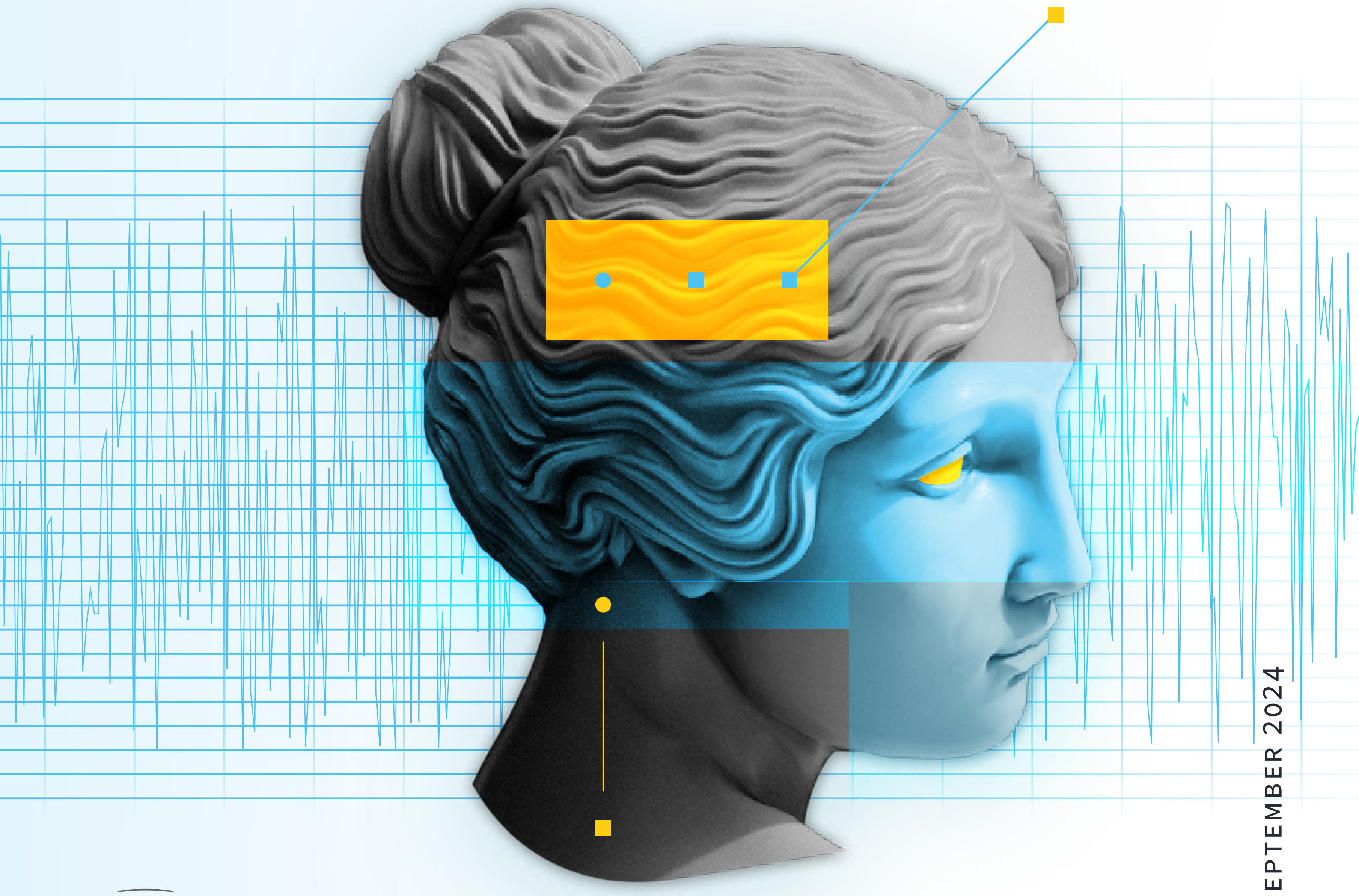
ART —— Analysis and Research Team

RESEARCH PAPER

From vision to reality

Promises and risks of Brain-Computer Interfaces



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The next frontier of human-machine interaction

Imagine seamlessly controlling your computer with just a thought - moving the cursor across the screen, typing, drawing, composing music or playing video games, all without lifting a finger. This once-distant vision has already become a reality in some cases and may be closer than previously imagined in others. **Brain-computer interfaces** (BCIs) **are transitioning** from the realm of speculative fiction **to reality**, with groundbreaking developments already underway which promise to unlock unprecedented ways of interacting with the digital world.

Attempting to directly link the brain to a computer is not a recent endeavour. Research started decades ago and as early as 1977, an experiment enabled a person to control a cursor on a screen using only brain activity[1]. Today, **companies and researchers are breaking new ground** with their work to help individuals with paralysis regain the ability to engage in everyday activities, such as shopping online, sending emails, communicating[2], or even playing video games[3], all through advanced brain implants.

Interest and investment in **BCI research** are **gaining momentum**[4], especially in the United States and China[5]. Progress is accelerating, bolstered by parallel advances in complementary fields, such as nanotechnology and artificial intelligence. AI in particular plays a crucial role in interpreting the vast and complex data generated by BCIs, enabling the development of more accurate and responsive systems, and is also key in speeding up research and lowering associated costs[6]. Several observers anticipate a **rapid growth in the global BCI market** in the coming years[7].

In the not-too-distant future, BCIs could change our lives as much as smartphones have in the past decade, if not more, given their direct connection to the human brain. This technology could impact nearly every aspect of our daily lives, which raises **crucial questions about its societal implications** and presents a wide **spectrum of policy challenges**. This paper aims to provide clarity on brain-computer interfaces and their potential consequences, with the specific goal of supporting informed decision-making on this set of technologies.

The first section clarifies what BCIs are, assesses their current state of development and identifies the main challenges that may hinder their full deployment in the short term, with a particular focus on technological and neurological limitations. The second section examines the present-day capabilities of BCIs, providing concrete examples to illustrate their practical applications, and explores their potential for future innovations across key sectors.

Given the vast potential BCIs represent, the third section analyses the main risks and threats associated with this neurotechnology, some of which are common to all groundbreaking innovations, while others are specific to the unique nature of BCIs. The conclusions highlight the importance of sustained attention and discussion regarding the evolution of BCIs. A proactive approach at EU level can promote preparedness and help shape a balanced governance framework, thus optimising the benefits of BCIs while mitigating their risks.

Understanding BCIs

Definition and mechanism

The term 'brain-computer interface' encompasses an array of neurotechnologies which enable direct communication between the brain and an external device. BCIs detect and interpret the brain's electrical signals and convert these neural impulses into computer-executable commands, enabling users to interact with computers or control devices purely through mental processes whilst bypassing the need for physical movement.

BCI systems employ various **methods to acquire brain signals**. These methods can be broadly classified as invasive, non-invasive[8] or partially invasive.

