ISSN 1831-9424

European Commission

EMERGING APPLICATIONS OF NEUROTECHNOLOGY AND THEIR IMPLICATIONS FOR EU GOVERNANCE

A technology foresight study

EU Policy Lab

2025

EMERGING TECHNOLOGIES

STRATEGIC FORESIGHT

ANTICIPATORY GOVERNANCE

Joint Research Centre

EUR 40312

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC141928

EUR 40312

PDF ISBN 978-92-68-27203-9 ISSN 1831-9424 doi:10.2760/8383402 KJ-01-25-273-EN-N

Luxembourg: Publications Office of the European Union, 2025

How to cite this report: European Commission: Joint Research Centre, Mochan, A., Parkin, B., Farinha, J. and Bailey, G., *Emerging applications of neurotechnology and their implications for EU governance,* Publications Office of the European Union, Luxembourg, 2025, https://data.europa.eu/doi/10.2760/8383402, JRC141928.

EMERGING APPLICATIONS OF NEUROTECHNOLOGY AND THEIR IMPLICATIONS FOR EU GOVERNANCE

A technology foresight study

Authors:

Mochan, A., Parkin, B., Farinha, J., Bailey, G.

Contact information

EU Policy Lab
Unit S.1 – EU Policy Lab : Foresight, Design and Behavioural Insights
Joint Research Centre, European Commission, Brussels, Belgium
JRC-Foresight@ec.europa.eu

EU Science Hub

https://joint-research-centre.ec.europa.eu

EU **Policy Lab**

The EU Policy Lab is a space for cross-disciplinary exploration and innovation in policymaking. We apply collaborative, systemic and forward-looking approaches to help bringing the scientific knowledge of the Joint Research Centre into EU policymaking.

We experiment with the new, the unprecedented and the unknown. We seek to augment our understanding of the present, challenge and reinvent the way we think about the future.

The EU Policy Lab is also a mindset and a way of working together that combines stories and data, anticipation and analysis, imagination and action. We bring new practical and radical perspectives to tackle complex problems in

policy-lab.ec.europa.eu

Contents

Abstract

This report sums up recent developments in neurotechnology, that is, technology that can monitor, measure and modify central nervous system activity . Some devices record information from the brain, and others deliver stimulation to the brain (and some do both).

These technologies are rapidly advancing and are likely to have a profound impact on various aspects of society. In the near future, neurotechnology has the potential to revolutionise the way we approach a range of policy areas, from healthcare, education, employment, law enforcement and security, to more obvious areas such as digital technologies and research.

The report analyses advances in the technologies for monitoring and stimulating the brain, some of which are incorporated into neurotechnology devices. It acts as a horizon-scan of new and emerging uses of these technologies, and takes these as inputs to pose a range of questions for the consideration of policymakers.

Executive summary

This report sums up recent developments in neurotechnology, that is, technology that can monitor, measure and modify central nervous system activity . Some devices record information from the brain, and others deliver stimulation to the brain (and some do both).

Policy context

These technologies are rapidly advancing and are likely to have a profound impact on various aspects of society. In the near future, neurotechnology has the potential to revolutionise the way we approach a range of policy areas, from healthcare, education, employment, law enforcement and security, to more obvious areas such as digital technologies and research.

For example, recent developments in Brain-computer Interfaces (BCIs) will enable people with paralysis or other motor disorders to interact with their environment in ways that would not previously have been considered possible, while neurostimulation techniques will offer new treatments for mental health disorders and neurological conditions. Advances in neurotechnology, coupled with other technological developments, such as artificial intelligence, will also raise important questions about personal identity, privacy, and agency, which policymakers will need to address. It is therefore essential that policymakers are aware of the potential benefits and challenges, so they can make informed decisions that ensure the responsible development and deployment of neurotechnology.

The OECD Framework for Anticipatory Governance of Emerging Technologies (OECD, 2024) situates horizon scanning as the first step in gathering strategic intelligence about a topic. Therefore, the first part of this report can be seen as a horizon scanning exercise, which seeks to identify "things to come" (Cuhls, 2019), as an input to consideration of an anticipatory governance approach to this area. It reviews the current and emerging state of technological development and applications, highlighting current, close-to-market and experimental applications and use cases. It examines technologies that are at low technology readiness levels (TRLs[1] 1-3) and identifies some possible, if speculative, applications of these technologies. In order to cover as broad a range as possible, signals are drawn from academic papers, news websites, company literature and other verifiable sources.

The report will then examine some of the implications for European Union policy suggested by these emerging signals.

Key conclusions

Based on this review, the authors have identified the following key points which can form the basis of future strategic intelligence regarding policymaking for neurotechnology:

- the major area of innovation in applications of neurotechnology is non-implanted wearables that monitor brain activity for non-medical ("lifestyle") uses, which are not currently covered by specific regulation at EU level;

[1] https://euraxess.ec.europa.eu/career-development/researchers/manual-scientific-entrepreneurship/major-steps/trl

- if neurotechnology devices develop in ways identified by this report, then a broad range of policy areas – from employment and health to defence, security and law enforcement - will be affected;
- the availability of devices that can both monitor and stimulate the brain will probably generate new considerations of the importance of individual rights, data privacy and data protection. At the very least, existing frameworks will need to be strengthened, so there is trust that they are operating effectively to protect existing rights.
- It could be useful for there to be some form of internal coordination within the European Commission to monitor developments in neurotechnology, taking the questions raised by this report as a starting point. This could be a precursor to a more innovative approach to regulation, such as the use of regulatory sandboxes (Attrey et al, 2020).
- Foresight's exploratory nature and participatory set-up offer policymakers the possibility of examining future implications in a non-binding way. The authors have developed formats for exploring these questions using foresight tools and methodologies and these are at the disposal of interested policymakers.

Main findings

The authors have collected signals according to a typology of non-implanted or implanted and monitoring, stimulating or both.

There is discussion about the accuracy of the terms "invasive" and "non-invasive" as applied to neurotechnology[2]. This paper will use the terms "implanted" and "non-implanted" in a spirit of objectivity.

Looking at each of these classifications, the authors have assigned use cases to each type of neurotechnology as follows:

Typology	Use cases
Non-implantable monitoring devices	Cognitive state monitoring
	Microsleep & drowsiness detection
	Enhanced sleep tracking and engineering
	Emotional state monitoring
	Neurofeedback
	Long term health monitoring
	Concussion detection and monitoring
	Detection of acute effects of intoxication

[2] See for example Salles et al, 2024

	Early seizure detection BCIs Brain fingerprinting Brain biometrics & authentication Neurotechnology assistants
Non-implantable stimulating devices	Treating depression Improving sleep quality, treating chronic insomnia Treating Premenstrual Syndrome Cognitive enhancement Military
Implanted neuro-prosthetic devices (monitoring and stimulating)	BCIs Addressing disability Visual prosthetics
Implanted deep brain stimulation devices	Treating serious medical conditions

The report also describes a number of emerging technologies that have not yet been developed as use cases but hold potential for the future.

Policy questions

Based on the consideration of the emerging technologies and their potential applications and use cases, the report puts forward questions in related policy fields. These questions are intended to spur discussion among relevant policymakers. The policy fields covered are:

- Consumer protection
- Human health
- Fundamental rights, including the rights of the child
- Employment/social affairs/human resources
- Defence, security and law enforcement
- Education
- Research, innovation and digital policy

1 Introduction

For the purposes of this report, "neurotechnology" refers to technology that can monitor, measure and modify central nervous system activity . Some devices record information from the brain, and others deliver stimulation to the brain (and some do both).

These technologies are rapidly advancing and are likely to have a profound impact on various aspects of society. In the near future, neurotechnology has the potential to revolutionise the way we approach a range of policy areas, from healthcare, education, employment, law enforcement and security, to more obvious areas such as digital technologies and research.

For example, recent developments in Brain-computer Interfaces (BCIs) will enable people with paralysis or other motor disorders to interact with their environment in ways that would not previously have been considered possible, while neurostimulation techniques will offer new treatments for mental health disorders and neurological conditions. Advances in neurotechnology, coupled with other technological developments, such as artificial intelligence, will also raise important questions about personal identity, privacy, and agency, which policymakers will need to address. It is therefore essential that policymakers are aware of the potential benefits and challenges, so they can make informed decisions that ensure the responsible development and deployment of neurotechnology.

The OECD Framework for Anticipatory Governance of Emerging Technologies (OECD, 2024) situates horizon scanning as the first step in gathering strategic intelligence about a topic. Therefore the first part of this report can be seen as a horizon scanning exercise, which seeks to identify "things to come" (Cuhls, 2019) as an input to consideration of an anticipatory governance approach to this area. It reviews the current and emerging state of technological development and applications, highlighting current, close-to-market and experimental applications and use cases. It examines technologies that are at low technology readiness levels (TRLs[3] 1-3) and identifies some possible, if speculative, applications of these technologies. In order to cover as broad a range as possible, signals are drawn from academic papers, news websites, company literature and other verifiable sources. Given the pace of developments in this field, the report cannot claim to be comprehensive. Nonetheless, it seeks to give an overview of the main emerging technologies and applications and consider them through a policymaking lens.

Neurotechnology is generally labelled according to how intrusive it is to the body. Non-invasive or non-implanted devices detect brain activity or deliver stimulation from outside of the body, while invasive or implanted devices are either placed within the brain's tissue or on the cortical surface itself. There is discussion about the accuracy of the terms "invasive" and "non-invasive" as applied to neurotechnology[4]. This paper will use the terms "implanted" and "non-implanted" in a spirit of objectivity.

[3] https://euraxess.ec.europa.eu/career-development/researchers/manual-scientific-entrepreneurship/major-steps/trl

[4] See for example Salles et al, 2024

2 Overview of current and emerging neurotechnologies

2.1 Non-implanted neurotechnology

The obvious benefits of non-implanted techniques are that they do not require surgery. They are also generally cheaper and have lower maintenance costs. However, as they measure neural responses from outside the skull, the signals they detect are less detailed and reliable. They also deliver stimulation with much less precision than implanted devices. In the near term, it is the non-implanted technology that is being used in wearable devices and likely to be deployed across a whole range of non-medical contexts.

Non-implanted neurotechnology can be divided into devices that (primarily) measure brain activity and those that deliver stimulation to the brain. There are some devices that do both.[5]

2.1.1 Non-implanted neurotechnology that measures brain activity

There are several different technologies that can be used in non-implanted neurotechnology, which are explored in this section. While traditional electroencephalography (EEG) is currently the most common, particularly for wearable devices, scientists and innovators are exploring whether other types of non-implanted neurotechnology can be developed into wearable technology.

When used outside of a medical context, these technologies are not regulated under medical device provisions in the European Union[6].

2.1.1.1 Electroencephalography

The most common direct-to-consumer wearable technologies that detect brain activity use EEG. This technology measures brain activity by placing sensors called electrodes on the scalp, which detect electrical activity of neuronal ensembles, primarily in the brain cortex. Traditionally, electrodes were applied using a cap soaked in wet saline solution by a trained technician and the technique was predominantly used to diagnose brain activity associated with epilepsy. The innovation of dry electrodes and improved signal processing has meant that these sensors are now being inserted into wearable devices such as hats, headbands, gaming headsets and sleep masks. A new set of 'hearable' devices are also being developed that record EEG using in-ear headphones (figure 1a/b)[7].

