Governing augmentative brain–computer interfaces



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Introduction

Brain-computer interfaces (BCIs) can measure brain activity, translate it into useful outputs, and in some cases modify that activity through targeted stimulation.[1] Invasive or non-invasive, they create a direct, real-time link between the brain and external devices.[2]

Policy discussions have highlighted the potential for BCIs to augment human physical, cognitive, affective, and moral capacities beyond the human range of what might be considered typical or average, raising ethical, social and legal challenges of a different order.[3,4,56] Despite their marketing claims, no commercially available BCI has yet demonstrated robust augmentation beyond normal human capabilities under real-world conditions, but technology leaps and visible pathways to augmentation make it timely to consider how such applications might emerge and what governance they would require.[7]

This report provides tools to help policymakers identify signals of BCI-enabled augmentation. We develop a structured characterisation of augmentation and use it to examine the ethical questions it raises and their governance implications. We identify the technical features that may enable augmentation and the signals that could help policymakers detect or anticipate it. Finally, we draw on other scientific domains to assess how well existing regulatory frameworks can address augmentation, using hypothetical scenarios to test their strengths and limitations.

The report draws on a narrative review of the ethics, governance and technical literature on BCIs and human augmentation, and on interviews with technical and legal experts.[8] A project workshop tested and refined a classification framework distinguishing augmentation from treatment, rehabilitation and optimisation; a subsequent validation workshop with policy experts refined the framework further, ensuring it is usable by a non-technical audience.

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[1] BCI Society, 'BCI Definition' (BCI Society 2024) https://bcisociety.org/bci-definition/ (accessed 18 July 2026).

[2] Saez, I, 'The Emerging Field of Cognitive Brain–Computer Interfaces' (2026) *Trends in Cognitive Sciences*, advance online publication https://doi.org/10.1016/j.tics.2026.06.012.

[3] UNESCO, *Recommendation on the Ethics of Neurotechnology* (UNESCO 2026) https://unesdoc.unesco.org/ark:/48223/pf0000394866 (accessed 31 July 2026).

[4] International Bioethics Committee, *Ethical Issues of Neurotechnology* (UNESCO 2022) https://doi.org/10.54678/QNKB6229.

[5] Garden, H et al., 'Responsible Innovation in Neurotechnology Enterprises' (OECD Science, Technology and Industry Working Papers No 2019/5, OECD Publishing 2019).

[6] Zuberi, S et al., *European Charter for the Responsible Development of Neurotechnologies* (European Brain Council 2025) https://www.braincouncil.eu/european-charter-for-the-responsible-development-of-neurotechnologies/ (accessed 31 July 2026).

[7] Enhancement and augmentation are often used synonymously in the policy, bioethics and technical literature, which addresses both questions of 'enhancement' and 'augmentation'. In this report we use augmentation to capture both the 'enhancement' of existing capabilities and 'extension' of capabilities, as discussed further below.

[8] A narrative review was deemed appropriate given the range of disciplines and academic and grey literature covered by the report, synthesising multiple perspectives. A list of included literature, along with details on interviews can be found in Annex 1.

Mechanics of Brain-Computer Interfaces

Neurons produce patterns of electrical activity that underlie perception, movement, memory, and cognition. This activity generates measurable electrical and magnetic signals and changes local blood flow. A BCI measures those signals and translates them into commands for external machines, or modifies them to alter brain function.