- **Invasive BCIs** involve surgical procedures to implant electrodes directly into the brain or on its surface. Although there are inherent risks and potential complications for the user associated with such systems, they offer high-resolution signal acquisition, which is critical for applications that require precise control.
- Conversely, **non-invasive BCIs** use external sensors, thereby eliminating the risks linked with surgery. These systems record brain activity using techniques such as electroencephalography (EEG). The trade-off is that non-invasive BCIs often have to contend with weaker signals and are more susceptible to noise and interference.
- Some innovative solutions feature **partially invasive BCIs**. These systems use implants that require minimal surgery or that make use of pre-existing medical technologies, such as stents and catheters, to insert electrodes in close proximity to the brain without the need for open surgery[9].

BCI signals can be divided according to the **directionality of the information flow**, reflecting how data is transmitted between the brain and the computer.

- **Unidirectional BCIs** typically operate from the brain to the computer, detecting and interpreting neural activity to execute commands or interact with external devices. BCIs can also work from the computer to the brain, delivering targeted electrical stimulation to the brain without concurrent signal detection.
- **Bidirectional BCIs** combine these functions, as they are simultaneously capable of recording neural activity and delivering targeted stimulation. This two-way communication enables a real-time and interactive exchange between the user and the computer.

Additionally, BCIs vary according to their **application**.

- At present, the majority of BCI systems are developed in clinical settings and used for **therapeutic treatments and rehabilitative support**. BCIs can offer remediation for lost or impaired functions, aiding individuals to regain abilities affected by injury or neurological conditions.

- However, applications of such technologies can include **cognitive or sensory enhancement**[10] which potentially augment the normal functions of healthy individuals and offer the user improved capabilities.

Whilst these categories give a better understanding of the potential uses of BCIs, it is important to recognise that this neurotechnology often defies strict classification due to its capacity to **blur traditional boundaries**.

Limitations and barriers

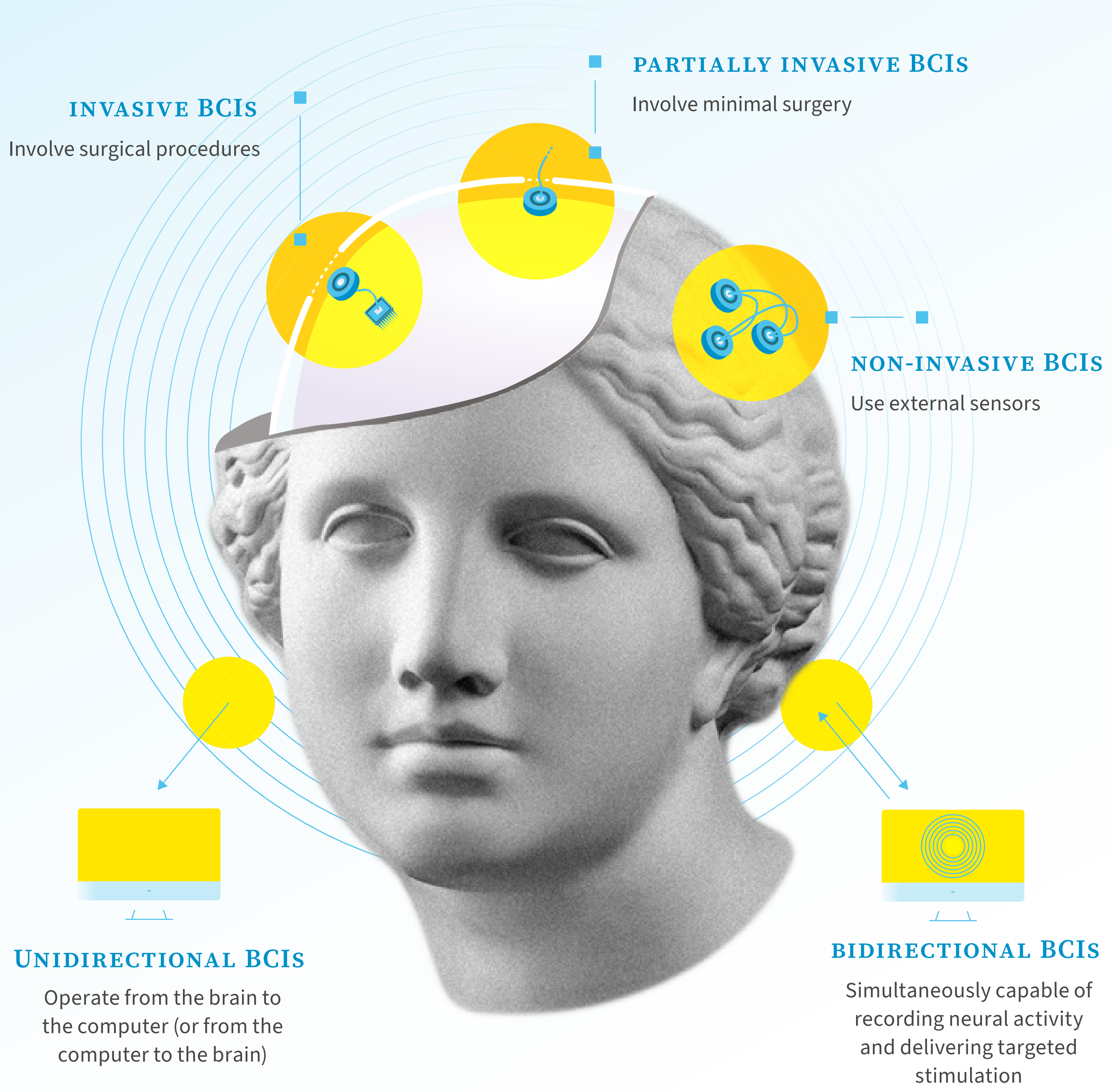
Despite significant advancements in recent years, brain-computer interface technologies are still subject to numerous limitations and barriers stemming from both **neurological and technological challenges**.

One of the foremost challenges is attaining a **comprehensive understanding of the human brain**'s intricate functions, a goal that may still take **decades**[11] to achieve. The brain's complexity is immense, with an estimated 86 billion neurons, each potentially forming thousands of synaptic connections with neighbouring cells[12]. The task of measuring, extracting, and interpreting the full spectrum of neural signals in real time – thus matching the speed of human thought – is formidable[13]. Adding to this challenge is the individual **variability of brain activity**, which affects the performance and reliability of BCIs. The way these signals are influenced by age, sex, lifestyle, underlying anatomy/pathology, and even moment-to-moment psychological states (e.g. attention, memory load, fatigue and emotional stress) remains largely unexplored. For example, some estimates suggest that 15-30% of individuals may not be able to produce brain signals that are robust enough to reliably operate a BCI[14]. The **need for highly personalised BCI designs** complicates the technology's widespread adoption in the near term.