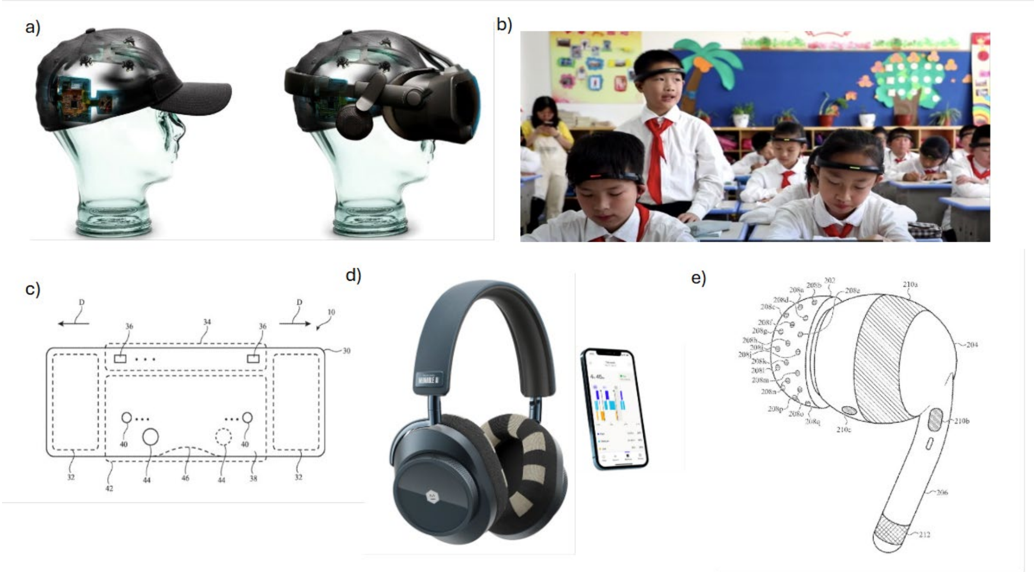
---

[5] Recording devices can also be considered active – where the use is directly engaged in a task using these devices, such as a brain-computer interface – or passive – where the user is not directly engaged, such as sleep monitoring. For the sake of reducing complexity these classifications have not been added to the typology of the current paper, but they are worth considering as part of the increasing development of neurotechnology.

[6] https://health.ec.europa.eu/medical-devices-sector_en

[7] For example, Apple has a number of patents relating to neuroscience: these include: a) airpods that measure EEG, published in July 2023 b) a flexible sleep eye mask that contains EEG sensors, published in March 2022 c) a headband containing EEG or fNIRS sensors which can be inserted into the Apple Vision Pro (virtual and augmented reality) headset. The patent reports these sensors can be tuned to record brain areas related to language, learning, memory, comprehension, sleep, stress, pain, attention, fear, and discomfort, with highlighted uses including visualisations of the user's attention and brain-computer interfaces, published in March 2024.

Figure 1. Brain sensor technology is being inserted into everyday wearable items.



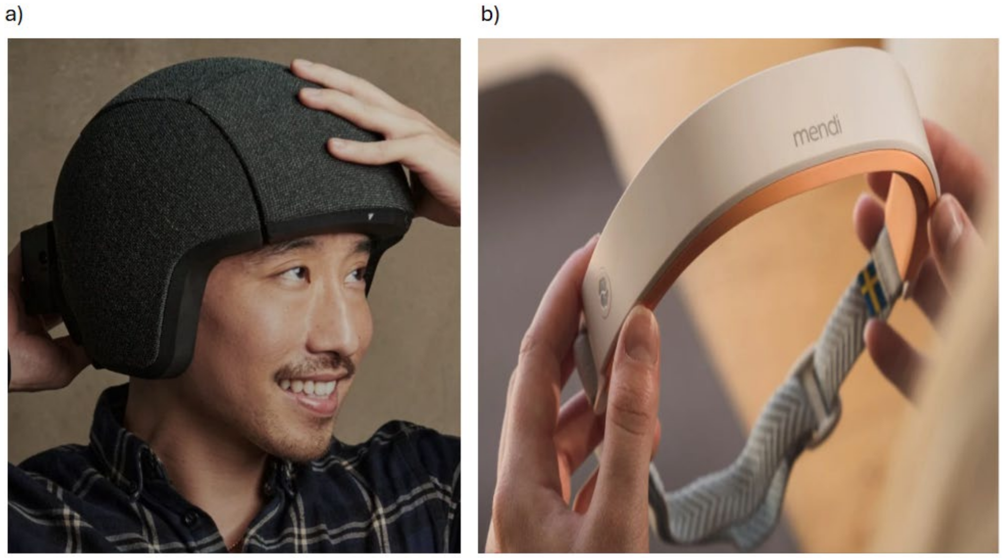
Source: Neuroconcise website/South China Morning Post/patents.google.com/Neurable website/ patents.google.com

Figure 1 shows some recent patents and products for wearable items with brain sensor technology. These include a) hats b) headbands c) sleep masks d) headphones and e) earbuds. These products are being developed by a) the start-up NeuroCONCISE; b) BrainCo (FocusCalm device); c) Apple; d) Neurable; e) Apple.

2.1.1.2 Functional Near-Infrared Spectroscopy

Functional Near-Infrared Spectroscopy (fNIRS) detects brain activity by measuring changes in blood flow revealed by near-infrared light that is shone through the skull. Haemoglobin found in the blood absorbs light in this spectrum, but other biological tissues (like the skull and skin) are relatively transparent. fNIRs can measure about 1cm into the surface of the brain; therefore more detailed inferences can be made about where in the brain the signal is coming from in comparison to EEG . There are a few examples of devices that use this technology (see Figure 2) for multiple applications (see Table 1). There is a need for more testing across diverse sample groups as near-infrared light is absorbed differently by certain hair and skin types (Webb et al, 2022).

Figure 2. The Kernel Flow and Mendi headsets use fNIRS technology



Source: Kernel website, https://www.kernel.com/ Mendi website, https://www.mendi.io/

2.1.1.3 Magnetoencephalography

A further imaging technique for measuring brain function is magnetoencephalography (MEG), which offers more precise spatial resolution compared to EEG[8]. Using highly sensitive magnetometers placed on the scalp, MEG detects very small magnetic fields produced by electric currents of populations of neurons. Performing an MEG scan has hitherto required individuals to remain still with their head encased in a helmet connected to a bulky scanner (Figure 3a) (Boto et al, 2018). This set-up is necessary as the sensors used by this technology need cooling and are housed within a liquid helium dewar (container), with a vacuum space separating them from the scalp.

Recent advancements have led to the development of optically-pumped MEG (OPM-MEG) systems, which use quantum sensors that do not require the same type of cooling. These sensors can be worn like a helmet, allowing for natural movement during scanning. It has been suggested that this innovation has the potential to lead to a new generation of neuroimaging headsets (Figure 3b).

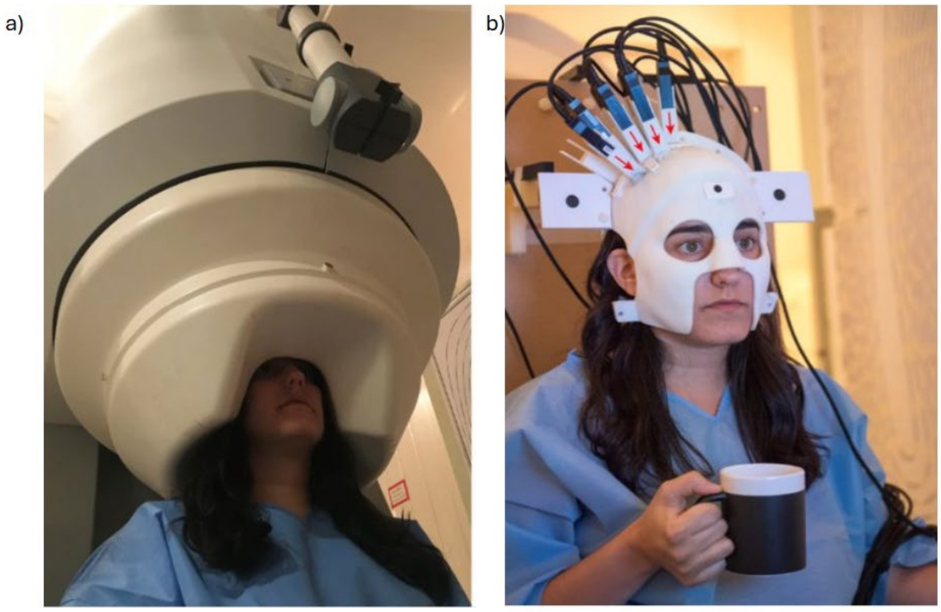
[8] In terms of spatial resolution (ie where in the brain activiation is happening)

- EEG has a spatial resolution of centimeters and limited below cortical surface.
- MEG has a spatial resolution of millimeters at cortex and is less precise for deep sources.
- fMRi has a spatial resolution of millimeters and is not limited to cortical areas.
- fNIRS has a spatial resolution of millimeters and is very limited below cortical surface.

In terms of temporal resolution (i.e. when a process is happening) EEG, MEG and NIRS have a temporal resolution of milliseconds while fMRI has a temporal resolution of 1 to 5 seconds. The hemodynamic activity detected by NIRS is a delayed representation of cortical activity as it measures blood flow.

However, several limitations currently prevent OPM-MEG technology from becoming a direct-to-consumer wearable device. One challenge is that these helmets need to be worn within an electromagnetically shielded room, which typically costs between €1–2 million. Researchers are working on devices that can operate with reduced shielding, such as using a copper cage, but even with this, the required shielding remains heavy and limits mobility. Additionally, the magnetometers in current OPM-MEG systems can heat up to around 40°C, making them uncomfortable to wear for extended periods. Researchers are working on improving the wearability of these headsets, making them lightweight by further miniaturising components and developing wireless machines.

Figure 3. Comparison of conventional MEG (left) with new OPM-MEG technology where the user can freely move their head (right)



Source: nature.com

2.1.1.4 Magnetic Resonance Imaging

Magnetic Resonance Imaging (MRI) is another neuroimaging technique which uses a strong magnetic field and radio waves to generate images of the structure of the brain, or in the case of fMRI the function of the brain, by detecting changes in blood flow. This is not a wearable technology and is unlikely to develop into one, due to the size, weight and strength of the magnets and their requirement for cryogenic refrigeration. Nonetheless, the development of low-field-strength MRI scanners has increased the portability of this type of scanning, increasing its accessibility especially in low resource settings (Arnold et al, 2023).

2.1.1.5 Use cases

Table 1 below summarises use cases of the technologies outlined above that are either available or under development. Given the pace of development, the table does not claim to be exhaustive. Rather it gives a sense of the various applications that are currently on or close to the market, or at an earlier stage of development.