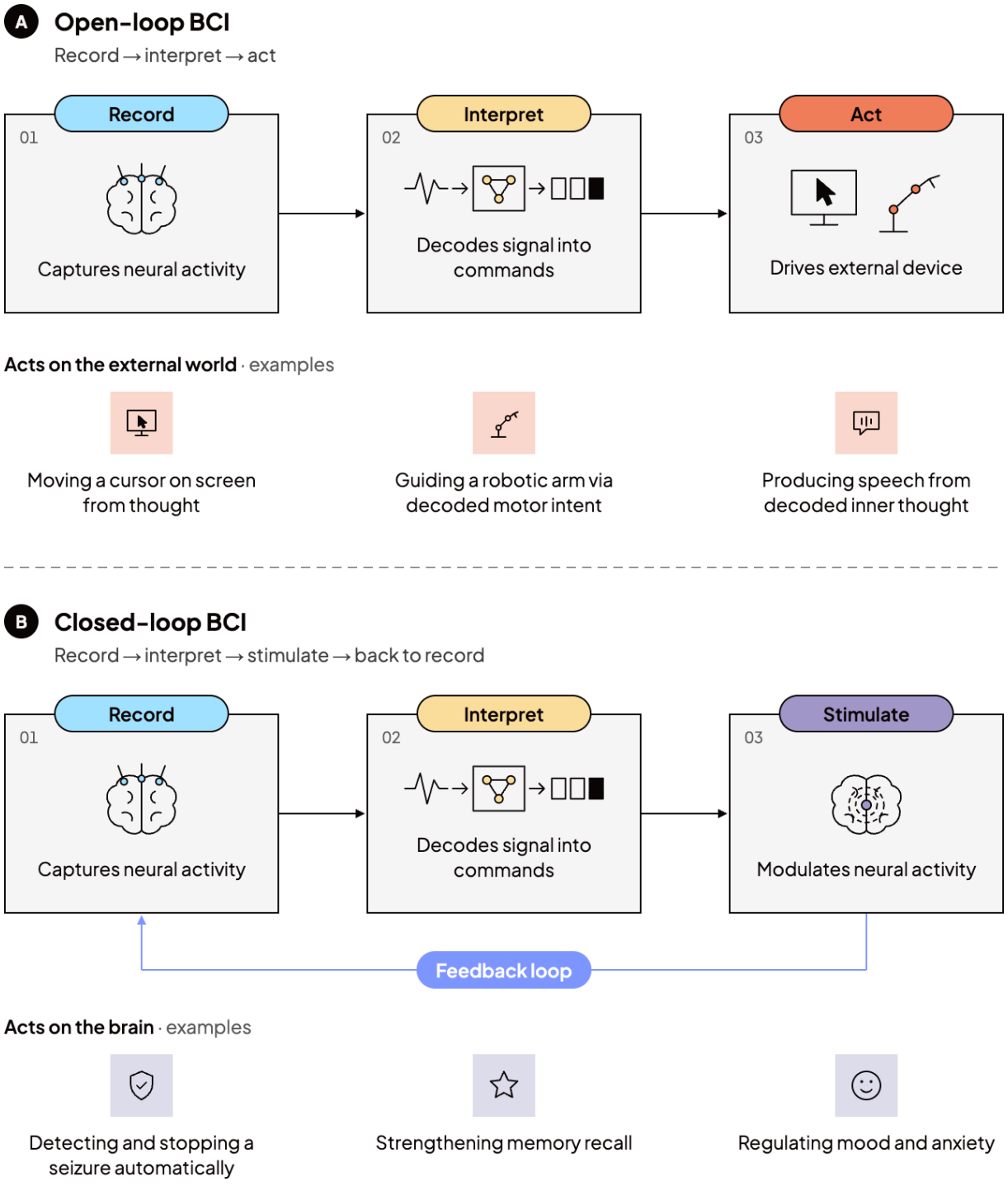


Figure 1. Open-loop BCIs extend a user's ability to interact with external systems without altering neural activity itself. Closed-loop systems act directly on neural activity.

BCIs that read and translate neural activity are called open-loop BCIs (Figure 1A). They enable, in their most advanced form, the control of devices such as robotic limbs or computer cursors using mental commands,[9,10] speech decoding,[11] or adaptations of technology to the user's mental state.[12] Other BCIs deliver energy, such as electrical currents, to influence brain activity and, in doing so, affect cognition, behaviour, or perception. BCIs that also deliver stimulation back to the brain in response to recorded activity are referred to as closed-loop (Figure 1B).

Most BCI development to date has focused on medical applications, for instance for speech decoding,[13,14] motor control,[15] sensory addition,[16] memory modulation,[17] or human–machine integration.[18] Clinical research has expanded rapidly, with the number of trials more than doubling in recent years and early regulatory approvals beginning to emerge.[19,20]

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[9] Ding, Y et al., 'EEG-Based Brain-Computer Interface Enables Real-Time Robotic Hand Control at Individual Finger Level' (2025) 16 *Nature Communications* 5401 https://doi.org/10.1038/s41467-025-61064-x.

[10] Card, NS et al., 'Long-Term Independent Use of an Intracortical Brain–Computer Interface for Speech and Cursor Control' (2026) 32 *Nature Medicine* 2504 https://doi.org/10.1038/s41591-026-04414-6.

[11] Jude, JJ et al., 'Decoding Intended Speech with an Intracortical Brain-Computer Interface in a Person with Long-Standing Anarthria and Locked-In Syndrome' (2026) 45(4) Cell Reports 117162 https://doi.org/10.1016/j.celrep.2026.117162.

[12] Zander, TO et al., 'Neuroadaptive Technology Enables Implicit Cursor Control Based on Medial Prefrontal Cortex Activity' (2016) 113(52) Proceedings of the National Academy of Sciences of the United States of America 14898 https://doi.org/10.1073/pnas.1605155114.

[13] Kunz, EM et al., 'Inner Speech in Motor Cortex and Implications for Speech Neuroprostheses' (2025) 188(17) *Cell* 4658 https://doi.org/10.1016/j.cell.2025.06.015.

