a broader push to improve the European funding landscape for deep-tech ventures. Finally, sensitive domains such as the police and other critical public services merit dedicated attention. EU member states should try to coordinate their efforts rather than pursuing

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Medical Devices," *Fieldfisher Insights*, March 8, 2023, https://www.fieldfisher.com/en/insights/the-nis-2-directive-implications-for-the-healthcare-sector-and-manufacturers-of-medical-devices.

[119] Anita S. Jwa and Russell A. Poldrack, "Addressing Privacy Risk in Neuroscience Data: From Data Protection to Harm Prevention," *Journal of Law and the Biosciences* 9, no. 2 (2022).

[120] Salles et al., *Towards Inclusive EU Governance of Neurotechnologies*.

[121] More generally on this issue, see Tim Rühlig, "The New Geopolitics of Technical Standardization: A European Perspective," *Future Europe Journal*, April 12, 2023, https://doi.org/10.53121/ELFFEUJ3.

technological sovereignty viewed through a narrow national lens, which would very likely lead to a duplication of efforts and more limited coverage of the relevant technology space.

- **Establish a regular monitoring of the global neurotech ecosystem for emerging dependencies and chokepoints, as well as for signs of unfair competition.** This should ideally be aligned with broader efforts to improve techno-industrial intelligence under the EU economic security doctrine being driven by the European Commission. Within such a framework, neurotechnology should be included among priority technology areas, including the allocation of sufficient capacity to enable close exchange with experts from research and industry as a basis for swift and effective responses to emerging concerns. Regarding the possibility of unfair competition, the important role of public research funding (including for the procurement of equipment) as well as reimbursement through public health systems in the sector widens the set of potential instruments at policymakers' disposal.

- **Clarify how existing EU regulations apply to neurotech and review their design and implementation to reduce obstacles to research and commercialization while fostering cyber and data security in a targeted way.** At a minimum, there is an urgent need for better guidance on questions such as what a "high risk system" under the EU AI Act entails and how resulting requirements can be met in practice. Actively addressing such matters, rather than waiting for relevant court cases to arise, could go some way in alleviating apprehension about the EU regulatory environment among neurotech stakeholders. The same applies to questions around neural data (for example, regarding the definition and coverage of inferences from such data under GDPR). Greater clarity on the status quo should serve as the foundation for a careful review in close consultation with academia and industry, with a view to making the regulatory landscape easier to navigate while effectively addressing genuine concerns, including proposals on how to better ensure data security. Various simplifications may even be achievable without reducing requirements per se, for instance, by using regulatory sandboxes as foreseen in the AI Act or by adopting a more dialogic approach to medical device approval along the lines of the FDA. Still, there will be matters on which policymakers need to consider very carefully whether maintaining more exigent requirements than other key jurisdictions ultimately advances or rather harms European public interest (take the EU's uniquely restrictive classification of non-implantable stimulation devices, for example).

- **Actively invest in responsibly making anonymized neural data available for innovation in Europe.** As noted in the first chapter, the lack of large, diverse and high-quality neural data from healthy individuals is a significant obstacle to R&D in the field. Building on efforts such as the European Health Data Space, the EU should take an active role in establishing public infrastructure to pool and make such data available responsibly. This would also put it in the position to set a global benchmark for standards on participant consent and technical and organizational safeguards to protect sensitive neural data, constructively alleviating some of the concerns currently addressed through regulation.

- **Promote cybersecurity-enhancing solutions in processes toward global technical standards.** Such an effort should start with a dialogue with European actors already involved in relevant processes. While excessive politicization would be unhelpful, this exchange should focus on identifying technical choices that do have a bearing on security questions and on developing a shared view on how those should be addressed. Moreover, policymakers should consider options to better incentivize the participation of European experts in these formats.

Pursuing Shared Benefits for Society

As the earlier discussion of potential use cases made clear, neurotechnology promises to deliver remarkable benefits for individual health and wellbeing, economic productivity and societal development. This most immediately applies to the new therapeutic avenues that it offers for patients suffering from severe conditions such as paralysis or neurodegenerative diseases, but also from a wide range of mental health disorders. Early-stage clinical successes with DBS, BCIs and neuromodulation demonstrate the potential to restore function and alleviate suffering where other treatments fall short. This is also a critical angle to consider in broader ethical and regulatory discussions, as an extreme precautionary stance can also have real human costs if it deprives potential users of options they would be willing to explore despite being well aware of the associated risks.[122]

But the relevance of neurotechnology for societal prosperity extends well beyond medical applications. Combined with advances in AI, robotics and other fields, neurotech is poised to emerge as a general-purpose technology transforming human-machine interfaces. The economic implications of such a development would be far-reaching and unfold at three levels.

First, neurotechnology is likely to develop into a substantial industry in its own right. While commercial estimates of the sector's near-term potential should be taken with a grain of salt, they highlight that medical use cases alone account for an opportunity plausibly worth hundreds of billions of euros.

Second, neurotechnology holds obvious potential for enhancing human productivity, from mental workload management and neurofeedback to optimizing the interplay between workers, computers and robots.

Third, and relatedly, neurotechnology is an enabler of adjacent technologies, most notably in terms of its convergence with AI, where neuromorphic approaches could deliver yet another breakthrough and help address key concerns such as burgeoning global energy consumption.