From a technological point of view, a significant obstacle is the **acquisition of high-resolution signals** from the brain, a problem which is closely linked to the **invasiveness of the devices**. There are inherent medical risks associated with invasive BCIs, such as the potential for infection, the body's rejection of the implanted materials or an inflammatory response to these foreign objects[15]. However, it is worth noting that implantable devices, such as deep brain stimulation, have been used for at least 30 years and have provided a good understanding of the short and long-term safety of brain implants[16]. From a practical standpoint, BCIs must be cost-effective to produce and maintain, sufficiently practical to be used outside of specialised settings and durable enough to require minimal maintenance. Current BCIs often fall short in these areas. AI algorithms have significantly advanced the field by enhancing the ability to interpret the brain's extensive data output and by translating these neural patterns into coherent commands for external devices. However, current systems are still in the nascent stages when it comes to fully understanding the brain's complex and multifaceted functions[17]. Considerable **improvements in both the hardware** involved in signal acquisition **and the software** for signal processing **will be essential** to make BCIs more broadly accessible.

Despite the need for cautious short-term expectations, the landscape of BCI applications is diverse and expanding, with several uses currently existing or in development and many more anticipated in the longer term.

DEFINITION AND MECHANISM



Exploring the current capabilities and prospects of BCIs

The field of brain-computer interface technologies is rapidly evolving and boasts an expanding range of applications across various domains. While further research and experimentation are essential, BCIs are already showing the potential to transform virtually every aspect of society. There is a strong consensus amongst researchers and analysts about the considerable market potential of these technologies[18]. This section provides concrete examples of the **current capabilities of BCIs, as well as how they may be used in the future**. It starts with the healthcare sector, reflecting the initial focus on the health-related uses of BCIs, and subsequently delves into economic and social applications before finally examining the technology's possible role in security and defence.

Health and wellbeing

In recent years, BCIs have achieved **substantial breakthroughs in the medical sector**. Their integration with assistive devices has significantly improved the quality of life for individuals with motor impairment. For instance, BCIs have enabled individuals **to regain control of paralysed limbs**[19] and to **manipulate robotic prosthetics**[20], thereby restoring some degree of autonomy and interaction with their environment. Furthermore, BCIs have made it possible for those unable to physically interact with technology[21], including patients with locked-in syndrome[22], to operate a computer exclusively through mental commands. In other applications, BCIs have been responsible for successful **speech recovery** in stroke victims who had previously lost the ability to communicate[23]. There are also initial but encouraging advancements in the potential **restoration of vision** for the visually impaired[24].

These pioneering applications demonstrate the vast potential of BCIs in healthcare. At the same time, **research is progressing** in the use of BCIs for **managing neurological conditions** such as epilepsy[25], depression, and Alzheimer's and Parkinson's diseases[26]. These innovative approaches, which include the direct modulation of brain activity, could offer new therapeutic applications beyond the capabilities of pharmaceuticals or conventional surgeries (e.g. deep brain stimulation). Concurrently, researchers are developing a new generation of BCI **wireless medical neurotechnologies** capable of recording and monitoring neural activity to assist in the diagnosis and treatment of neurologic disease[27]. Advanced BCI systems may soon make it possible to recover more complex motor functions and provide richer sensory feedback for prosthetic users. Overall, these advancements could greatly contribute to a **more inclusive society** for individuals with disabilities.

Beyond their immediate medical applications, BCIs have the potential to enhance general well-being, especially in the areas of **mental health and meditation**. By providing immediate feedback on an individual's brainwave patterns during mindfulness practices, BCIs could guide users towards enhanced states of relaxation and concentration. Additionally, BCIs could be capable of modulating brain activity, which could help individuals to **tackle** mental and emotional challenges such as **anxiety, stress and attention difficulties**. Moreover, the reciprocal relationship between BCIs and mindfulness is garnering attention as recent studies suggest that mindfulness training can improve an individual's proficiency with BCI systems[28].

Economic and social implications

The promising results in the healthcare sector have paved the way for an **expansion of BCI applications into wider societal contexts**. While most BCI tools are still experimental, some have reached the consumer market[29], with prices ranging from a few hundred to several thousand euros, depending on how advanced they are. In the future, BCI innovations could significantly **transform our approaches to work, creativity, education, leisure** and **social interaction**.

In professional environments, one of the immediate impacts of BCIs could be the ability to closely **monitor brain activity**, thereby **enhancing performance** and productivity[30]. In this context, BCIs could enhance safety for high-risk tasks by warning workers when they are distracted or in danger. Additionally, these tools may enable hands-free access to information and precision control of machines, which could impact many sectors and industries[31]. BCIs have shown they can facilitate tasks such as sending emails, online shopping, communicating and controlling the settings of lighting, heating and other systems, all without requiring physical action[32]. Research into translating brain signals into spoken words at speeds comparable to natural speech is also progressing[33]. Such advancements could **change workplaces**[34] by enabling thought-driven typing and data tasks, bypassing the need for conventional input devices like keyboards, mouses or touchscreens. Consequently, BCIs have the potential to accelerate digital workflows, which could affect many office jobs. Furthermore, BCIs may give rise to **new collaborative tools** and platforms that render remote work more natural and immersive.

In the same vein, BCIs could significantly **change creative expression**, allowing individuals to generate art or music simply by thinking about it[35], thus opening up unprecedented avenues for personal creativity. In education, BCIs could **transform learning processes**. Tools currently available, such as smart glasses, provide instant feedback to help users concentrate[36]. Looking ahead, BCIs could facilitate direct learning interfaces, enabling the rapid assimilation of complex concepts and possibly even instant knowledge transfer, such as learning a new language. This technology could tailor educational experiences to individual learning styles, potentially making **education more efficient** and accessible.

The gaming industry is another sector that could be altered by this new set of technologies. **Gaming experiences** could become more interactive and engaging, allowing players to control a game using their thoughts and narrowing the gap between virtual and actual realities, offering new opportunities for the development of the Metaverse[37] in the process. This potential was illustrated in 2021 when a monkey played a video game using an implanted device[38]. This feat not only highlights the possible advancements in gaming interactivity, but also suggests that humans could eventually interpret and engage with animal cognitive processes and in doing so open the door to unprecedented forms of interspecies communication. Furthermore, in the marketing sector, BCIs have the potential to redefine consumer research by providing real-time insights into emotional and cognitive responses which could lead to a **deeper understanding of consumer behaviour**.

Security and defence

The emergence of brain-computer interfaces is set to have a transformative impact on security and defence. Although research and experimentation are still in their early stages, BCIs could eventually **revolutionise warfare**, for example by streamlining the operation of unmanned vehicles, such as drones[39], and enabling soldiers to manage weaponry remotely through neural commands. The US Defence Advanced Research Projects Agency (DARPA) is actively working to develop non-invasive or minimally invasive BCIs to control cyber defence systems or swarms of unmanned aerial vehicles[40].