Table 1. Non-implanted neurotechnologies for monitoring: use cases

Use case	Application	Technology	Description	Status
Attention monitoring: Wearable neurotechnology devices are being developed to detect brain activity associated with different levels of attention; these metrics are then presented back to the user, similar to health activity trackers.	Tracking attention of pupils in educational settings	EEG	There are reports from China of this technology being used in schools to provide real-time data of pupils' attention levels in class. This allowed closer monitoring of pupils by teachers as well as providing performance feedback to parents ([1]).	Commercially available
	Tracking attention of employees in the workplace	EEG	JLL Asia Pacific, an international real estate and investment management firm, has been using devices to 'help promote worker productivity'. In this case attention levels of employees were used to compare the productivity of remote workers to those working from an office, and to assess the optimal times of day for employees to take breaks ([2]).	Commercially available
	Tracking states of attention in everyday life	EEG	Neurable headphones measure the wearer's brain activity which can then be tracked through an app ([3]).	Pre-release orders being taken
	Tracking and manipulating states of attention	EEG	When the Neurosity Crown consumer headset detects certain brain frequencies associated with distractibility, it plays music to help re-orientate the user's focus ([4]).	Commercially available
Microsleep & drowsiness detection: Wearable neurotechnology detects microsleep events in the	Monitoring alertness of safety critical workers	EEG	Safety helmets with brain sensors have been developed for real-time fatigue management. When microsleep brain activity is detected, an early warning alarm system is triggered to reorientate the user. This technology has been adopted extensively in the mining sector, for example a large copper mine in the South Asia has reported zero fatigue incidents for operators of mining	Commercially available

Use case	Application	Technology	Description	Status
brain to identity levels of drowsiness.			and fleet vehicles wearing the SmartCap device over three years and across 1.1 million hours of operation ([5]). There have also been news stories relating to their use by railway and factory workers in China ([6]).	
	Automobile safety	EEG	There has been some interest in fitting cars with EEG sensors in the headrest to monitor driver drowsiness, as an additional safety feature ([7]).	Experimental
Enhanced sleep tracking and engineering: Devices monitor brain states associated with different stages of sleep. Innovators are also exploring how they can manipulate these rhythms to improve health and cognition.	Sleep eye mask with biometric sensors	EEG	Apple has a patent for this device ([8]). Enhanced sleep tracking can also be undertaken with other EEG headsets.	Patented & commercially available
	Measuring and manipulating sleep with targeted sounds and light	EEG/ fNIRS	These devices emit sounds that align with the oscillatory activity of the brain to help people fall or stay asleep. Examples are the Tone Buds being developed by My Tone ([9]).	Commercially available
	Improving sleep to enhance learning	EEG	One application could follow from studies that have shown that once sounds have been paired with learning material when awake, representing these sounds during sleep stages involved in memory consolidation can improve learning ([10]).	Experimental
Emotional state monitoring: Devices perform rudimentary classifications of different emotional states, with detection of experiences of anger, sadness, happiness and contentment.	Personalised neuromarketing	EEG, fMRI	Marketers use brain responses to gain insights into how best to promote their products and services, for instance by observing reactions to advertisement campaigns ([11]). If neurotechnology is added to everyday wearable devices this data could be used to gain a real time read out of user's brain states to target advertisements at opportune moments. This could also be used for the targeting of political campaigning to those with certain brain biomarkers or brain states ([12]).	Commercially available Speculative

Use case	Application	Technology	Description	Status
	Responsive computing systems in gaming	EEG	A computer adjusts features according to the user's internal state, thus creating closed-loop systems between the user's brain responses and computerised systems ([13]).	Experimental
Neurofeedback: Devices that display a real-time read out of the user's brain waves, and the user learns different activities to promote neural frequencies associated with a desired mental state. Example mental tasks include focusing on one's breath, trying to sustain a relaxed state, or concentrating on a computerised character. Feedback is given, through visual or auditory cues, such as changes to a video game or the playing of different sounds, to indicate that a desired state has been achieved. With repeated sessions, the user learns more optimal brain functioning that modifies their baseline state.	Clinical applications	EEG	As accessibility of neurotechnology increases, the use of neurofeedback for clinical applications is expanding. These include attention training in individuals with ADHD ([14]), and emotion modulation in anxiety or the management of chronic pain ([15]). These techniques are usually used as an adjunct to other therapies for these disorders, as their efficacy is not currently that well established.	Commercially available
	Wellness and cognitive enhancement	EEG/fNIRS	Neurofeedback is used for non-clinical ends, for example attention training in healthy individuals to improve focus and reduce procrastination ([16]), as well as emotion modulation to increase relaxation and wellness. The Mendi device uses fNIRS and has gamified neurofeedback to make brain training enjoyable and effective, encouraging regular use and long-term benefits ([17]). The benefits advertised are lower stress, increased focus and improved overall wellbeing.	Commercially available
	Meditation	EEG	Consumer meditation headsets monitor brain activity during meditation sessions and translate this brain activity into auditory feedback ([18]).	Commercially available
	Training the brain for elite sporting performance	EEG	Athletes operate under conditions of exceptionally high stress and have been reportedly using neurofeedback to train their brains for peak performance ([19]).	Commercially available
	Closed loop neurofeedback	EEG	These devices modulate brain waves by playing the user different sounds. An example is Neudio which is	Research devices available

Use case	Application	Technology	Description	Status
			developing this technology to promote mental wellbeing ([20]).	
Long term health monitoring: Consumer wearable devices that can detect risk factors for e.g. brain health.	Identifying cognitive decline	fNIRS/ EEG	Datasets are being collected to train models to spot biomarkers of cognitive decline and mental health ([21]). The use of these signals for treatment response predictions is also being investigated.	Experimental
Concussion detection and monitoring: Wearable neurotechnology that can identify abnormal patterns related to brain injury to detect and monitor concussion.	Objective diagnosis of concussion severity	fNIRS	Headsets have obvious applications in impact sports, aiding decisions over whether a player can return to the pitch after injury ([22]).	Research devices available
Detection of acute effects of alcohol/drug intoxication	Monitoring use of alcohol and other drugs	fNIRS	The Kernel Flow device claims to detect biomarkers indicative of alcohol and ketamine intoxication ([23]).	Commercially available
Early seizure detection	Wearable devices that monitor brain activity to help predict seizures before they occur	EEG	These devices monitor brain activity, and alert users or carers via a paired smart phone device when a seizure is imminent, 1-3 minutes before an episode occurs ([24]).	Commercially available
Brain computer interfaces (BCIs): Translating signals from the brain into a command for an external	Control of assistive technology	EEG	Brain signals can be translated to move prosthetic limbs, or a wheelchair, or direct control of a cursor ([25]).	Commercially available
	Gaming	EEG	BCIs offer the possibility of hands-free control of computer games, or brain-controlled interaction in virtual reality worlds like the metaverse ([26]). Having said that,	Commercially available

Use case	Application	Technology	Description	Status
device, providing a direct communication pathway between the brain and the computer. The user trains the system to recognise specific patterns of neural activity which they generate by imagining certain scenarios. One commonly used command is motor imagery, such as imagining moving your left or right hand. Importantly, non-implanted devices allow very rudimentary control of external devices, though these devices are relatively slow to respond and require considerable training and effort to use.			each individual user needs to undergo considerable time to train direct-to-consumer BCIs , but this may change with the availability of large data sets	
	Hands-free control of autonomous weapons systems	EEG	The Australian army is exploring the use of wearable BCIs to direct autonomous weapon systems ([27]).	Experimental
Brain fingerprinting: Wearable neurotechnology assesses whether specific information is stored in a person's brain, measuring a neural response when a	Deception detection	EEG	Neurotechnology is being used to determine if a suspect recognises crime-related information that only a perpetrator would know. An example of a commercially-available device for this application is the iCognative ([28]).	Commercially available
	Enhanced eyewitness information extraction	EEG	Neurotechnology is being applied experimentally to enhance eyewitness testimony, for example showing eye-	Experimental

Use case	Application	Technology	Description	Status
person recognises meaningful stimuli.			witnesses photos of suspects and monitoring their neural responses for signs of familiarity ([29]).	
Brain biometrics & authentication: Brain-based biometrics can be used for identification or authentication. These methods are thought to be advantageous as unlike facial IDs and fingerprints, they are concealed, dynamic and incredibly complex.	Increased digital security	EEG	Current research has shown that it is possible to correctly re-identify participants from resting state EEG data (recorded when a person is sitting relaxed in a chair), as well from EEG activity evoked when viewing images or listening to audio ([30]). Identifying people based on their EEG data without their training data is currently not possible. The training data has to be recent as people's brains change over time. However, if wearable neurotechnology becomes widespread and embedded in everyday devices, this data can potentially be recorded for biometric purposes when the technology is being used for a different purpose.	Experimental
Neurotechnology assistants: Detecting brain responses to certain stimuli. Computer programs are being developed to respond to these neural signals to improve the detection of threats.	Improving the accuracy of object detection in baggage searches	EEG	A system classifies the brain responses of security workers as they view X-ray images and alerts them whenever their brains indicate the detection of something unusual that warrants closer examination ([31]).	Pilot
	Early detection in gaming and military	EEG	It takes 300ms for the brain to detect a stimulus, but about 600ms for the body to react ([32]). Research is exploring whether technologies can be developed that can respond to just our brain signals, in a way that 'surpasses the limitations of the body'. In 2011 DARPA announced the success of the Cognitive Technology Threat Warning System program ([33]), which involved using an EEG device to record when the operator detects a threat, though this is not yet being deployed in combat, probably for reliability reasons.	Experimental

[1] This was part of a study to recruit 10,000 school children; the study was ended early as the neurotech company BrainCo providing the headband received negative press coverage. (Hong et al, 2019)
[2] Jones Lang Lasalle IP Inc, 2022
[3] Neurable, 2025
[4] Neurosity, 2025
[5] Wenco International Mining Systems, 2025
[6] World Economic Forum, 2018
[7] Fleming, 2011
[8] Purcher, 2022
[9] MyTone, 2025
[10] Abdellahi et al, 2023
[11] Emotiv, 2025
[12] Galli et al, 2021
[13] Beauchemin et al, 2024
[14] Myndlift, 2025
[15] Exsurgo, 2025
[16] FocusCalm, 2025
[17] Mendi, 2025

Source: Authors

[18] Muse, 2025
[19] Liverpool Football Club in the English Premier League have been using such devices (Liverpool FC, 2022), as well as American football and basketball players (Myndlift, 2023) and youth football in England (English Schools' Football Association, 2024).
[20] Neudio, 2025
[21] Clinicaltrials.gov, 2024
[22] Brainscope, 2025
[23] Castillo et al, 2023 ; Dubois et al, 2023
[24] Epilepsy Alarms, 2025
[25] e.g. ETH Zürich, 2025
[26] Perri, 2024
[27] A video of this can be viewed here: https://www.youtube.com/watch?v=hs8hjdoSKNQ. The Open BCI Galea headset has been used to fly a drone (OpenBCI, 2025).
[28] Brainwave Science, 2025
[29] Klaming & Vedder, 2009
[30] Zhang et al, 2019, Sooriyaarachchi et al, 2021
[31] Ackerman, 2022
[32] Heil et al, 2000
[33] HRL Laboratories, 2012

2.1.2 Non-implanted neurotechnology that applies stimulation to the brain

As with monitoring devices, there are several different technologies that can be used for applying stimulation to the brain from non-implanted devices. All such devices are covered under the EU's Medical Devices Regulation (MDR)[9] whether they are for medical or consumer use. Indeed, non-implantable stimulation devices are considered in the highest risk category, which has raised criticisms regarding the effect of this regulation on future innovation within the EU (Baeken et al, 2023).