Yet alongside its promise, neurotechnology also presents complex political and ethical challenges that could end up undermining societal prosperity. At worst, a proliferation of neurotech devices in the absence of inclusive governance could threaten social cohesion and stability and reduce individual autonomy and democratic control over decisions of major societal importance, undermining the normative cornerstones of European polities.[123]

One important risk associated with neurotech is exacerbating and entrenching social inequalities. Access to the most powerful devices — whether for therapeutic use or capability enhancement — is likely to be, in large measure, a matter of the resources at an individual's disposal, raising concerns about fairness and equity.

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[122] See, for example, the work of BCI Pioneers, a forum led by implantable BCI research participants committed to "advancing the widespread, ethical adoption of BCI for individuals with disabilities." https://bcipioneers.org/#about

[123] Also see Salles et al., *Towards Inclusive EU Governance of Neurotechnologies*.

Moreover, the spread of neurotechnology devices raises important ethical questions around mental and bodily autonomy.[124] One area of concern has to do with the functioning of devices that could conceivably influence users' perceptions, thinking and decision-making in ways that they may not even be aware of. Security issues and crime aside, this possibility could also be abused at scale to advance specific political or commercial agendas.

Equally important are the powerful social dynamics these technologies may trigger. Once certain tools become entrenched in professional settings, individuals may face considerable pressure to adopt them to remain employable. Conversely, it would be a major infraction of personal autonomy to prevent somebody from using a technology purely on account of competitive pressures that may result for others. This tension will be particularly difficult to navigate in a world of widespread cross-border migration and travel: Would policymakers be willing and able to force individuals who have been implanted with a BCI abroad, perhaps even deliberately in an act of "medical tourism," to turn off or even explant their devices?[125]

While such questions may still seem far-fetched, they illustrate the importance of an early and substantive political debate on neurotechnology, within states but also at the international level. Besides the UNESCO process already mentioned, substantial work among a smaller group of advanced economies has taken place under the auspices of the OECD. Specifically focusing on responsible innovation in neurotechnology, the organization has published a set of recommendations in 2019 and a toolkit in 2024 to support its implementation in practice.[126] Such processes will continue to be important, especially in establishing shared basic principles with actors beyond Europe and its close allies.

In sum, advancing societal prosperity through policy on neurotechnology is a matter of unlocking innovation *and* of managing the complex political and ethical challenges associated with the field. Foreign policy will have a role to play in both.

Recommendations for German and European Policymakers:

- **Foster the exchange of expertise and good practices among policymakers and agencies working on neurotech, both within the EU and with like-minded countries.** Though applying to all relevant policy angles, this could be particularly beneficial with regard to innovation agencies, which face similar challenges in their efforts to support neurotech ventures but can usually dedicate only limited capacity to any individual technology field. While a significant level of exchange already occurs in practice, including with actors outside the EU that have a strong focus on neurotech, such as ARIA in the UK, this should be intensified and institutionalized, not least to tackle the key challenge of cross-border scaling facing many European startups.
- **Continue active engagement in shaping global ethical standards.** In particular, the processes driven by UNESCO and by the OECD, respectively,

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[124] For a much more detailed and systematic discussion, see Farahany, *The Battle for Your Brain*.

[125] For further discussion of the medical tourism challenge, see Joseph DeFranco et al., "The Emerging Neurobioeconomy: Implications for National Security," *Health Security* 18, no. 4 (2020): 267–77.

[126] OECD, *Recommendation of the Council on Responsible Innovation in Neurotechnology* (OECD/LEGAL/0457, 2019); OECD Working Party on Biotechnology, *Nanotechnology and Converging Technologies, Neurotechnology Toolkit to Support Policymakers in Implementing the OECD Recommendation on Responsible Innovation in Neurotechnology* (2024), https://www.neuron-eranet.eu/wp-content/uploads/neurotech-toolkit-implementing-OECD-Recommendation.pdf.

have already achieved significant progress. In addition to at least maintaining the current level of involvement, more could also be done to raise awareness domestically of these processes and the principles being discussed. This could enable greater engagement of the broader public in deliberating the priorities that Germany and Europe are pursuing at this level, as well as fostering knowledge of the technology and its challenges, but also its potential, across society.

CONCLUSION

Neurotechnology will confront societies with remarkable novel possibilities and challenging policy questions in the coming years and is likely to become a key element of global competition over technology leadership.

This study has provided an assessment of where the field is standing today, its likely trajectory, as well as the variation across and dynamics within the global neurotech ecosystem. On this basis, it has set out foreign and security policy priorities for Germany and Europe to strategically position themselves and to shape a future in which neurotechnology benefits society and advances their security interests.

Putting the recommendations of this report into practice will require sustained political commitment to act in a field that is not yet at the focus of public attention, as well as concerted initiatives across a range of policy areas. Berlin and Brussels have seen a step change in terms of recognizing the centrality of economic statecraft and technology issues to the continent's security in recent years. But a lot of work remains to be done to enable well-informed and effective decision-making and to strengthen the interface of politics, industry and research – an interface that is critical to advancing many of the recommendations outlined here.[127] While the analysis and recommendations of this report will hopefully stand the test of time, navigating the emergence of a technology as dynamic and consequential as neurotech should be approached as continual work in progress.

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[127] Thorsten Benner et al., "Updating Germany's Security Apparatus," *Internationale Politik Quarterly*, February 24, 2025, https://ip-quarterly.com/en/updating-germanys-security-apparatus.

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lvi This number is strongly driven by the company LivaNova, with 2,900 employees.

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