On the battlefield, BCIs have the potential to **augment human capabilities**. By enhancing cognitive functions, this technology could improve soldiers' performance, accelerate decision-making and increase situational awareness, which are vital factors in the success of military operations. Additionally, BCIs might be applied to **manage physical and emotional states**, potentially reducing pain or regulating emotions such as fear during combat[41].

Military training stands to gain significantly from the integration of BCIs. These interfaces could be used to expedite and **enhance training simulations** and create realistic and immersive experiences[42]. Not only would these simulations be more engaging, but training could also be tailored to the individual, ensuring that each soldier achieves optimal preparedness. Such adaptive training environments could simulate high-stress scenarios and in doing so prepare soldiers for the psychological demands of actual combat situations.

When it comes to **security screening and detection**, the potential impact is immense. BCIs could offer a new dimension to monitoring systems, where operators could use neural inputs to control and interpret surveillance data with unprecedented speed and efficiency. Therefore, the ability to process complex data rapidly could improve the detection and **prediction of security threats**.

Looking further ahead

Beyond the abovementioned applications, the future of BCIs may hold even more profound potential that extends to the very core of human interaction. The prospect of decoding thoughts directly from neural patterns could pave the way for a form of **telepathy**, where individuals communicate through thought alone without the need for speech or written language[43].

Current research includes efforts to reconstruct dreams from brain signals, using AI and EEG data to generate images from the subconscious[44]. Further progress could open up possibilities that seem completely fantastical now, such as being able to digitally record all of a person's life experiences. A concept once hypothesised by Stephen Hawking, the **uploading of the human mind into a computer**, may be another possibility[45].

Brain-to-brain interfaces (BBIs) represent another frontier and hint at a future where one could potentially control or influence another's movements or decisions through direct neural connections[46]. Experiments have already demonstrated the potential for **cross-species connections**. In one case, a human was able to control the movement of a rat's tail with thought alone[47].

Though these futuristic applications remain largely within the realm of science fiction and are not on the immediate horizon, the continuous progression of BCI and BBI technologies could one day challenge this boundary. The notion that humans might need to merge with machines and become cyborgs to stay relevant in an era dominated by AI[48] might seem extreme now, however speculation of this nature highlights the importance of **considering the long-term trajectory** and implications **of BCI development**.

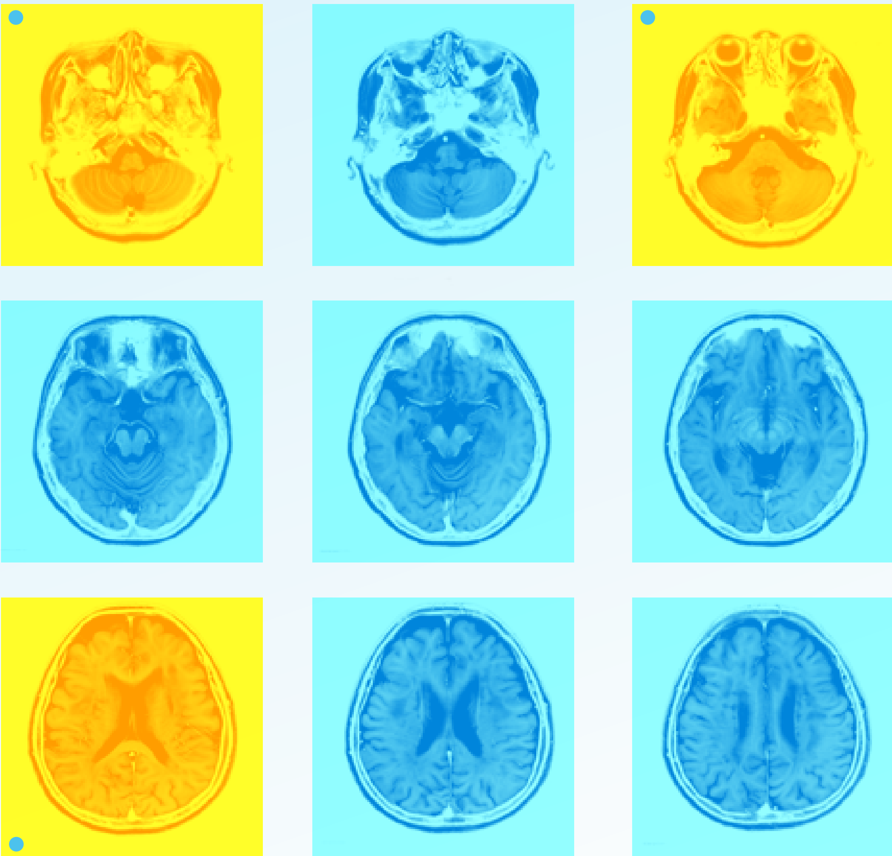
CURRENT CAPABILITIES AND PROSPECTS OF BCIs

ECONOMIC AND SOCIAL IMPLICATIONS

BCIs could significantly impact professional environments and social life by monitoring brain activity, enhancing performance and productivity, changing creative expression, transforming learning processes, and advancing sectors like the gaming industry.

HEALTH AND WELLBEING

BCIs have made substantial breakthroughs in the medical sector, particularly in assistive devices, and progress is also happening for neurological conditions and mental health.



SECURITY AND DEFENCE

BCIs could transform security and defense by revolutionising warfare. Still in early research stages, this technology may streamline the operation of unmanned vehicles like drones and enable soldiers to manage weaponry remotely through neural commands.

Navigating the global BCI ecosystem: developments in the EU, US and China

The development of BCIs has caught the **attention of major global powers**, each of which approaches the technology differently based on their cultural, economic and strategic priorities. However, delineating the precise position of each country in the BCI race is challenging at this stage given that progress in this area is the result of converging advancements in different fields. Currently, the US leads the competition, both in terms of private and public investments, while China is increasing its pace and creating the conditions for large-scale industrial development.

The **European Union** has taken a collaborative and ethical approach to BCI development with a strong emphasis on medical applications and improving the quality of life for individuals with disabilities. The EU has funded projects through programmes like Horizon 2020 and its successor, Horizon Europe, which aim to encourage research and innovation in a wide range of fields, including BCIs. As an example, the EU is providing support for the B-CRATOS project[49], which is coordinated by Uppsala University in Sweden and aims to enable brain-machine-body connectivity.

In the **United States**, BCI development is driven by both government agencies and private companies. Agencies such as DARPA[50] have invested in BCIs for military applications, which could also boost developments for civilians, for example in terms of less invasive technologies. DARPA is driving research to enhance soldiers' cognitive abilities and mitigate the human consequences of armed conflicts by developing solutions like prosthetic limbs or post-traumatic stress disorder therapies[51]. The National Institutes of Health and the National Science Foundation have supported medical research. Private companies like BlackRock, Kernel and Neuralink are pushing the boundaries of BCI technology with the aim of developing interfaces that could augment human cognitive abilities and treat neurological disorders. The US's substantial venture capital has led to a flourishing BCI startup ecosystem.