[14] Lévy, J et al., 'Noninvasive Decoding of Typed Sentences from Human Brain Activity' (2026) *Nature Neuroscience* https://doi.org/10.1038/s41593-026-02303-2.

[15] Hochberg, LR et al., 'Reach and Grasp by People with Tetraplegia Using a Neurally Controlled Robotic Arm' (2012) 485(7398) *Nature* 372 https://doi.org/10.1038/nature11076.

[16] Flesher, SN et al., 'A Brain-Computer Interface that Evokes Tactile Sensations Improves Robotic Arm Control' (2021) 372(6544) *Science* 831 https://doi.org/10.1126/science.abd0380.

[17] Ezzyat, Y et al., 'Closed-Loop Stimulation of Temporal Cortex Rescues Functional Networks and Improves Memory' (2018) 9(1) *Nature Communications* 365 https://doi.org/10.1038/s41467-017-02753-0.

[18] Zander, TO and Kothe, C, 'Towards Passive Brain–Computer Interfaces: Applying Brain–Computer Interface Technology to Human–Machine Systems in General' (2011) 8(2) *Journal of Neural Engineering* 025005 https://doi.org/10.1088/1741-2560/8/2/025005.

[19] Hamzelou, J, 'Brain-Computer Interface Trials Are Taking Off' *MIT Technology Review* (19 June 2026) https://www.technologyreview.com/2026/06/19/1139270/brain-computer-interface-trials-are-taking-off/ (accessed 31 July 2026).

[20] Fieldhouse, R and You, X, 'China Approves Brain Chip to Treat Paralysis — A World First' (2026) 651 *Nature* 865 https://doi.org/10.1038/d41586-026-00849-6.

The most visible expansion is in the consumer market, with consumer neurotechnology companies now outnumbering medical ones.[21] EEG sensors and non-invasive stimulation are now built into headbands, earbuds, glasses and wristbands. These products are marketed for wellbeing, relaxation, focus, gaming and entertainment with some systems letting users control virtual environments directly or tailoring experiences in real time to inferred cognitive or emotional states.[22] Most companies position their products as wellness tools rather than treatments, though many sit close to that boundary - a framing that has regulatory consequences.[23]

A parallel set of applications is emerging in settings where the user is typically not the purchaser. In the workplace, organisations are trialling BCIs to monitor fatigue and support concentration in safety-critical environments such as aviation and mining.[24] In defence, brain-machine interfaces could enable personnel to control multiple assets simultaneously, improve learning and cognitive performance through transcranial stimulation, and offset performance decline caused by fatigue or stress.[25,26] These institutional contexts introduce questions about consent, employer–employee power dynamics and acceptable thresholds of intervention.[27]

Two enablers are accelerating uptake across both consumer and institutional domains. First, less-invasive hardware is lowering the physical and psychological barriers to adoption.[28,29,30] Second, advances in AI, particularly in signal processing and adaptive algorithms, are improving the precision and usability of BCI systems, widening the range of viable applications and potential concerns.

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[21] Bernáez Timón, L and Mahieu, V, *Neurotech Consumer Market Atlas* (Centre for Future Generations 2025) https://cfg.eu/neurotech-market-atlas/ (accessed 31 July 2026).

[22] Information Commissioner's Office, *ICO Tech Futures: Neurotechnology* (Information Commissioner's Office 2023) https://ico.org.uk/media2/about-the-ico/research-and-reports/ico-tech-futures-neurotechnology-0-1.pdf (accessed 31 July 2026).

[23] Bernáez Timón, L and Mahieu, V, 'Introducing "Neurotech between Wellness and Medicine"' (Centre for Future Generations 24 March 2026) https://cfg.eu/introducing-neurotech-between-wellness-and-medicine/ (accessed 31 July 2026).

[24] Wenco, 'Wearable Technology for Effective Fatigue Management' (Wenco 2026) https://www.wencomine.com/our-solutions/safety (accessed 31 July 2026).

[25] Science and Technology Organization, *Neuroenhancement in Military Personnel: Conceptual and Methodological Promises and Challenges* (NATO n.d.) https://www.sto.nato.int/document/neuroenhancement-in-military-personnel-conceptual-and-methodological-promises-and-challenges-report/ (accessed 27 July 2026).

[26] Binnendijk, A et al., *Brain-Computer Interfaces: U.S. Military Applications and Implications, An Initial Assessment* (RAND Corporation 2020) https://www.rand.org/pubs/research_reports/RR2996.html (accessed 31 July 2026).

[27] UNESCO; Between-Science-Fact-and-Science-Fiction-Innovation-and-Ethics-in-Neurotechnology.pdf

[28] Cox, SS et al., 'A Comprehensive Review of Low-Intensity Focused Ultrasound Parameters and Applications in Neurologic and Psychiatric Disorders' (2025) 28(1) *Neuromodulation* 1 https://doi.org/10.1016/j.neurom.2024.07.008.