2.1.2.1 Transcranial Electrical Stimulation

Direct-to-consumer non-implanted devices that deliver stimulation to the brain use a technique called transcranial electrical stimulation, which entails applying a small electrical current between two electrodes placed on the scalp. Techniques differ according to whether a direct current is applied (tDCS) or an alternating current (tACS). This technique induces subthreshold changes in the excitability of the neurons under the electrodes, making them more or less likely to fire.

Studies have applied transcranial electrical stimulation in an attempt to improve learning, alter aspects of cognitive functioning and improve symptoms of clinical disorders (Parkin et al, 2015). Overall, there are some positive studies that show small effects, but these techniques are generally limited as the stimulation is not very focal and unable to reach deep within the brain. One promising study showed how applying tACS caused working memory improvements in 50-year-olds to the extent that their memory capabilities aligned with 20-year-old participants for 50 minutes post stimulation (Reinhart and Nguyen, 2019). In the EU, tDCS devices have been approved for the treatment of depression and chronic pain [10].

2.1.2.2 Transcranial Magnetic Stimulation

Another method of brain stimulation is Transcranial Magnetic Stimulation (TMS). TMS applies an electromagnetic coil to the scalp which induces an electrical current in the brain. This electrical current causes the neurons under the coil to fire. Depending on the number and speed of the stimulation pulses, TMS can have an inhibitory or excitatory effect on the brain.

2.1.2.3 Transcranial Ultrasound Stimulation

Transcranial Ultrasound Stimulation (TUS) is an emerging brain stimulation technique, that surpasses the capabilities of the technologies described in 2.1.2.1 and 2.1.2.2. It is able to deliver very focalised stimulation of structures deep within the brain, results only otherwise achievable using deep brain stimulation. Low energy frequency ultrasound can modulate highly-targeted regions of the brain; at higher frequencies this device can create permanent brain lesions. It is thought that transcranial ultrasound could be ground-breaking in healthcare as it could replace the need for implanted deep brain stimulation (see section 2.2.2 below) and may allow stimulation which creates a larger degree of enhancement in the healthy brain (Murphy and Fouragnan, 2024).

---

[9] https://health.ec.europa.eu/medical-devices-sector_en

[10] E.g. the Soonamedical website states that its device is EU MDR approved for clinical and at-home care https://soomamedical.com/depression-treatment/

2.1.2.4 Temporal Interference stimulation

Temporal interference stimulation is another emerging non-implanted brain stimulation technique. This technique applies multiple high-frequency electrical currents via electrodes attached to the scalp. Where these currents overlap with each other in the brain, they produce a lower frequency envelope signal that can be used to target deep brain structures without affecting overlying tissues. Initial demonstrations have shown this technique is able to enhance the accuracy of episodic memories in healthy humans (Violante et al, 2023).

2.1.2.5 Use cases

Table 2 below summarises known use cases of the technologies outlined above that are either available or under development.

Table 2. Non-implanted neurotechnologies for stimulation: use cases

Use case	Technology	Description	Status
Treating depression	tDCS	Neurostimulation devices are reaching the market for use in relieving the symptoms of major depressive disorder ([1]).	Commercially available
Treating depression and OCD	TMS	TMS has been approved as a treatment for depression and OCD in the US. Sessions of 30-40 minutes are delivered over 6-8 weeks.	Approved for medical use
Improving sleep quality, treating chronic insomnia	tDCS	Neurostimulation devices that help the user fall and stay asleep are being marketed to consumers ([2]).	Commercially available
Treating Premenstrual Syndrome	tDCS	Direct-to-consumer neurostimulation devices that improve symptoms of period pain and elevate mood are being marketed to consumers ([3]).	Commercially available
Cognitive enhancement	tDCS	Direct to consumer neurostimulation devices are marketed as aids for working memory or enhancing cognitive functions, e.g. to increase focus, attention, and alertness ([4]).	Commercially available
Military	TUS	In 2019 as part of DARPA's Next Generation Nonsurgical Neurotechnology (N3) program, it was announced that current non-implanted neurotechnologies do not offer the precision, resolution or portability required for advanced applications in real world combat settings. The following round of funding of DARPA's N3 program is focused on developing new non-implanted technologies, one of which is transcranial ultrasound ([5]).	Experimental

[1] Burkhardt et al, 2023
[2] Neurovalens, 2025, Somnee, 2025
[3] Samphire Neuroscience, 2025
[4] Liftid, 2025
[5] DARPA, 2019

Source: Authors

2.2 Implanted neurotechnology

Implanted neurotechnology refers to devices placed in the brain or on its surface. Neurosurgical procedures are required to insert them and to date they have only been used for medical applications.

There are currently two broad applications of implanted neural devices: neural prosthetics and therapeutic deep brain stimulation.

Implanted neurotechnology devices intended for medical use, to be placed in the brain or on its surface, are classified as high-risk Class III medical devices under the EU's MDR. The Regulation explicitly notes that it does not apply to devices such as implanted electrodes for neural recordings or deep brain stimulation because these devices are not yet marketed for non-medical purposes in the EU.

2.2.1 Neural prosthetics

To date implanted devices used for BCIs have mainly detected signals from the brain using electrocorticography (ECoG) or penetrating microelectrode arrays (MEAs). Emerging technologies include 'The Link' (developed by Neuralink) and the Stentrode (developed by Synchron). These devices allow recordings from the brain at an unprecedented level of detail (Rapeaux and Constandinou, 2021).

Advanced BCIs that can control robotic limbs have bidirectional capabilities in that they also deliver stimulation back into the brain: receiving this stimulation allows the user to substantially improve the use of robotic limbs. For example, a recent study (Flesher et al, 2021) showed that the time taken to complete motor actions with a robotic arm was reduced by half when the tactile stimulation of the robotic arm grasping objects was stimulated back into the brain.

2.2.1.1 Electrocorticography

ECoG uses electrodes to record electrical activity directly from the exposed surface of the brain. This method was originally developed for short term exploration of the brain to identify regions responsible for initiating epileptic seizures prior to surgery. Its longer-term use for BCIs has since been developed.

2.2.1.2 Penetrating Microelectrode Arrays & Neuropixels

Penetrating microelectrode implants or intracortical microeletrode array (MEA) are directly inserted into the cortex. One of the most widely known devices is the Utah array used by BrainGate, developed by a consortium of US universities. The electrodes penetrate about 1mm into the surface of the brain. They detect neural firing and transmit this via wires to a titanium pedestal on the scalp, connected to a computer. In the latest models this is done wirelessly via an antenna.

Similarly, neuropixels are single electrode probes that are directly inserted into the cortex with a dense number of recording sites along them (over 5000 in Neuropixel 2.0), which are able to record the activity of hundreds of neurons in the brain (Paulk et al, 2022).

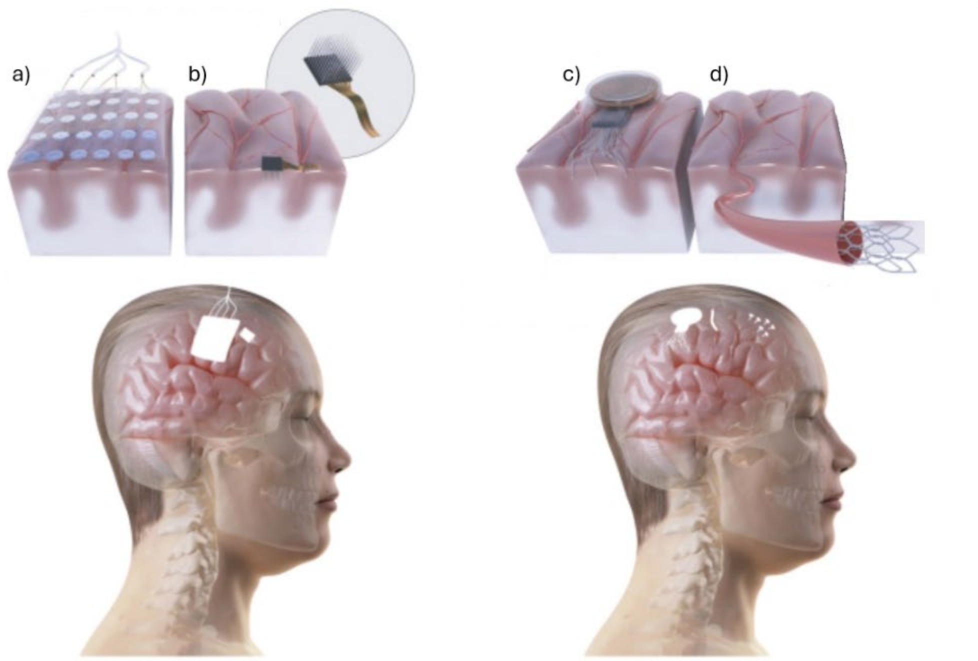
2.2.1.3 Stentrode

The Stentrode (Synchron, 2025) is another type of implanted device. Stents are devices used in medicine to hold open blood vessels to prevent blockages that lead to heart attacks. Stentrodes are stents that have electrodes on. They are injected via a catheter into blood vessels over the motor and somatosensory cortex in the brain. This allows changes in blood flow to these parts of the brain to be recorded. This device is advantageous as it is inserted through the jugular vein in the neck avoiding brain surgery. In January 2023 the first successful demonstration took place of a patient using this device to operate a computer to email, text and shop online (via directional use of a cursor and mouse click encoding) with no adverse events.

2.2.1.4 The Link

'The Link' is the implanted device developed by Neuralink (Neuralink, 2025). It contains 'neural lace', small polymer threads thinner than a human hair, containing electrodes. The current version being used in clinical trials has 64 threads which allows single cell recording from 1,024 sites. The device is implanted by a neurosurgical robot, in conjunction with a neurosurgeon. At the end of 2024 two patients had been using this device for BCIs.

Figure 4. Types of implanted devices used for neural prosthetics.
Current technologies: a) Electrocorticography b) Intracortical microelectrode array.
Emerging technologies c) Neuralink Chip d) Stentrode.



Source: Current Opinion in Biotechnology

2.2.1.5 Use cases

Table 3 below summarises known use cases of the technologies outlined above that are either available or under development.

Table 3. Implanted neural prosthetics: use cases

Use case	Application	Technology	Description	Status
Brain-computer interfaces	Control of assistive devices and assistive communication	ECoG, MEA, The Link, Stentrode	Neural prosthetics which use BCIs translate neural firing into the control of assistive devices, such as artificial limbs, cursors on a screen or to restore speech. They are being developed for patients who have paralysis caused by motor neuron disease, spinal cord injury or brainstem stroke, and allow much more detailed inferences to be drawn than from wearable devices. For example, at present these devices can decode a user imagining handwriting and translate this to typing at a speed of 90 characters a minute ([1]). In addition, signals from these devices can decode intentions to perform skilled movements with a robotic arm, such as grasping a cup and bringing it to the user’s mouth ([2]).	Experimental
	Decoding abstract thoughts	ECoG, MEA, The Link,	BCIs could be placed over other areas of the cortex to access different types of cognitive information. For example, neurons in the medial temporal lobe known as "concept cells" have been found to respond to abstract concepts, such as a particular person or place,	Speculative

Use case	Application	Technology	Description	Status
			becoming active when viewing an image or recalling a memory associated with the concept (3). Recording from these concept cells could allow BCIs to decode more abstract thoughts, paving the way for extracting complex intentions from patients.	
Addressing disability	Reanimating paralysed limbs	ECoG	Recent demonstrations have shown that brain-spine interfaces are capable of creating 'digital bridges' between the brain and the spinal cord to enable an individual with chronic tetraplegia to stand and walk naturally in community settings. Here the BCI extracts neural signalling encoding motor intentions and wirelessly transfers this past an injured spinal cord directly to the peripheral nervous system (4).	In development
Visual prosthetics	Restore sight	Multiple	These devices are used to bypass damage to the eye. They work by transducing light into electrical signals that are then transmitted directly onto the optic nerve, retinal	Research[11]

[11] Devices have been previously clinically approved but subsequently discontinued.