China has identified BCI technology as a strategic priority and is investing heavily in research and development[52]. The Chinese government's approach is part of a broader initiative to become a global leader in high technology, as outlined in its Made in China 2025 plan[53]. China's rapid advancements focus on neuro-prosthetics and cognitive enhancement technologies. Whilst most of the Chinese BCI ecosystem is based on non-invasive technologies, China is also speeding up research into invasive BCIs[54] to catch up with the US. As an example, in early 2023, the Chinese Institute for Brain Research initiated a programme which aims to break through key technologies in invasive BCI and achieve initial clinical applications in three to five years[55]. Chinese tech giants like Baidu and Tencent, along with academic institutions, have been ramping up their efforts, often with state support.

There are also **other significant players** in the BCI ecosystem who are using innovative methods. For instance, the Israeli startup InnerEye uses EEG technology to directly tap into the brain's visual processing, which facilitates swifter image recognition and has the potential to improve workplace efficiency[56]. In Australia, Synchron is using pre-existing medical technologies, such as stents and catheters, to access the brain with a less invasive approach[57].

Assessing the potential risks and threats posed by BCIs

Given the potential of BCIs to transform society, it is essential to critically assess the challenges that come with this cutting-edge technology. This section delves into a range of interconnected risks and threats associated with BCIs and considers how neurotechnology might affect core human rights. The analysis begins with **safety and health concerns** and addresses the possible immediate implications for users' well-being. It then examines broader societal issues, particularly those of **equality and accessibility**, related to the fair distribution and availability of BCIs to different sectors of a given population. Subsequently, it explores the risks related to **privacy and data security**, a matter of utmost importance given the highly personal nature of the information processed by BCIs. Finally, it offers a reflection on the implications for **individual autonomy and personal freedoms**.

Safety and health concerns

The most immediate risk posed by invasive BCIs is the potential health impact associated with their implantation. There are **inherent medical concerns** associated with the use of implanted devices, including infections and haemorrhages which could potentially damage brain tissue[58]. The body's immune response may also lead to the rejection of the implant, whilst post-surgical scar tissue formation could impair signal quality over time. Device malfunctions or failures present serious safety issues, which not only means that **maintenance** would be required, but also that considerations should be given to the long-term **durability** of implantable BCIs as well as their reversibility. Along the same lines, technological senescence is another problem, necessitating upgrades to the implanted systems as well as management of abandoned hardware inside the body.

Both invasive and non-invasive techniques may raise diverse health concerns relating to the **user's physical and psychological well-being**. Individuals may experience cognitive fatigue, skin irritation, headaches or eye strain from extended use. There is also a psychological dimension to consider as BCIs have the potential to influence emotions, personality and memory[59]. For example, the brain's natural mechanism to suppress traumatic memories could be compromised[60]. Currently, knowledge in this domain is very limited, as only 1% of BCI-related publications originate from the field of psychology[61]. **Electromagnetic interference** between BCIs and other medical devices poses additional risks, including the potential for heating brain tissue during magnetic resonance imaging[62], for example.

Current scientific evidence indicates that health risks associated with BCIs are relatively low[63]. Nevertheless, the **long-term effects on cognitive functions** and overall health are yet to be fully understood. Rigorous clinical trials and device surveillance are imperative to establish the safety and effectiveness of this neurotechnology. As one BCI expert put it, enhancing a car's engine might boost its performance, but it also risks compromising the vehicle's integrity[64].

Equality and accessibility

The emergence of BCIs raises profound ethical questions relating to fairness and social justice. The **line separating human enhancement from therapeutic intervention is often ambiguous**, while the definition of what is considered 'normal' in terms of human capabilities is a matter of continuous debate[65]. Several current initiatives, including those led by DARPA[66], clearly aim to enhance cognitive functions, which illustrates the potential of BCIs to transcend traditional limits. With the advancement of research and applications, and given the high cost of sophisticated BCIs, a **new digital divide might emerge** where only a privileged few can afford the benefits of this technology.

Over time, societies could become divided between individuals who have undergone neuro-enhancements and those who have not[67]. Such a divide could **exacerbate existing socioeconomic inequalities** and in doing so leave marginalised groups even further behind. In this context, it is important to underline that equitable access to BCIs is closely tied to the infrastructure needed to support their use. Regions and countries with limited healthcare facilities, lower levels of technological infrastructure and fewer specialised medical professionals may struggle to implement and maintain BCIs.

Beyond the financial and infrastructural barriers, there are also significant ethical and policy considerations regarding who can access these technologies and for what purposes. The **allocation of resources** for BCI development and distribution **needs to be guided by social equality principles**, ensuring that vulnerable populations, such as individuals with disabilities or chronic illnesses, are prioritised. However, without deliberate and inclusive policies they might be overlooked in favour of more profitable applications of the technology.

Privacy and data security

As BCI technologies advance, the **once-impenetrable fortress of the mind** could be **breached**. This development carries profound implications for personal privacy and the security of the extensive data collected by BCIs[68]. By directly interfacing with the brain, this technology may capture and process an array of highly sensitive information, ranging from thoughts and emotions to preferences and intentions.

The intimate nature of the data gathered by BCIs demands **stringent privacy protections** and **ethical considerations**. These include the right to delete brain data upon request to ensure individuals maintain control over their cognitive privacy. Furthermore, safeguards may be needed to prevent the accumulation and monopolisation of brain data by a limited number of private companies[69], which could potentially exploit this information for political or commercial gain, such as targeted advertising[70].

Concurrently, the storage and transmission of neural information pose significant challenges in terms of data security. Any **data is vulnerable** to unauthorised access[71]. BCIs rely on complex systems of sensors, processors and wireless communication protocols to capture and transmit neural signals, thus exposing them to external actors. Such vulnerabilities could lead to the interception, manipulation or theft of data, which could potentially result in identity theft, blackmail or other forms of **exploitation and manipulation**. This could include combining neural data with other personal information to build increasingly detailed user profiles for exploitative uses.

Moreover, as BCIs increasingly interface with external devices and networks, issues related to **data ownership and intellectual property rights** are further amplified[72]. When individuals use neurotechnology to interact with computers, smartphones and other connected devices, sensitive information could be inadvertently shared with third-party service providers or data brokers. This underscores the importance of clarifying who owns this data, how consent is obtained and managed, the purposes for which the data can be collected and used, the conditions under which it can be shared and the security measures in place to prevent unauthorised use and protect privacy rights[73].

Autonomy and freedom

BCIs are poised to profoundly impact individual autonomy, self-determination and personal freedoms[74]. These technologies hold the potential to enhance cognitive abilities and thus broaden an individual's capacity for informed decision-making. Nonetheless, there is a risk that certain types of BCIs could be employed to **manipulate or influence decisions, undermining** the very essence of **free will**[75].