[29] Meta AI, 'TRIBE v2' (Meta AI 2026) https://aidemos.atmeta.com/tribev2 (accessed 19 July 2026).

[30] Edelman, BJ et al., 'Non-Invasive Brain-Computer Interfaces: State of the Art and Trends' (2025) 18 *IEEE Reviews in Biomedical Engineering* 26 https://doi.org/10.1109/RBME.2024.3449790.

As these applications move beyond healthcare, questions arise about how BCIs should be governed and specifically about their use for augmentation.[31] Addressing these questions, however, first requires understanding what distinguishes augmentation from other uses of technology, and second, identifying what governance and regulatory requirements follow from that distinction.[32,33]

Defining augmentation

We define human augmentation technologies as those that **aim at improving human beings beyond what might otherwise be considered typical or average**. A useful starting point is to distinguish therapeutic improvement, which restores or sustains health, from augmentation, which seeks to improve functioning beyond what is required for health or ordinary functional recovery.[34,35] Such definitions of augmentation can be difficult to apply in practice and become ambiguous in real-world settings where applications may lie on a spectrum between therapy and augmentation.[36,37,38] As a result, many guidelines and codes of practice avoid offering a formal definition of augmentation.[39] However, the difficulty of drawing this boundary does not remove the need to attempt to do so,[40] not least because the lack of clear definition makes augmentation difficult to identify as an object of governance.

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[31] Goering, S et al., 'Recommendations for Responsible Development and Application of Neurotechnologies' (2021) 14(3) *Neuroethics* 365 https://doi.org/10.1007/s12152-021-09468-6.

[32] Bostrom, N and Roache, R, 'Ethical Issues in Human Enhancement' in Ryberg, J (ed.), *New Waves in Applied Ethics* (Palgrave Macmillan 2007).

[33] Erden, YJ and Brey, PAE, 'Ethics Guidelines for Human Enhancement R&D' (2022) 378 *Science* 835 https://doi.org/10.1126/science.add9079.

[34] Moseley, D and Juengst, E, 'Human Enhancement' in Zalta, EN and Nodelman, U (eds), *The Stanford Encyclopedia of Philosophy* (Winter 2025 edn, Stanford University 2025) https://plato.stanford.edu/archives/win2025/entries/enhancement/ (accessed 31 July 2026).

[35] National Academies of Sciences, Engineering, and Medicine, 'Enhancement' in *Human Genome Editing: Science, Ethics, and Governance* (National Academies Press 2017) https://www.ncbi.nlm.nih.gov/books/NBK447264/ (accessed 31 July 2026).

[36] Jensen, SR, *SIENNA D3.4: Ethical Analysis of Human Enhancement Technologies* (Version V1.1, Zenodo 2020) https://doi.org/10.5281/zenodo.4068071.

[37] Moseley, D and Juengst, E, 'Human Enhancement' in Zalta, EN and Nodelman, U (eds), *The Stanford Encyclopedia of Philosophy* (Winter 2025 edn, Stanford University 2025) https://plato.stanford.edu/archives/win2025/entries/enhancement/ (accessed 31 July 2026).

[38] Agid, Y et al., *The Use of Biomedical Techniques for "Neuroenhancement" in Healthy Individuals: Ethical Issues* (Comité Consultatif d'Ethique 2024).

[39] Tambornino, L and Lanzerath, D, *SIENNA D3.3: Survey of REC Approaches and Codes for Human Enhancement* (Version V3.0, Zenodo 2019) https://doi.org/10.5281/zenodo.4066874.

[40] García, L and Winickoff, D, 'Brain-Computer Interfaces and the Governance System: Upstream Approaches' (OECD Science, Technology and Industry Working Papers No 2022/01, OECD Publishing 2022) https://doi.org/10.1787/18d86753-en.

A boundary can be drawn in different ways.[41] A professional-domain approach asks whether an intervention falls within accepted healthcare practice; a normal-function approach asks whether it restores functioning to an individual or population baseline; and a disease-based approach asks whether it responds to a diagnosable condition.[42] These approaches help explain why BCI uses may move between treatment and augmentation depending on purpose, user and context.

In this report, we consider BCI applications as falling along **a continuum from treatment and restoration, through assistance and optimisation, to augmentation**.[43,44] At one end are technologies designed to restore or compensate for functions lost because of neurological disease, injury or congenital conditions. At the other end of the spectrum are applications designed to supplement or improve the performance of people who do not have a medical condition. Instead of treating illness or restoring lost function, these applications aim to improve or expand human capabilities, either temporarily or permanently and "make us better than well".[45]

This spectrum is summarised in **Table 1**. The distinction is best treated as a practical governance tool rather than a fixed conceptual boundary: it helps identify when additional scrutiny may be needed, even if cases at the margins remain contestable. Whether a BCI is used for augmentation has important implications for how it should be governed. The rest of this section examines whether, and how, augmentation can be distinguished from other uses in a way that is useful for policy and regulation.