Use case	Application	Technology	Description	Status
			tissue or the occipital visual cortex in the brain. They have shown that otherwise blind patients are able to sense motion, locate objects, follow a path and recognise large letters ([5]).	

1 Willett et al., 2021
2 Flesher et al, 2021
3 Roelfsema et al, 2018
4 Lorach et al., 2023
5 Ramirez et al, 2023

Source : Authors

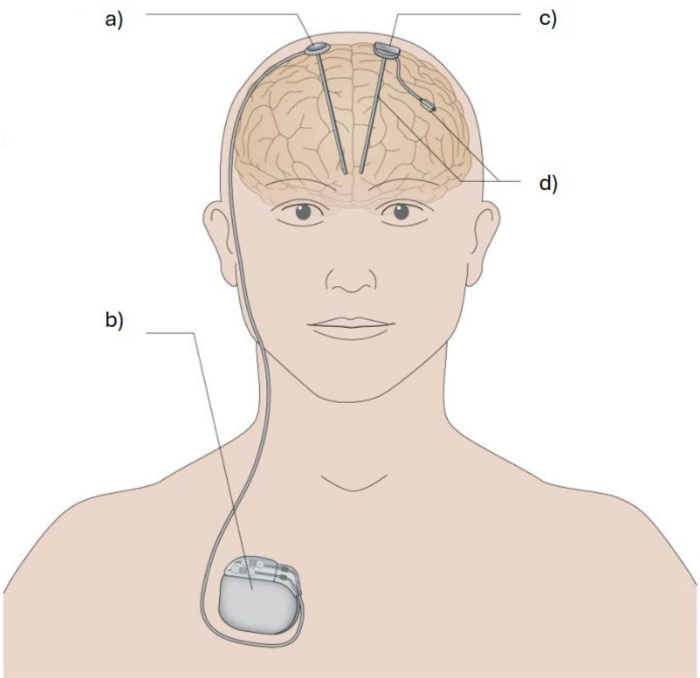
2.2.2 Therapeutic Deep Brain Stimulation

Therapeutic Deep Brain Stimulation (DBS) devices implant electrodes mainly into the brain's subcortical structures, and apply stimulation to enhance neuronal activity (e.g. in substantia nigra) of cells whose activity in not any longer within the normal physiological range, due to disease.

Systems can be 'open-loop', i.e. requiring a neurologist to manually adjust the stimulation parameters according to patient needs. However newer devices have self-calibrating 'closed-loop' systems, which monitor brain activity directly and adjust stimulation according to the current state of the brain.

Future deep brain stimulation devices may be able to more directly influence behaviour. For example, in monkeys, the activation of neurons that process rewards and punishment have been shown to produce, reinforce and inhibit certain behaviours. (Arsenault et al, 2014)

Figure 5. Current deep brain stimulators with a) single or bilateral electrode, with extension cables to b0 implantable pulse generator placed in the chest, stimulation is adjusted by a physician with a 3-5 year battery life. Future DBS system c) the implantable pulse generator is placed into the head and is rechargeable, d) the electrodes are capable of sensing and stimulating and with closed loop/adaptive functionality.



Source: Nature Reviews Neurology

2.2.2.1 Use cases

Table 4 below summarises known use cases of the technologies outlined above that are either available or under development.

Table 4. Deep Brain Stimulation: use cases

Use case	Application	Technology	Description	Status
Treating serious medical conditions	Managing epilepsy	Closed loop DBS	These devices monitor brain activity to detect the unusual activity associated with the onset of an epileptic seizure; they then deliver stimulation to normalise brain activity and reduce the chance of a seizure. An example is the NeuroPace RNS System. In patients with drug resistant epilepsy this system resulted in a 53% medium reduction in seizure frequency over two years ([1]).	Approved for medical use
	Managing tremor in Parkinson's disease	DBS	Devices have been approved as medical treatments for Parkinson's Disease where stimulation is applied to disrupt the brain activity that produces tremors ([2]). New closed-loop systems that self-adjust DBS therapy to individual brain activity in real time for people with Parkinsons have just been approved in the US ([3]).	Approved for medical use
	Treating depression, obsessive-compulsive disorder and drug addiction	DBS	There is currently work exploring whether DBS can treat other disorders, such as major depression disorder, OCD, epilepsy and drug addiction. ([4])	Research
	Restoring memory for patients with neuro-degenerative diseases	Intercranial depth electrodes	DARPA's 2013 Restoring Active Memory program focused on the use of implanted neurotechnology to restore normal memory function. Here researchers demonstrated that using implanted electrodes that record and then reinforced neural patterns associated with memory improvements to short-term	Research

Use case	Application	Technology	Description	Status
			working memory by 37% and longer-term episodic memories by 35% could be made ([5]). Therefore, a longer-term aim may be restoring memory in people with neurodegenerative diseases.	

[1] Neuropace, 2025
[2] Parkinson's Foundation, 2025
[3] Medtronic, 2025
[4] E.g. Sullivan et al, 2021
[5] Hampson et al, 2018

Source : Authors

2.3 Emerging technologies

There are a number of technologies which are currently at an early stage of development, having to date been only used in animals, but which could point to future directions of neurotechnology.

2.3.1 Neural dust

Neural dust is a tiny (0.8mm x 3mm x1mm), completely wireless device that has been shown to monitor and stimulate peripheral nerves and muscles in anesthetised rats. This uses ultrasound, which is returned by the device with a signal about the nerve's electrical activity without the need for wires or batteries (Seo et al, 2016).

2.3.2 Optogenetics

Optogenetic and magnogenetic techniques involve genetically modifying neurons to express proteins sensitive to light or magnetic fields. Applying optogenetics in animal studies with mice, in combination with replacing part of the skull with a glass window, has made it possible to record from more than a million neurons in a single animal (Kim et al, 2016). There are significant technical, legal and ethical challenges connected with applying genetic modification technology in humans, as well as the issues of optical access to brain tissue and the application of high precision microscopes. Despite these obstacles, this method has shown potential to stimulate neurons in highly refined pattens, significantly enhancing the possibility of writing information directly to the brain.

2.3.3 Nanotransducers

Nanotransducers are introduced into the body via an intravenous injection that targets a particular brain region. These nanotransducers transmit electrical signals and induce electric currents into the brain when exposed to a magnetic field.

In a recent study, magnetoelectric nanodiscs (MENDs) measuring 250 nm in diameter and 50 nm thick were injected into mice, successfully modulating neurons in the ventral tegmental area of the subthalamic nucleus, enabling wireless magnetic control of reward and motor behaviours (Kim et al, 2025). The authors of this work suggest that this approach could be scaled to humans by employing a magnetic helmet.

DARPA has funded Battelle (Battelle, 2019) to develop these types of devices for use in humans. The system is called BRAINSTORMS (Brain System to Transmit Or Receive Magnetoelectric Signals), which envisions temporary nanotransducers communicating with a helmet-based transceiver, which are then magnetically guided out of the brain into the bloodstream for safe removal. The transceivers could also send magnetic signals back to the nanotransducer enabling stimulation of the brain and two-way communication.

2.3.4 Brain Organoids

A brain organoid is a 3D tissue made by differentiating stem cells into neurons. These have been used in medical research for modelling neurodegenerative disorders, neuroinflammation and brain tumors (Sun et al, 2021). Other uses in bio-computing are also being explored. 'Brainoware' is an AI hardware approach that uses the brain organoid to perform computations by sending and receiving information using a high-density multielectrode array (Cai et al, 2023). Private companies such as Cortical Labs (Cortical Labs, 2025) are developing a biological intelligence operating system: so far these cultured brain cells have learnt to play the computer game Pong (Kagan et al, 2022).

2.3.5 Speculative possibilities of emerging technologies

Augmented Cognition: augmented cognition refers to the use of neurotechnology to increase the cognitive repertoire of the human mind. A longer-term goal proposed by those developing implanted neurotechnology (e.g. Neuralink) is that it could one day lead to the "symbiosis" of the healthy human brain with artificial intelligence-based software. At the moment implanted BCIs are being developed for medical and assistive purposes: the question of cognitive enhancement will nonetheless come when the capabilities of these devices surpass those of healthy individuals. The augmented abilities of most use to humans are those that increase the bandwidth of information into and out of the brain. The development of augmented cognition will however require significant advances in the capacity to record and stimulate the brain, as well as knowledge of the neural code that underpins these higher order cognitions (Roelfsema et al, 2018).

Enhancing working memory: working memory refers to the ability to retain information. This domain of human cognition is limited, so improvement by an augmented BCI could dramatically increase its computational power. A speculative BCI system of this type could connect neurons to an external memory store allowing users to offload intermediate computations with a brain-reading operation, and subsequently access this information by stimulating these representations back into the brain.

Enhancing long-term memory: the human brain has generally poor recollection of past events, so a BCI system could be used to improve the longer-term recollection of events, recording users' experiences and storing them externally for when they may be needed in the future.

Extending a sensory neuroprosthesis: a further speculative augmented BCI application is transitioning an assistive sensory neuroprosthesis to increase the depth of sensory processing of healthy humans, perhaps by supplementing sensory experiences or helping the user prioritise certain information. One example is a visual neuroprosthesis to allow the wearer to see beyond the usual range

Augmented learning: augmented BCIs could one day provide advanced feedback mechanisms for learning, or even transmitting knowledge directly into the brain, rather than through traditional learning methods. This could also give rise to brain-to -brain teaming, a term used to describe the ability to transmit information directly from one user's brain to another, which would dramatically improve the efficiency in which we can communicate abstract concepts. Such abilities of neurotechnology are thought to be far in the future.

3 Possible policy impacts

Having identified the various types of technologies and applications that are emerging, it was considered useful to assess which policy areas may be impacted by advances in neurotechnology in the short-, medium- or long-term. As well as indicating areas of possible policy relevance, it was deemed useful to pose some questions about what the implications might be for that policy area.

3.1 Consumer protection

Applications such as

- Direct-to-consumer products for gaming or recreational activities, particularly through AR/VR headsets
- Direct-to-consumer products for wellness, such as neurofeedback for relaxation/ increased focus/ personalised advice on brain health/ enhanced sleep tracking
- Responsive computing that adapts to the individual's brain state
- Brain sensors integrated into existing products
- Neural data used to customise marketing that can draw on dimensions of neural biomarkers and real time brain states
- The use of neural data to develop addictive algorithms that keep users engaged with tech
- Neuromarketing to children who may be particularly vulnerable due to neurodevelopmental immaturity of their brains
- Devices that have medical and consumer applications
- Third party apps using neural data from devices for additional functionalities
- Devices that manipulate the brain with auditory and visual stimulation[12] to promote wellness

Have implications for

- Consumer product regulations[13]
- Unfair commercial practices[14]
- Medical devices regulations [15]

[12] Not regulated by the Medical Devices Regulation, unlike electrical stimulation.