If used on a large scale, BCIs could have considerable **implications for democracy**. Democratic systems operate on the principle that citizens have the autonomy to form opinions and make choices free from manipulation. The use of neurotechnology adds a new dimension to the already intricate landscape of media influence and propaganda. BCIs could jeopardise the integrity of personal opinion formation and independent decision-making. Political actors and interest groups might exploit this technology to alter perceptions, thereby **swaying public opinion and affecting electoral outcomes**.

Furthermore, BCIs could enable an **unprecedented level of surveillance**, thus allowing totalitarian regimes to access and monitor mental states of individuals and groups. This could facilitate the **identification of dissent** and simplify efforts to suppress it and consolidate power[76]. With possible advances in brain-to-brain interfaces, the very essence of human individuality could be at risk, as some people might be reduced to instruments in the hands of others[77].

These possible developments also raise the **issues of responsibility and accountability**. In the event of unethical or illegal actions, identifying who is responsible would become controversial. For example, some patients who have undergone deep brain stimulation have experienced behavioural changes, including increased recklessness and impulsivity[78]. The use of BCIs could alter a user's mental state to the extent that they are no longer the same person they were prior to using the technology. As a result, it would be challenging to determine who should be held accountable for certain actions, along with the ensuing legal ramifications[79].

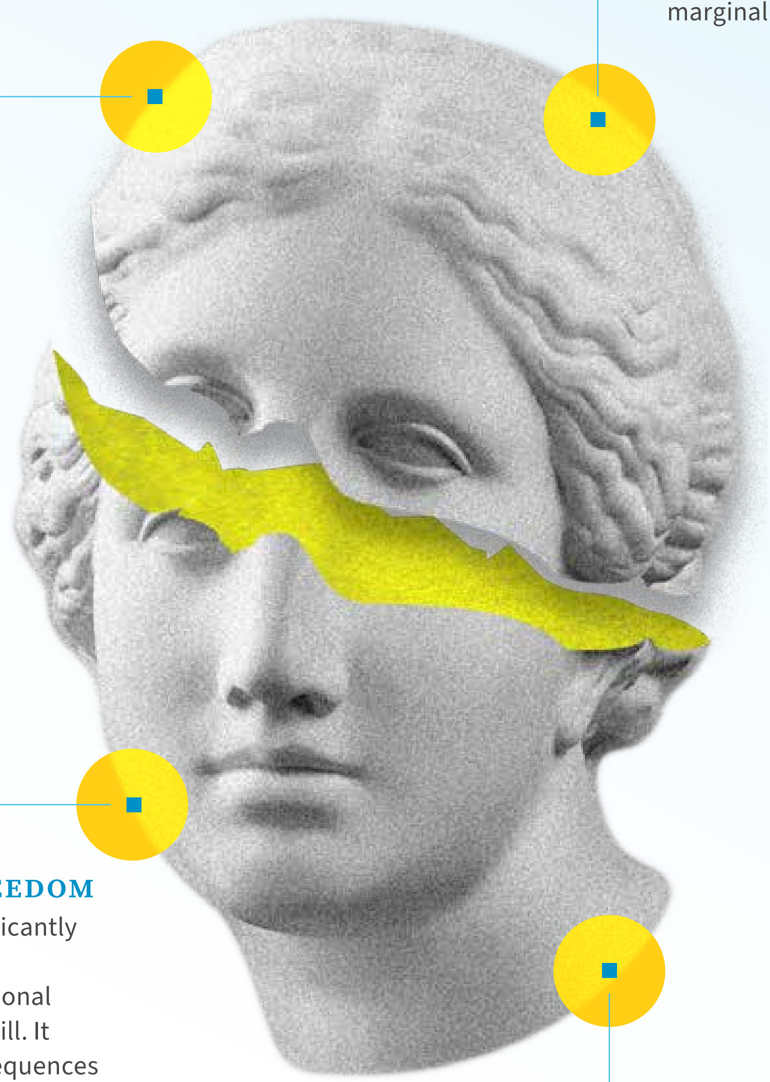
ASSESSING THE POTENTIAL RISKS AND THREATS POSED BY BCIs

SAFETY AND HEALTH CONCERNS

Health risks could include infections, hemorrhages, and brain tissue damage and could affect users' physical and psychological well-being.

EQUALITY AND ACCESSIBILITY

Ethical questions arise about fairness and social justice, potentially widening socioeconomic inequalities and marginalising certain groups.



AUTONOMY AND FREEDOM

This technology could significantly affect individual autonomy, self-determination and personal freedom, threatening free will. It could also have major consequences for democracy.

PRIVACY AND DATA SECURITY

Personal privacy could be threatened by the capturing of sensitive data like thoughts and emotions as well as misuse by private companies.

Early stages of competition between tech giants on BCIs?

The development of BCIs represents a **new frontier of technological competition for tech giants** and a potentially considerable new market. Major tech companies such as Apple, Meta, Microsoft and Neuralink are channelling investments into BCIs to gain the edge in this burgeoning domain, each with their own strategy and focus areas.

With a history of creating user-centric devices, **Apple**'s investment in BCIs could lead to more intuitive ways of interacting with technology[80]. The tech giant is well placed to explore BCI technologies as part of its broader health and augmented reality efforts. The potential integration of BCIs into everyday products, such as AirPods[81], could transform personal audio devices into advanced neural interfaces. The application of BCIs in devices like the Apple Watch may also enhance their accessibility and integration into daily activities. This holds significant promise, especially for health and fitness tracking, as well as for augmented reality experiences.

Meta's acquisition of CTRL-Labs[82] and investment in non-invasive BCIs highlight its interest in integrating the human brain with computing for augmented reality and virtual reality applications. The deal is estimated to be worth somewhere between USD 500 million and USD 1 billion, which represents the most substantial acquisition Meta has made in the last five years. Their work leans towards creating interfaces that can interpret neural signals without the need for surgical implants, which could have widespread consumer applications in their social media and virtual platform products. Meta is also testing an AI system capable of decoding the unfolding of visual representations in the brain using non-invasive methods[83]. Meta also worked on the development of non-invasive BCIs designed to decode neural signals to enable users to type by simply imagining speech, but this project was later abandoned[84].

Microsoft is focusing on non-invasive BCIs to enhance productivity. By researching how BCIs can help people with disabilities, the company aims to expand the ways in which individuals can interact with computers and the digital world. This technology could potentially integrate with existing products, such as HoloLens, which already support interaction through hand gestures, voice commands and even eye tracking.

Neuralink is working on cutting-edge invasive BCI technology. Its approach is currently primarily aimed at medical applications, such as helping individuals with paralysis or neurological disorders regain certain functions. However, its long-term vision extends to cognitive enhancement and undoubtedly many other applications.