[41] Juengst, ET et al., 'Preventive Human Genome Editing and Enhancement: Candidate Criteria for Governance' (2024) 54(5) *Hastings Center Report* 14 https://doi.org/10.1002/hast.4913.

[42] Moseley, D and Juengst, E, 'Human Enhancement' in Zalta, EN and Nodelman, U (eds), *The Stanford Encyclopedia of Philosophy* (Winter 2025 edn, Stanford University 2025) https://plato.stanford.edu/archives/win2025/entries/enhancement/ (accessed 31 July 2026).

[43] Wolpaw, JR et al., 'Brain-Computer Interfaces: Definitions and Principles' (2020) 168 *Handbook of Clinical Neurology* 15 https://doi.org/10.1016/B978-0-444-63934-9.00002-0.

[44] Gordon, EC and Seth, AK, 'Ethical Considerations for the Use of Brain-Computer Interfaces for Cognitive Enhancement' (2024) 22(10) *PLOS Biology* e3002899 https://doi.org/10.1371/journal.pbio.3002899.

[45] Gordon, EC and Seth, AK, 'Ethical Considerations for the Use of Brain-Computer Interfaces for Cognitive Enhancement' (2024) 22(10) *PLOS Biology* e3002899 https://doi.org/10.1371/journal.pbio.3002899.

Table 1. The augmentation continuum

Goal	Repair	Treat	Assist	Optimise	Augment
Description	Replacing or restoring a lost or missing function	Remediating reduced or impaired function	Supporting functioning or task performance	Improving to the limit of an individual's own capabilities	Enhancing human capabilities beyond the individual's own range or beyond normal population norms
Target	Restoration of individual's prior functional baseline	Achievement of population-level norms of health or functioning	Sufficient functioning relative to situational or task-specific demands (e.g. workplace)	Realising an individual's latent capacity, bringing performance up to the maximum they could achieve through their intrinsic capabilities	Functioning that exceeds intrinsic individual capabilities or population norms or introduces novel traits
Examples	Control of a robotic limb after spinal cord injury (e.g. Bitbrain); visual prosthetic BCIs partially restoring sight (PRIMA BCI).	DBS; post-stroke rehabilitation (e.g. g.tec's recoveriX); neurofeedback for epilepsy, depression, dementia (OpenBCI headware)	Attention state detection (e.g. Emotiv headsets); non-invasive BCIs enabling use of connected devices (e.g. g.tec's Mindbeagle)	BCIs marketed to improve attention/ memory (e.g. EMOTIV EEG headphones; NeuroSky); workplace neurofeedback (e.g. Neurable's MW75 Neuro LT)	BCIs enabling brain-to-brain communication or pooling of signals; BCIs conferring new sensory modalities (e.g. infrared perception)

Distinguishing forms of augmentation

The continuum is the first step in distinguishing augmentation from, for example, assistance. However, different forms of augmentation may change human capabilities in different ways and with different consequences for governance.[46]

One way to think about augmentation is to ask **what improvement is measured against**. A person's capabilities can be enhanced relative to their own baseline or relative to what most

[46] Brunyé, TT et al., 'A Review of US Army Research Contributing to Cognitive Enhancement in Military Contexts' (2020) 4 *Journal of Cognitive Enhancement* 453 https://doi.org/10.1007/s41465-020-00167-3.

people can achieve (see Figure 2).[47,48] This distinction affects both the size of the advantage gained and the equity questions that follow.[49]

Personal-referent or **weak enhancement** (Augmentation type 1, A1) improves an individual's capabilities relative to their own starting point, but not necessarily beyond the normal human range.[50] A person with a naturally poor memory, for instance, might improve substantially while still having a worse memory than someone who is naturally gifted.[51] This kind of enhancement can be transformative for individuals but does not create abilities unavailable to others. It may be difficult to distinguish from optimisation.

Population-referent or **"strong" enhancement** (A2) pushes performance beyond what any non-augmented person can achieve. From a governance perspective, this raises additional questions about fairness, social impacts and whether technology could redefine the limits of human performance.

It is important to note, however, that norms vary between populations and can change over time. Second, identifying A1 augmentation requires comparison with a hypothetical alternative. For example, if someone's memory improves, we would need to understand how much improvement they might have achieved through more conventional means such as better sleep, education or diet. Similarly determining whether a capability falls outside the normal human range requires baseline data that often does not exist and may vary across populations.[52] Nevertheless, identifying the degree to which a technology moves someone beyond existing human baselines provides a practical way of thinking about different forms of augmentation. This could be valuable in consumer protection settings, for example when assessing product claims that appear to promise enhanced human capabilities.