[13] https://commission.europa.eu/law/law-topic/consumer-protection-law_en

[14] https://commission.europa.eu/law/law-topic/consumer-protection-law/unfair-commercial-practices-and-price-indication/unfair-commercial-practices-directive_en

[15] https://health.ec.europa.eu/medical-devices-sector_en

- Data privacy[16]
- Regulations relating to Artificial Intelligence[17]

And raise questions such as:

- Is it warranted to regulate neurotechnology according to its use (medical vs non-medical) rather than the type of technology used, when the line between medical and non-medical can be blurred?
- Do consumer rights laws and/or frameworks for online safety of children need updating to reflect developments in neurotechnology? need to be updated to keep up with these developing technologies?
- Does the current regulatory framework for misleading advertising cover adequately "neurohype" - the gap between claims made about a device and the reality of its use?
- Should uses of neural data that drive compulsive or addictive uses of technology be addressed by regulators?
- Do devices that manipulate the brain with auditory and visual stimulation need special attention from regulators?

3.2 Human Health

Applications such as

- Use of diagnostic devices to monitor the brains of children outside of the hospital, increase accessibility and improve early and real-time diagnosis of developmental disorders
- Diagnosis and monitoring on-pitch of concussive injuries during sport
- Third party apps using neural data from devices for additional functionalities
- Early detection (and possible disruption) of seizure activity in epilepsy
- Long term brain health monitoring with non-implanted devices
- Implanted stimulation devices currently used for therapeutic brain stimulation such as preventing tremors in Parkinsons, which can be used for other disorders such as the treatment of depression/ OCD/ anorexia
- Closed loop devices, that 'decide' when to deliver treatment

[16] https://commission.europa.eu/law/law-topic/data-protection/legal-framework-eu-data-protection_en

[17] https://digital-strategy.ec.europa.eu/en/policies/regulatory-framework-ai

- Neural prosthetics which bypass damaged neurons (e.g. visual prosthetics)
- Use of non-implanted stimulation to increase muscular responses, or cognitive abilities
- Neuromodulation devices to analyse and modulate concentration levels (in particular to achieve relaxed brain states at moments of peak stress)
- Use of devices to treat and monitor insomnia
- Treatment of Alzheimer’s through visual and auditory stimulation

Have implications for

- Diagnosis
- Monitoring
- Treatment
- Human enhancement
- Ageing

And raise questions such as:

- What safeguards can be put in place for patients that have devices implanted that are made and monitored by a commercial entity that later ceases trading?
- Can a line be drawn between healthcare applications and wellness/enhancement applications for regulatory or other purposes?
- Are there certain applications that should be more strictly regulated – such as those that can manipulate brain function e.g. memory?
- Are international anti-doping frameworks able to address issues of fairness when it comes to enhancements using neurotechnology?
- If such devices are found to have beneficial effects, how can equality of access be safeguarded?

3.3 Fundamental Rights, including rights of the child

Applications such as

- EEG responses used to predict voting behaviour
- Neural markers used to predict risk taking propensity and impact adolescent criminal culpability.
- Use of neurofeedback on juvenile defenders
- Neural data biomarkers used by insurance companies

Have implications for

- Freedom of thought/expression
- Mental privacy
- Criminal justice
- Anti-discrimination[18]

And raise questions such as:

- Do existing legal frameworks need to be updated and/or enforced more strictly to protect the rights of individuals with regard to the use and storing of their neuro-data?
- Do anti-discrimination regulations cover discrimination due to neural information?
- Can policy frameworks take into account that physical characteristics (e.g. skin tone, hair thickness) can lead to different readings?

3.4 Employment/social affairs/human resources

Applications such as

- Monitoring employees' attention and focus, with a specific focus on office workers and possible application in monitoring of remote workers
- Developing neurotechnology assistants that respond to a brain state or response
- Monitoring employees' drowsiness, with a specific focus on safety critical workers (transport/ mining sectors)
- Using neuroprofiling in hiring to pinpoint characteristics such as neurodivergence
- Workplace wellness initiatives where employees are given neurofeedback devices
- Applications/devices to improve the workplace integration of people with disabilities

Have implications for

- Worker rights and protections[19]
- Workplace safety standards[20]
- Anti-discrimination

[18] https://commission.europa.eu/aid-development-cooperation-fundamental-rights/your-fundamental-rights-eu/know-your-rights/equality/non-discrimination_en

[19] https://employment-social-affairs.ec.europa.eu/policies-and-activities/rights-work_en

[20] https://employment-social-affairs.ec.europa.eu/policies-and-activities/rights-work/health-and-safety-work_en

- Privacy and data security
- Disability in the workplace

And raise questions such as:

- Would such technologies be more or less acceptable/useful/desirable in particular industries?
- How is consent given and on the basis of what information? Can there be legal restrictions on use of data retrieved from non-implanted devices? How to avoid such data being sold to third parties?
- How can frameworks avoid monitoring technology being used for coercive control or punishment in the workplace, particularly given the unreliability of readings (i.e. factors such as hair thickness can impact readings)?
- How can workers be protected from requirements to use such devices?
- How to ensure the minimum data required is retrieved and stored securely?
- How to ensure that employees have the right to access/delete/withdraw their data at any time?
- Can neural data be used to train an AI to replace that worker? And if so, should that use be limited or prevented?
- Are there any conditions under which the use of non-implanted neurotechnology could be mandated, for example for safety reasons?
- How can the right to disconnect be protected with such devices available?
- Who owns the neural data related to a sportsperson/employee when they move to a different club/workplace?

3.5 Defence, security and law enforcement

Applications such as

- Brain-biometrics
- BCIs to fly drones or advanced human machine teaming whereby autonomous AI systems adjust behaviour based on neural signals
- Enhancement of military personnel
- Detection of deception in interrogation or intelligence-gathering
- Enhanced eyewitness information extraction
- Data from wearable devices being used for law enforcement surveillance purposes
- Intoxication detection headsets

Have implications for

- Cybersecurity
- Military hardware
- Dual use goods[21]
- Law enforcement

And raise questions such as:

- What does it imply if Member States apply different status to information gained through neurotechnology?
- Will law enforcement agencies be able to access information from such devices held by third parties?
- Should there be export controls on neurotechnology, as a dual-use good?

3.6 Education

Applications such as

- Direct-to-consumer devices used in classrooms to monitor students' attention levels, understand conditions for optimal learning, create personalised teaching strategies, highlight when students are tired or stressed
- Immersive educational experiences that stimulate different areas of the brain
- Cognitive enhancement through neurostimulation

Have implications for

- Equality of access/Fairness
- Educational technology

And raise questions such as:

- Should there be age-related guidelines for access to/use of neurotechnology, that include issues around consent?
- If such devices are found to have beneficial effects, how can equality of access be safeguarded?
- Does use of enhancement constitute cheating?

[21] https://policy.trade.ec.europa.eu/help-exporters-and-importers/exporting-dual-use-items_en

3.7 Research, innovation and digital policy

Discussion of the policy areas mentioned above raises additional questions relating to research, innovation and digital policy more broadly.

- Is more research needed on the effects of brain monitoring and stimulation on human health?
- Could regulatory sandboxes be a useful tool to balance the significant innovation breakthroughs in this space with the legitimate questions that their use brings up?
- Does more research need to be done on the impact of neurotechnology on children's brain development before products are made available to them?
- Does research that underpins the development of neurotechnology products need to be more regulated, e.g. the use of human subjects in neuromarketing?
- Should there be rules on extrapolating research undertaken with adults to children without adequate testing on how impacts may be different for the developing brain?
- Should there be international standard-setting on neurotechnology?
- Should AI regulation address algorithmic bias coming from the processing of the neurodata and unrepresentative training sets? Should it address the right not to provide brain data for AI models?
- Do we have an ethical framework for implanted neurotechnology devices and do the ethics of medical implants suffice?
- How should the end of life of implanted devices be addressed? What safeguards can be put in place to guard against abandonment of a patient if the device provider fails?
- Where do we draw the line between medical treatment and human augmentation?
- The development of implanted neurotechnology requires the extensive use of research animals, and particularly monkeys, for BCIs. Should the EU work at an international level to reduce the impact on animals in general and primates in particular?
- There are two emerging neurotechnologies that use genetic modifications. Should such development be subject to more detailed scrutiny?

3.8 Environment and circularity

- Can environmental aspects – use of critical raw materials, retrieval of devices, recycling – be addressed?

4 Conclusions

The intention of this report is to provide a summary of important developments in neurotechnology, their application and their possible implications for EU policymaking. It is a starting point for further consideration, and given that this is a fast-moving field, makes no claim to be exhaustive.

Nonetheless, there are some key elements from this report that are useful to highlight.

1. The first is the observation that there many applications emerging in the area of non-implanted monitoring devices, with many of them for non-medical uses, such as personal wellbeing, workplace safety, personal enhancement, gaming and cyber-security. This is relevant because this category, when not used for medical purposes, is not covered by the EU's Medical Devices Regulation. It could therefore be useful to consider whether the general consumer legislation provides sufficient safeguards, given the sensitivity of brain activity and neural data. An additional consideration is the use of non-electrical means to stimulate the brain (visual/auditory) which is not regulated in the same way as electrical stimulation.

2. Looking at the topic from a European Commission perspective, there is currently no forum within the organisation that brings together those working in policy areas that are connected to neurotechnology. It is therefore difficult to gauge which policy areas are considering its impact. The list of questions that are provided in this report are intended as a starting point for such a consideration within the European Commission. They could of course be a useful starting point for other organisations.

3. Given the speed of development both in neuroscience and machine learning/artificial intelligence, it is likely that data recorded from the brain could provide more information in the future than it does now[22.] Devices are being developed that both "read" and "write to" the brain. This would imply the need to consider whether current legislative frameworks on data privacy, storage and consent as well as individual rights are appropriate for a future where, for example, data retrieved from the brain can make involuntary disclosures.

4. Foresight is a useful tool for policymakers in this context. Its exploratory nature and participatory set-up offer policymakers the possibility of examining future implications in a non-binding way. The authors have developed formats for exploring these questions using foresight tools and methodologies and these are at the disposal of interested policymakers.

[22] E.g research has already shown that EEG data can be a predictor of voting behaviour (Galli et al, 2021) and sexual preference (Ziogas et al, 2023).

References

- Abdellahi, M. E. A., Koopman, A. C. M., Treder, M. S. and Lewis, P. A. (2023), 'Targeted memory reactivation in human REM sleep elicits detectable reactivation', *eLife*, Vol. 12, p. e84324, https://doi.org/10.7554/eLife.84324.

- Ackerman, E. (2022), 'Are You Ready for Workplace Brain Scanning? - IEEE Spectrum', IEEE Spectrum website, 9 November 2022, accessed 17 February 2025, https://spectrum.ieee.org/neurotech-workplace-innereye-emotiv.

- Arnold, T. C., Freeman, C. W., Litt, B. and Stein, J. M. (2023), 'Low-field MRI: Clinical promise and challenges', *Journal of Magnetic Resonance Imaging*, Vol. 57, Issue 1, pp. 25–44, https://doi.org/10.1002/jmri.28408.