Development and commercialisation of BCI technologies **in the US** benefit from **significant investment and a risk-taking culture**, particularly in Silicon Valley. In contrast, the European ecosystem relies on strong academic and research institutions with more limited resources. For instance, Onward, a company founded by one of the leading European centres for neurotech, the École Polytechnique Fédérale de Lausanne, has raised just over EUR 170 million since its foundation in 2014, while Neuralink has secured USD 687 million, surpassing most competitors[85].

Preparing for the advent of BCIs

Brain-computer interfaces' transition from science fiction to tangible reality marks a pivotal moment in the interaction between humans and technology. Once confined to imagination, BCIs now stand at the forefront of innovation and have the potential to profoundly transform society in the not-too-distant future. The **question** is not whether BCIs will become mainstream, but rather when they will do so, and more importantly, **how they will be integrated into everyday life**. To ensure beneficial integration, policymakers need to adopt a proactive stance in **shaping robust governance frameworks** for neurotechnology[86]. Failing to do so now will make it more challenging later, as the market and major tech companies may take matters into their own hands, potentially amplifying risks for society.

Fostering continuous and well-informed dialogues on neurotechnology is essential to **heighten awareness** and **enhance public understanding** of both the potential benefits and challenges presented by BCIs. Various initiatives reflect this growing attention. The **OECD**'s Recommendation on Responsible Innovation in Neurotechnology sets the first international standard, guiding governments and innovators to anticipate and address ethical, legal and social challenges while fostering innovation[87]. **UNESCO** is working on a global framework for the ethics of neurotechnology and aims to submit it for adoption by the end of 2025[88]. Similarly, under the **Spanish Presidency** of the EU, the first European declaration to protect digital rights in the development of neurotechnology was adopted in León in October 2023[89]. **France** has introduced a charter for the responsible development of neurotechnology, with plans to expand this initiative across the EU[90].

Within the European Union, existing legislation already addresses several aspects pertinent to BCI development and application, including regulations on medical device safety[91], data protection, artificial intelligence and cybersecurity. Future efforts may focus on identifying and **closing potential loopholes that could lead to unethical use** or insufficient protection of individuals' rights and freedoms[92]. Globally, several actors are taking steps in this regard. In 2021, Chile became the first country to amend its constitution to safeguard citizens' brain data and privacy[93]. In April 2024, Colorado was the first US state to pass a law protecting data derived from brainwaves[94].

As these initiatives progress, it will be important to **maintain a delicate balance** that does not impede innovation and investment, particularly in light of the remarkable success BCIs have demonstrated in the medical field. To **guide the development of BCIs** it is therefore necessary to establish robust ethical standards, foster a regulatory environment that promotes both safety and innovation and ensure there is effective collaboration between public and private stakeholders. Such an approach would help **maximise the benefits of BCIs while minimising the risks**, ultimately contributing to societal well-being and progress.

References

1 C. Marquez-Chin et al., 'Brain–Computer Interfaces', *Synthesis*, 2021.

2 T. Shepherd, 'Brain chips: the Sydney researchers 'miles ahead' of Elon Musk's Neuralink', *The Guardian*, 16 March 2024.

3 'Elon Musk's Neuralink shows brain-chip patient playing online chess', *The Guardian*, 21 March 2024.

4 S. Saha, 'Progress in Brain Computer Interface: Challenges and Opportunities', *Frontiers*, February 2021.

5 B. Maiseli et al., 'Brain–computer interface: trend, challenges, and threats', *Brain Informatics*, August 2023.

6 U. Asgher, 'Advances in artificial intelligence (AI) in brain computer interface (BCI) and Industry 4.0 for human machine interaction', *Frontiers*, 5 December 2023. See also X. Zhang et al., 'The combination of brain-computer interfaces and artificial intelligence: applications and challenges', *Annals of Translational Medicine*, June 2020.

7 J. Rafferty, 'Brain Computer Interfaces: A New Existential Risk Factor', *Journal of Futures Studies*, 2021. See also 'Brain Computer Interface Market - Research Report 2023-2031', 'Brain-Computer Interfaces: Global Markets', 'Brain Computer Interface Market Size, Share & Trends Analysis Report'.

8 B. Maiseli et al., op. cit.

9 T. Shepherd, op. cit.

10 L. V. Garcia and D. E. Winickoff, 'Brain-computer interfaces and the governance system', *OECD*, 12 April 2022, p. 12.

11 M. Vahle, 'Opportunities and implications of brain- computer interface technology', *Air Command and Staff College*, July 2020.

12 C. Caruso, 'A New Field of Neuroscience Aims to Map Connections in the Brain', *Harvard Medical School*, 19 January 2023.

13 S. Perkowitz, 'Plug me in: the physics of brain–computer interfaces', *Physics World*, 17 October 2023.

14 S. Saha et al., op. cit.

15 M. Vahle, op. cit.

16 O. Jitkritsadakul, 'Systematic review of hardware-related complications of Deep Brain Stimulation: do new indications pose an increased risk?', Brain Stimulation, September-October 2017.

17 B. Marr, 'AI's Next Frontier: Are Brain-Computer Interfaces The Future Of Communication?', *Forbes*, 11 August 2023.

18 J. Rafferty, op. cit.

19 T. Freeman, 'Brain–spine interface enables natural walking after spinal cord injury', *Physics World*, 1 June 2023.

20 M. Asghar, 'Online correction improves robotic arm control', *Physics World*, 9 January 2018.

21 T. Shepherd, op. cit. See also A. Puniani, 'Novel decoder helps people with paralysis click-and-drag a computer cursor using just their thoughts', *Physics World*, 8 October 2021.

22 The locked-in syndrome is a condition where a patient is conscious but unable to move or speak due to paralysis of nearly all voluntary muscles. S. Rezvani, 'A review on the performance of brain-computer interface systems used for patients with locked-in and completely locked-in syndrome', *Cognitive Neurodynamics*, 19 August 2023.

23 'High-performance brain implants restore communication to those who cannot speak', *Physics World*, 20 September 2023.

24 'Brain implant enables blind woman to see simple shapes', *Physics World*, 3 December 2021.

25 Treating epilepsy with physics, *Physics World*, 10 September 2019.

26 B. Stecher, 'Interview With Neuromodulation Expert Dr. Alfonso Fasano', *Journal of Parkinson's Disease*, 13 December 2017.

27 BrainGate research program, *Carney Institute for Brain Science*.

28 J. Stieger, 'Mindfulness Improves Brain–Computer Interface Performance by Increasing Control Over Neural Activity in the Alpha Band', *Cerebral Cortex*, January 2021.

29 L. V. Garcia and D. E. Winickoff, op. cit., p. 12.

30 'Ready for Brain Transparency?', *Presentation* at the Annual meeting of the World Economic Forum, Davos 2023.

31 S. Saha et al., op. cit., p. 11.

32 N.J. Hill and J.R. Wolpaw, 'Brain-Computer Interface', *Reference Module in Biomedical Sciences*, 2016. See also T. Shepherd, op. cit.