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[47] Presidential Commission for the Study of Bioethical Issues, *Gray Matters: Topics at the Intersection of Neuroscience, Ethics, and Society, Volume 2* (Presidential Commission for the Study of Bioethical Issues 2015).

[48] International Bioethics Committee, *Ethical Issues of Neurotechnology* (UNESCO 2022) https://doi.org/10.54678/QNKB6229.

[49] Gyngell, C and Selgelid, MJ, 'Human Enhancement: Conceptual Clarity and Moral Significance' in Clarke, S et al. (eds), *The Ethics of Human Enhancement: Understanding the Debate* (Oxford University Press 2016) 111 https://academic.oup.com/book/7172/chapter/151766538 (accessed 31 July 2026).

[50] This definition parallels what has been described as the 'prevalence principle' in human gene editing (HGE), whereby editing to give someone the most prevalent variant would allow editing to 'become ordinary' to relieve disease''; Evans, J. H. (2021) 'Setting Ethical Limits on Human Gene Editing after the Fall of the Somatic/Germline Barrier'. Proceedings of the National Academy of Sciences 118, no. 22: e2004837117. https://doi.org/10.1073/pnas.2004837117.

[51] Bostrom, N and Sandberg, A, 'Cognitive Enhancement: Methods, Ethics, Regulatory Challenges' (2009) 15(3) *Science and Engineering Ethics* 311 https://doi.org/10.1007/s11948-009-9142-5.

[52] There may be some settings, such as education, in which detailed baseline performance data is available to assess how the application of augmentative technologies relates to population distributions.

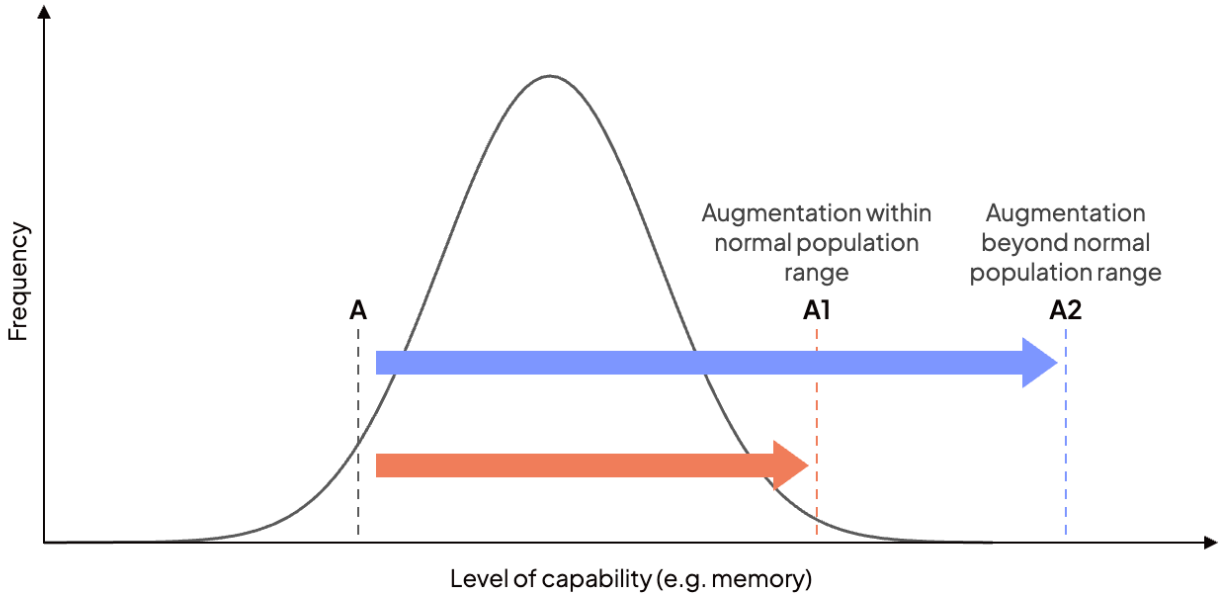


Figure 2. The red arrow represents A1: augmentation within the population distribution, from a lower position to a higher one. The blue arrow represents A2: augmentation beyond the population distribution entirely.

A second way to distinguish between forms of augmentation is by looking at the **type of capability** affected. Unlike the forms of augmentation described above, these forms of augmentation involve adding **new capabilities** rather than improving existing ones (augmentation type B). They cannot be placed on a population distribution because **there is no existing human baseline** against which to measure them.

Together, these distinctions provide a practical framework for identifying how different augmentation applications may raise different concerns and why a proportionate approach to governance is needed. **Table 2** summarises these different types of augmentation and situates them within the spectrum introduced above.