- Arsenault, J. T., Rima, S., Stemmann, H. and Vanduffel, W. (2014), 'Role of the primate ventral tegmental area in reinforcement and motivation', *Current Biology*, Vol. 24, Issue 12, pp. 1347–1353, https://doi.org/10.1016/j.cub.2014.04.044.

- Attrey, A., M. Lesher and C. Lomax (2020), "The role of sandboxes in promoting flexibility and innovation in the digital age", *OECD Going Digital Toolkit Notes*, No. 2, OECD Publishing, Paris, https://doi.org/10.1787/cdf5ed45-en.

- Baeken, C., Arns, M., Brunelin, J., Chanes, L., Filipcic, I. et al. (2023), 'European reclassification of non-invasive brain stimulation as class III medical devices: A call to action', *Brain Stimulation*, Vol. 16, Issue 2, pp. 564–566, https://doi.org/10.1016/j.brs.2023.02.012.

- Battelle, 'Battelle-Led Team Wins DARPA Award to Develop Injectable, Bi-Directional Brain Computer Interface| Battelle Press Release', Battelle website, 20 May 2019, accessed 17 February 2025, https://www.battelle.org/insights/newsroom/press-release-details/battelle-led-team-wins-darpa-award-to-develop-injectable-bi-directional-brain-computer-interface.

- Beauchemin, N., Charland, P., Karran, A., Boasen, J., Tadson, B. et al. (2024), 'Enhancing learning experiences: EEG-based passive BCI system adapts learning speed to cognitive load in real-time, with motivation as catalyst', *Frontiers in Human Neuroscience*, Vol. 18, p. 1416683, https://doi.org/10.3389/fnhum.2024.1416683.

- Boto, E., Holmes, N., Leggett, J., Roberts, G., Shah, V. et al. (2018), 'Moving magnetoencephalography towards real-world applications with a wearable system', *Nature*, Vol. 555, Issue 7698, pp. 657–661, https://doi.org/10.1038/nature26147.

- Brainscope, 'BrainScope Completes Proof-of-Concept for Groundbreaking Early Alzheimer's Prediction Biomarker', Brainscope website, accessed 17 February 2025, http://brainscope-7520044.hs-sites.com/hs-web-interactive-7520044-135662216238.

- Brainwave Science, 'Home | Brainwave Science', Brainwave Science website, accessed 17 February 2025, https://brainwavescience.com/.

- Burkhardt, G., Kumpf, U., Crispin, A., Goerigk, S., Andre, E. et al. (2023), 'Transcranial direct current stimulation as an additional treatment to selective serotonin reuptake inhibitors in adults with major depressive disorder in Germany (DepressionDC): a triple-blind, randomised, sham-controlled, multicentre trial', *Lancet*, Vol. 402, Issue 10401, pp. 545–554, https://doi.org/10.1016/S0140-6736(23)00640-2.

- Cai, H., Ao, Z., Tian, C., Wu, Z., Liu, H. et al. (2023), 'Brain organoid reservoir computing for artificial intelligence', *Nature Electronics*, Vol. 6, Issue 12, pp. 1032–1039, https://doi.org/10.1038/s41928-023-01069-w.

- Castillo, A., Dubois, J., Field, R. M., Fishburn, F., Gundran, A. et al. (2023), 'Measuring acute effects of subanesthetic ketamine on cerebrovascular hemodynamics in humans using TD-fNIRS', *Scientific Reports*, Vol. 13, Issue 1, p. 11665, https://doi.org/10.1038/s41598-023-38258-8.

- Clinicaltrials.gov, 'Study Details | Investigating Mild Cognitive Impairment in Patients And Controls With TD-fNIRS | ClinicalTrials.gov', 3 July 2024, accessed 17 February 2025, https://clinicaltrials.gov/study/NCT05996575.

- Cortical Labs 'Cortical Labs - DishBrain Intelligence', Cortical Labs website, accessed 17 February 2025, https://corticallabs.com/.

- Cuhls, K. E. (2020), 'Horizon Scanning in Foresight – Why Horizon Scanning is only a part of the game', *FUTURES & FORESIGHT SCIENCE*, Vol. 2, Issue 1, p. e23, https://doi.org/10.1002/ffo2.23.

- DARPA 'Six Paths to the Nonsurgical Future of Brain-Machine Interfaces', DAPRA website, 20 May 2019, accessed 19 March 2025, https://www.darpa.mil/news/2019/nonsurgical-brain-machine-interfaces.

- Dubois, J., Field, R. M., Jawhar, S., Jewison, A., Koch, E. M. et al. (2023), 'Change in brain asymmetry reflects level of acute alcohol intoxication and impacts on inhibitory control', *Scientific Reports*, Vol. 13, Issue 1, p. 10278, https://doi.org/10.1038/s41598-023-37305-8.

- Emotiv, "How neuromarketing is the most reliable tool for market research", Emotiv website, accessed 17 February 2025, https://www.emotiv.com/blogs/news/neuromarketing-in-market-research.

- English Schools' Football Association, 'English Schools' FA announces new partnership with i-Brain Tech – English Schools' Football Association', EFSA website, 16 January 2024, accessed 17 February 2025, https://schoolsfootball.org/2024/01/16/english-schools-fa-announces-new-partnership-with-i-brain-tech/.

- Epilepsy Alarms, 'mjn-SERAS – Ground-Breaking Seizure Detection Device | EAUK', Epilepsy Alarms website, accessed 26 February 2025, https://www.epilepsyalarms.co.uk/product/mjn-seras/

- ETH Zürich, 'Brain-Computer Interface Race Tasks', Cybathlon website, accessed 17 February 2025, https://cybathlon.com/en/events/challenges/challenges-2024/bci-tasks.

- Exsurgo, "Axon for Chronic Pain Management", Exsurgo website, accessed 26 February 2025, https://exsurgo.com/product/axon-neurofeedback-system/

- Fleming, N., 'Automakers Test In-Car Brain Sensors', MIT Technology Review website, 18 August 2011, accessed 17 February 2025, https://www.technologyreview.com/2011/08/18/192304/automakers-test-in-car-brain-sensors/.

- Flesher, S. N., Downey, J. E., Weiss, J. M., Hughes, C. L., Herrera, A. J. et al. (2021), 'A brain-computer interface that evokes tactile sensations improves robotic arm control', *Science*, Vol. 372, Issue 6544, pp. 831–836, https://doi.org/10.1126/science.abd0380.

- Flow Neuroscience, 'tDCS depression treatment - Flow Neuroscience', Flow Neuroscience website, accessed 17 February 2025, https://www.flowneuroscience.com/.

- FocusCalm, 'FocusCalm – Biofeedback Device, EEG Headband, Brain Training', FocusCalm website, accessed 26 February 2025, https://focuscalm.com/products/focuscalm-eeg-headband

- Galli, G., Angelucci, D., Bode, S., De Giorgi, C., De Sio, L. et al. (2021), 'Early EEG responses to pre-electoral survey items reflect political attitudes and predict voting behavior', *Scientific Reports*, Vol. 11, Issue 1, p. 18692, https://doi.org/10.1038/s41598-021-96193-y.

- Hampson, R. E., Song, D., Robinson, B. S., Fetterhoff, D., Dakos, A. S. et al. (2018), 'Developing a hippocampal neural prosthetic to facilitate human memory encoding and recall', *Journal of Neural Engineering*, Vol. 15, Issue 3, p. 036014, https://doi.org/10.1088/1741-2552/aaaed7.

- Heil, M., Osman, A., Wiegelmann, J., Rolke, B. and Hennighausen, E. (2000), 'N200 in the Eriksen-task: Inhibitory executive process?', *Journal of Psychophysiology*, Vol. 14, Issue 4, pp. 218–225, https://doi.org/10.1027/0269-8803.14.4.218.

- Hong, S., Wang, Y. and Tai, C. (2019), 'China's Efforts to Lead the Way in AI Start in Its Classrooms', *Wall Street Journal*, 24 October, https://www.wsj.com/articles/chinas-efforts-to-lead-the-way-in-ai-start-in-its-classrooms-11571958181.

- HRL Laboratories, 'HRL Laboratories : DARPA Announces Success of Cognitive Technology Threat Warning System (CT2WS)' HRL website, 18 September 2011, accessed 17 February 2025, https://www.hrl.com/hrlDocs/pressreleases/2012/prsRls_120918.html.

- International Centre for Future Generations (Salles, A., Mahieu, V., Rommelfanger, K., Porcello, D., Tournas, L.) , 'TOWARDS INCLUSIVE EU GOVERNANCE OF NEUROTECHNOLOGIES', November 2024, International Centre for Futures Generations, https://www.researchgate.net/publication/385622032_TOWARDS_INCLUSIVE_EU_GOVERNANCE_OF_NEUROTECHNOLOGIES_1_Towards_Inclusive_EU_Governance_of_Neurotechnologies.

- Jones Lang Lasalle IP Inc, 'JLL taps into the power of neuroscience to shape the future of work', 10 August 2022, accessed 17 February 2025, https://www.jll.co.in/en/newsroom/jll-taps-into-the-power-of-neuroscience-to-shape-the-future-of-work.

- Kagan, B. J., Kitchen, A. C., Tran, N. T., Habibollahi, F., Khajehnejad, M. et al. (2022), 'In vitro neurons learn and exhibit sentience when embodied in a simulated game-world', *Neuron*, Vol. 110, Issue 23, pp. 3952-3969.e8, https://doi.org/10.1016/j.neuron.2022.09.001.

- Kim, T. H., Zhang, Y., Lecoq, J., Jung, J. C., Li, J. et al. (2016), 'Long-Term Optical Access to an Estimated One Million Neurons in the Live Mouse Cortex', *Cell Reports*, Vol. 17, Issue 12, pp. 3385–3394, https://doi.org/10.1016/j.celrep.2016.12.004.

- Kim, Y. J., Kent, N., Vargas Paniagua, E., Driscoll, N., Tabet, A. et al. (2025), 'Magnetoelectric nanodiscs enable wireless transgene-free neuromodulation', *Nature Nanotechnology*, Vol. 20, Issue 1, Nature Publishing Group, pp. 121–131, https://doi.org/10.1038/s41565-024-01798-9.

- Klaming, L. and Vedder, A. (2009), 'Brushing Up our Memories: Can we use Neurotechnologies to Improve Eyewitness Memory?', *Law, Innovation and Technology*, Vol. 1, Issue 2, pp. 203–221, https://doi.org/10.1080/17579961.2009.11428371.

- Liftid, 'tDCS Device for Improving Focus - LIFTiD Neurostimulation' Liftid website, accessed 17 February 2025, https://www.getliftid.com/.

- Liverpool FC, 'Explained: How neuro11's brain training with the Liverpool squad works - Liverpool FC', Liverpool FC website, 5 August 2022, accessed 17 February 2025, https://www.liverpoolfc.com/news/explained-how-neuro11s-brain-training-liverpool-squad-works

- Lorach, H., Galvez, A., Spagnolo, V., Martel, F., Karakas, S. et al. (2023), 'Walking naturally after spinal cord injury using a brain-spine interface', *Nature*, Vol. 618, Issue 7963, pp. 126–133, https://doi.org/10.1038/s41586-023-06094-5.