33 'The year of brain–computer interfaces', *Nature Electronics*, 25 September 2023

34 A. Gonfalonieri, 'What Brain-Computer Interfaces Could Mean for the Future of Work', *Harvard Business Review*, 9 October 2020.

35 B. Marr, op. cit.

36 'Smart Glasses Focus Attention with NASA Neurofeedback Technology', *NASA*, 22 October 2020.

37 'Metaverse – Virtual world, real challenges', *ART research paper*, Council of the European Union.

38 J. Wakefield, 'Elon Musk's Neuralink 'shows monkey playing Pong with mind', *BBC*, 9 April 2021.

39 'Brain-Computer Interfaces Are Coming. Will We Be Ready?', *RAND*, 27 August 2020.

40 A. Willis, 'Next-Generation Nonsurgical Neurotechnology', *DARPA*. See also 'Researchers look to Rice University for nonsurgical brain interfaces to control weapons and computers', *Military & Aerospace Electronics*, 12 November 2020.

41 'Brain-Computer Interfaces Are Coming. Will We Be Ready?', *RAND*, 27 August 2020.

42 M. Vahle, op. cit., p. 1 and 15.

43 A. Krausova, 'Legal Aspects of Brain-Computer Interfaces', *Masaryk University Journal of Law and Technology*, January 2014.

44 T. Shepherd, op. cit.

45 N. Collins, 'Hawking: 'in the future brains could be separated from the body', *The Telegraph*, 20 September 2013.

46 G. Gage, 'How to control someone else's arm with your brain', *TED*, April 2015.

47 Seung-Schik Yoo et al., 'Non-invasive brain-to-brain interface (BBI): establishing functional links between two brains', *Plos One*, April 2013.

48 O. Solon, 'Elon Musk says humans must become cyborgs to stay relevant. Is he right?', *The Guardian*, 15 February 2017.

49 'Wireless Brain-Connect inteRfAce TO machineS: B-CRATOS', *European Commission*.

50 'Six Paths to the Nonsurgical Future of Brain-Machine Interfaces', *DARPA*.

51 'How DARPA drives Brain Machine Interface Research', *From the Interface*, November 2020.

52 E. Mullin, 'China Has a Controversial Plan for Brain-Computer Interfaces', *Wired*, 30 April 2024.

53 M. J. Zenglein and Anna Holzmann, *Evolving Made in China 2025*, Merics, July 2019.

54 Cheng Yu, 'BCI - the next frontier for high-tech business', *China Daily*, 17 July 2023.

55 Gu Yekai and Yang Yanfan, 'China accelerates efforts to develop brain-computer interface technology', *People's Daily*, 15 April 2024.

56 E. Ackerman and E. Strickland, 'Are You Ready for Workplace Brain Scanning?', *IEEE Spectrum*, 19 November 2022.

57 T. Shepherd, op. cit.

58 B. Maiseli et al., op. cit., p. 9. See also 'How Neuralink keeps dead monkey photos secret', *Wired*, 4 October 2023.

59 S. Saha et al., op. cit., p. 11.

60 B. Marr, op. cit.

61 B. Maiseli et al., op. cit., p. 10.

62 M. Akhavan, 'Possible risks in using brain-computer interfaces', *Open MIT*, June 2023.

63 Ibid.

64 M. T. Bell, 'How Will Brain-Computer Interfaces Change Your life?', *Medium*, 27 April 2018.

65 L. V. Garcia and D. E. Winickoff, op. cit., p. 17

66 A. Willis, op. cit.

67 Xiao-yu Sun and Bin Ye, 'The functional differentiation of brain–computer interfaces (BCIs) and its ethical implications', *Humanities and Social Sciences Communications*, 27 November 2023, p. 4.

68 A. Krausova, op. cit., p. 205.

69 León Declaration on European neurotechnology: a human focused and rights' oriented approach, *Spanish Presidency of the Council of the EU*, 24 October 2023.

70 J. Greenberg, 'Brain-computer interfaces: privacy and ethical considerations for the connected mind', *Future of Privacy Forum*, 21 September 2021.

71 B. Maiseli et al., op. cit., p. 9.

72 L. V. Garcia and D. E. Winickoff, op. cit., p. 17.

73 Xiao-yu Sun and Bin Ye, op. cit., p. 5.

74 O. Friedrich, 'An Analysis of the Impact of Brain-Computer Interfaces on Autonomy', *Neuroethics*, 18 April 2018.

75 L. V. Garcia and D. E. Winickoff, op. cit., p. 16.

76 J. Rafferty, op. cit.

77 A. Krausova, op. cit., p. 206.

78 M. Fumagalli and A. Priori, 'Functional and clinical neuroanatomy of morality', *Brain*, July 2012.

79 B. Maiseli et al., op. cit., p. 9. See also Xiao-yu Sun and Bin Ye, op. cit., p. 5.

80 S. Boamah and M. Mills, 'Meta, Apple are investing in tech that can decode your thoughts', *Yahoo Finance*, 13 May 2024.

81 'Apple Invents a next-generation AirPods Sensor System that could measure Biosignals and Electrical Activity of a user's Brain', *Patently Apple*, 20 July 2023.

82 N. Statt, 'Facebook acquires neural interface startup CTRL-Labs for its mind-reading wristband', *The Verge*, 24 September 2019.

83 'Toward a real-time decoding of images from brain activity', *Meta*, 18 October 2023.

84 R. Schwarzlose, 'Why we should worry about Big Tech's investment in a new brain technology', *Los Angeles Times*, 12 September 2021.

85 O. Cookson and R. Waters, 'The transformative potential of computerised brain implants', *FT*, 3 June 2024.

86 L. V. Garcia and D. E. Winickoff, op. cit., p. 24-34.

87 OECD Recommendation on Responsible Innovation in Neurotechnology, *OECD*, 11 December 2019.

88 'The Ethics of Neurotechnology: UNESCO appoints international expert group to prepare a new global standard', *UNESCO*, 22 April 2024.

89 León Declaration on European neurotechnology: a human focused and rights' oriented approach, *Spanish Presidency of the Council of the EU*, 24 October 2023.

90 Charte de développement responsable des neurotechnologies, *Ministère de l'Enseignement supérieur et de la Recherche*, 17 November 2022.

91 E. Steindl, 'Consumer neuro devices within EU product safety law: Are we prepared for big tech ante portas?', *Computer Law & Security Review*, April 2024.

92 A. Krausova, op. cit., p. 207.

93 'Histórica aprobación: información cerebral estará protegida en la Constitución', *Republica de Chile – Senado*, 22 September 2021. See also A. McCay, 'Neurorights: the Chilean constitutional change', *AI and Society*, 2 March 2022.

94 B. Brooks, 'First law protecting consumers' brainwaves signed by Colorado governor', *Reuters*, 18 April 2024.

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