Table 2. An adapted continuum of BCI uses describing forms of augmentation by reference frame and capability type.

Repair	Treat	Assist	Optimise	Augment	
	A1		A2		B
	Personal-referent enhancement		**Population-referent enhancement**		**Extrinsic capability extension**
Definition	Enhancement of a natural capability beyond the individual's own unaided ceiling, while remaining within the range achievable by other non-augmented humans.		Enhancement of a natural capability beyond the range achievable by any non-augmented human		A novel capability that no non-augmented human possesses
Reference frame	The individual's own unaided maximum		The population distribution		None: no human baseline exists
Example	Someone with poor natural memory achieving recall better than they could reach unaided, but not beyond what good natural memorisers achieve		Memory recall exceeding any documented human capacity		A BCI conferring infrared perception or direct brain-to-brain communication

A continuum, not a pathway

The continuum of goals and outcomes presented in Table 2 is potentially valuable in thinking about acceptability of different forms of augmentation. As discussed, however, it can be challenging to situate a given BCI application at a particular point on the spectrum. Applications may start with multiple use cases, or these may change over time. Moreover, technologies do not necessarily move in a straight line from treatment and restoration, through assistance and optimisation, to augmentation.

Figure 3 illustrates these non-linear trajectories using the example of a robotic limb control system. This system might begin as a treatment that restores lost motor function. It could later be used as an assistive tool for people with limited mobility and, eventually, provide strength or dexterity beyond the normal human range. Equally, it might 'leapfrog', moving directly from treatment to augmentation without intermediate uses. The example highlights how the same underlying BCI can serve different purposes over time, moving between treatment, assistance, optimisation and augmentation as its users, goals and context change.

This matters for governance. Oversight needs to track technologies as they move between uses, rather than treating their original classification as permanent. This requires attention to the technical, scientific and commercial developments that may signal a new augmentation use

before it becomes widely used. The next section looks at the signals that may help identify when BCI technologies are beginning to move towards augmentation.

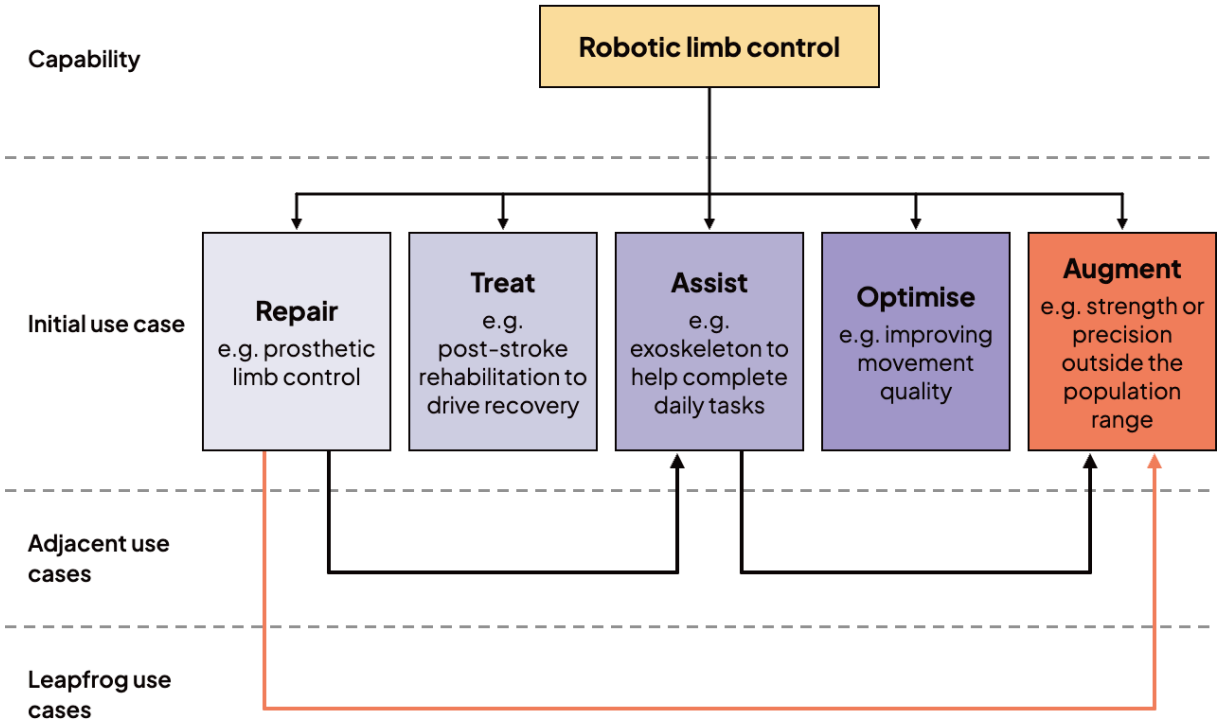


Figure 3: Representations of augmentation pathways, showing BCIs that have initial use cases across the spectrum, some of which may then lead sequentially or directly to uses for augmentation.