- Medtronic, 'Medtronic earns U.S. FDA approval for the world's first Adaptive deep brain stimulation system for people with Parkinson's' 24 February, 2025, Medtronic News website, accessed 19 March 2025, https://news.medtronic.com/2025-02-24-Medtronic-earns-U-S-FDA-approval-for-the-worlds-first-Adaptive-deep-brain-stimulation-system-for-people-with-Parkinsons.

- Mendi, "Mendi.io – Better Focus, Better Performance", Mendi website, accessed 26 February 2025, https://www.mendi.io/

- Murphy, K. and Fouragnan, E. (2024), 'The future of transcranial ultrasound as a precision brain interface', *PLOS Biology*, Vol. 22, Issue 10, Public Library of Science, p. e3002884, https://doi.org/10.1371/journal.pbio.3002884.

- Muse, "Muse™ EEG-Powered Meditation & Sleep Headband", Muse website, accessed 17 February 2025, https://choosemuse.com/.

- Myndlift (Rebic, D.), '4 Athletes Who Use Neurofeedback to Improve Sports Performance', Myndlift website, 31 August 2023, accessed 17 February 2025, https://www.myndlift.com/post/4-athletes-who-use-neurofeedback-to-improve-sports-performance.

- Mytone, 'Tone Buds', MyTone website, accessed 17 February 2025, https://mytone.io/products/tone-smartbuds.

- Neudio, 'Neudio' , Neudio website, accessed 17 February 2025, https://www.neudio.com.

- Neurable, "MW75 Neuro by Neurable | Work Smarter, Not Longer", Neurable website, accessed 17 February 2025, https://www.neurable.io/products.

- Neuralink 'Neuralink — Pioneering Brain Computer Interfaces', Neuralink website, accessed 26 February 2025, https://neuralink.com/.

- Neuropace, ‘The RNS System’, *NeuroPace, Inc.*, accessed 19 March 2025, https://www.neuropace.com/patients/neuropace-rns-system/.
- Neurosity, ‘Introducing the Crown | Neurosity’, Neurosity website, accessed 17 February 2025, https://neurosity.co/.
- Neurorights Foundation (Genser, J., Damianos, S. and Yuste, R.), ‘Safeguarding Brain Data: Assessing the Privacy Practices of Consumer Neurotechnology Companies’, April 2024, https://www.perseus-strategies.com/wp-content/uploads/2024/04/FINAL_Consumer_Neurotechnology_Report_Neurorights_Foundation_April-1.pdf
- Neurovalens, ‘The Sleep Aid Device to Conquer Insomnia – Modius Sleep’, Neurovalens website, accessed 17 February 2025, https://neurovalens.com/modiussleep/.
- OECD, ‘Framework for Anticipatory Governance of Emerging Technologies’, OECD Science, Technology and Industry Policy Papers, No. 165, 24 April 2024, https://doi.org/10.1787/0248ead5-en.
- Open BCI, ‘OpenBCI | Home’, OpenBCI website, accessed 17 February 2025, https://openbci.com/.
- Parkin, B. L., Ekhtiari, H. and Walsh, V. F. (2015), ‘Non-invasive Human Brain Stimulation in Cognitive Neuroscience: A Primer’, *Neuron*, Vol. 87, Issue 5, pp. 932–945, https://doi.org/10.1016/j.neuron.2015.07.032.
- Parkinson’s Foundation, ‘Deep Brain Stimulation (DBS) | Parkinson’s Foundation’, Parkinson’s Foundation website, accessed 19 March 2025, https://www.parkinson.org/living-with-parkinsons/treatment/surgical-treatment-options/deep-brain-stimulation.
- Paulk, A. C., Kfir, Y., Khanna, A. R., Mustroph, M. L., Trautmann, E. M. et al. (2022), ‘Large-scale neural recordings with single neuron resolution using Neuropixels probes in human cortex’, *Nature Neuroscience*, Vol. 25, Issue 2, pp. 252–263, https://doi.org/10.1038/s41593-021-00997-0.
- Perri [@perrikaryal], ‘WE DID IT I beat the Elden Ring DLC - Shadow of the Erdtree - with MIND CONTROL’, *Twitter*, 28 July 2024, accessed 17 February 2025, https://x.com/perrikaryal/status/1817597037203816541.
- Potomac Institute (Swetnam, M., McBride, D., Herzfeld, C., Barnett, J., Schiller, K. Gallington, D., Retelle, J., Siegrist, D., Buss, J., Giordano, J.), ‘Neurotechnology Futures Study’, April 2013, https://www.potomacinstitute.us/reports/43-pips-reports/328-neurotechnology-futures-study-2.
- Purcher, J., ‘Apple has won a patent for an all-new AirPods-Related Eye Mask Device that promotes Rest and jammed with Biometric Sensors’, Patently Apple website, 29 March 2022, accessed 17 February 2025, https://www.patentlyapple.com/2022/03/apple-has-won-a-patent-for-an-all-new-airpods-related-eye-mask-device-that-promotes-rest-and-jammed-with-biometric-sensors.html.

- Ramirez, K. A., Drew-Bear, L. E., Vega-Garces, M., Betancourt-Belandria, H. and Arevalo, J. F. (2023), 'An update on visual prosthesis', *International Journal of Retina and Vitreous*, Vol. 9, Issue 1, p. 73, https://doi.org/10.1186/s40942-023-00498-1.
- Rapeaux, A. B. and Constandinou, T. G. (2021), 'Implantable brain machine interfaces: first-in-human studies, technology challenges and trends', *Current Opinion in Biotechnology*, Vol. 72, pp. 102–111, https://doi.org/10.1016/j.copbio.2021.10.001.
- Reinhart, R. M. G. and Nguyen, J. A. (2019), 'Working memory revived in older adults by synchronizing rhythmic brain circuits', *Nature Neuroscience*, Vol. 22, Issue 5, pp. 820–827, https://doi.org/10.1038/s41593-019-0371-x.
- Roelfsema, P. R., Denys, D. and Klink, P. C. (2018), 'Mind Reading and Writing: The Future of Neurotechnology', *Trends in Cognitive Sciences*, Vol. 22, Issue 7, pp. 598–610, https://doi.org/10.1016/j.tics.2018.04.001.
- Samphire Neuroscience, 'Nettle', Samphire Neuroscience website, accessed 17 February 2025, https://samphireneuro.com/pages/nettle.
- Seo, D., Neely, R. M., Shen, K., Singhal, U., Alon, E. et al. (2016), 'Wireless Recording in the Peripheral Nervous System with Ultrasonic Neural Dust', *Neuron*, Vol. 91, Issue 3, pp. 529–539, https://doi.org/10.1016/j.neuron.2016.06.034.
- Somnee, 'Somnee | Inside Somnee's World-Class Sleep Tech', Somnee website, accessed 17 February 2025, https://somneesleep.com/pages/how-it-works.
- Sooriyaarachchi, J., Seneviratne, S., Thilakarathna, K. and Zomaya, A. Y. (2021), 'MusicID: A Brainwave-Based User Authentication System for Internet of Things', *IEEE Internet of Things Journal*, Vol. 8, Issue 10, pp. 8304–8313, https://doi.org/10.1109/JIOT.2020.3044726.
- Sullivan, C. R. P., Olsen, S. and Widge, A. S. (2021), 'Deep brain stimulation for psychiatric disorders: From focal brain targets to cognitive networks', *NeuroImage*, Vol. 225, p. 117515, https://doi.org/10.1016/j.neuroimage.2020.117515.
- Sun, N., Meng, X., Liu, Y., Song, D., Jiang, C. et al. (2021), 'Applications of brain organoids in neurodevelopment and neurological diseases', *Journal of Biomedical Science*, Vol. 28, Issue 1, p. 30, https://doi.org/10.1186/s12929-021-00728-4.
- Synchron, 'The Technology', Synchron website, accessed 26 February 2025, https://synchron.com/technology.
- Violante, I. R., Alania, K., Cassarà, A. M., Neufeld, E., Acerbo, E. et al. (2023), 'Non-invasive temporal interference electrical stimulation of the human hippocampus', *Nature Neuroscience*, Vol. 26, Issue 11, Nature Publishing Group, pp. 1994–2004, https://doi.org/10.1038/s41593-023-01456-8.
- Webb, E. K., Etter, J. A. and Kwasa, J. A. (2022), 'Addressing racial and phenotypic bias in human neuroscience methods', *Nature Neuroscience*, Vol. 25, Issue 4, Nature Publishing Group, pp. 410–414, https://doi.org/10.1038/s41593-022-01046-0.
- Wenco International Mining Systems, 'Fatigue Management: Large Copper Mining Operation in South East Asia | Wenco International Mining Systems' Wenco Mine website, accessed 17

February 2025, https://www.wencomine.com/case-studies-and-white-papers/fatigue-management-large-copper-mining-operation-in-south-asia.

- Willett, F. R., Avansino, D. T., Hochberg, L. R., Henderson, J. M. and Shenoy, K. V. (2021), 'High-performance brain-to-text communication via handwriting', *Nature*, Vol. 593, Issue 7858, Nature Publishing Group, pp. 249–254, https://doi.org/10.1038/s41586-021-03506-2.
- World Economic Forum, 'These Chinese workers' brain waves are being monitored', World Economic Forum website, 1 May 2018, accessed 17 February 2025, https://www.weforum.org/stories/2018/05/china-is-monitoring-employees-brain-waves-and-emotions-and-the-technology-boosted-one-companys-profits-by-315-million/.
- Zhang, R., Yan, B., Tong, L., Shu, J., Song, X. et al. (2019), 'Identity Authentication Using Portable Electroencephalography Signals in Resting States', *IEEE Access*, Vol. 7, pp. 160671–160682, https://doi.org/10.1109/ACCESS.2019.2950366.
- Ziogas, A., Mokros, A., Kawohl, W., de Bardeci, M., Olbrich, I. et al. (2023), 'Deep Learning in the Identification of Electroencephalogram Sources Associated with Sexual Orientation', *Neuropsychobiology*, Vol. 82, Issue 4, pp. 234–245, https://doi.org/10.1159/000530931.

List of abbreviations and definitions

Abbreviations	Definitions
AI	Artificial Intelligence
AR	Augmented Reality
BCI	Brain-Computer Interface
DARPA	Defense Advanced Research Projects Agency
DBS	Deep Brain Stimulation
ECoG	Electrocorticography
EEG	Electroencephalography
fNIRS	Functional Near-Infrared Spectroscopy
MDR	Medical Devices Regulation
MEA	Microelectrode Array
MEG	Magnetoencephalography
MEND	Magnetoelectric nanodisc
MRI	Magnetic Resonance Imaging
OCD	Obsessive-Compulsive Disorder
OECD	Organisation for Economic Cooperation and Development
OPM-MEG	Optically pumped magnetoencephalography
tACS	Transcranial Alternating Current Stimulation
tDCS	Transcranial Direct Current Stimulation
TMS	Transcranial Magnetic Stimulation
TUS	Transcranial Ultrasound Stimulation
VR	Virtual Reality

List of figures

List of tables

Getting in touch with the EU

In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

— at the following standard number: +32 22999696,

— via the following form: european-union.europa.eu/contact-eu/write-us_en.

Finding information about the EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

EU open data

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.

Science for policy

The Joint Research Centre (JRC) provides independent, evidence-based knowledge and science, supporting EU policies to positively impact society

EU Science Hub
Joint-research-centre.ec.europa.eu

Publications Office of the European Union