The current and future augmentation potential of BCIs

In interviews, experts agreed that no augmentative BCI systems are currently available, at least to a stage in which they are safely, reliably, and reproducibly deployed in humans. However, proof-of-concept demonstrations indicate that BCIs may not be far from augmentative effects.

Table 3 surveys recent research relevant to augmentation by domain. However, a variety of technological features shape the capabilities, limitations, and potential applications of a BCI.[53] These include invasiveness, the physical principle (or modalities) employed for recording or stimulating, spatial and temporal resolution, brain coverage, and depth of brain access. They are described in **Figure 4**. These dimensions provide a common framework against which to assess the technical potential for augmentation. We review established recording and stimulation technologies using this framework in **Annex 2 (Tables S1 and S2)**, highlighting trade-offs between invasiveness, signal quality, precision, coverage, and accessibility, with no single approach optimising all dimensions.

Invasive technologies that combine multiple physical principles, high resolution, wide brain coverage, and the ability to reach deep brain structures have the greatest potential for augmentation because they can record from and influence neural activity with greater specificity, breadth, and effectiveness. However, non-invasive technologies could support augmentation under appropriate conditions and may continue to expand their capabilities. For example, the combination of magnetoencephalography (MEG) and electroencephalography (EEG) for non-invasive speech decoding shows how improvements in signal processing and multimodal integration can enhance the performance of non-invasive BCIs.[54]

Emerging technologies, meanwhile, aim to overcome the trade-offs associated with existing technologies, potentially enabling safer,more capable, and more accessible forms of brain augmentation in the future. They seek to achieve high-fidelity recording and stimulation while reducing or eliminating invasiveness, and hence, the need for neurosurgery. To date, however, they carry substantial challenges regarding delivery, control, long-term durability, and safety. Examples include:

- Neural dust, which consists of millimetre- or submillimetre-scale implantable sensors distributed throughout neural tissue and powered and interrogated through ultrasonic backscatter. [55] It eliminates wired connections and implanted batteries.

[53] Luan, L et al., 'Recent Advances in Electrical Neural Interface Engineering: Minimal Invasiveness, Longevity and Scalability' (2020) 108(2) *Neuron* 302 https://doi.org/10.1016/j.neuron.2020.10.011.

[54] Lévy, J et al., 'Noninvasive Decoding of Typed Sentences from Human Brain Activity' (2026) *Nature Neuroscience* https://doi.org/10.1038/s41593-026-02303-2.

[55] Neely, RM et al., 'Recent Advances in Neural Dust: Towards a Neural Interface Platform' (2018) 50 *Current Opinion in Neurobiology* 64 https://doi.org/10.1016/j.conb.2017.12.010.

- Nanoparticle-based BCIs replace implanted hardware with injectable particles capable of crossing the blood-brain barrier. These particles could transduce externally applied magnetic fields, ultrasound, or light into local neural stimulation.[56, 57]
- Injectable electronics, such as syringe-delivered mesh electrodes, aim to minimise tissue damage while preserving the recording quality of implanted electrodes.[58]
- Endovascular BCIs, such as Synchron's Stentrode, are delivered through the cerebral vasculature rather than by open-brain surgery, allowing neural recording without craniotomy and improving safety.[59] However, they can only interface with neural tissue adjacent to accessible blood vessels.

Even for novel and emerging technologies, experts agreed that **individual technologies, whatever their particular features, neither lead to augmentation nor necessarily preclude it**. For example, even though invasiveness may offer the possibility to finely control the neural circuits associated with complex cognitive functions, non-invasive technologies could also be augmentative when the target function relies on neural activity that is macroscopic, stereotypical, and reliably captured at the scalp level, such as sleep or motor decoding. Augmentation potential, therefore, emerges from **how recording and stimulation components are assembled in systems for a specific use rather than individual technical capability**.

Experts suggested that the first augmentative effects of BCIs will most likely occur in applications related to motor control of external devices, motor extension, and more broadly, in ways of interacting with external devices that depend on motor intent decoding from the motor cortex. Motor augmentation will likely be followed by speech decoding using non-invasive technologies, which was seen as relatively feasible in the short-term. In the medium to long term, experts noted that sensory extensions (e.g. perceiving infra-red, expanding the spectrum of detectable odours) could be the first augmentative applications of invasive devices introducing completely new capabilities.

[56] Liu, Y et al., 'Nanomaterial-Based Microelectrode Arrays for In Vitro Bidirectional Brain–Computer Interfaces: A Review' (2023) 9(1) *Microsystems & Nanoengineering* 13 https://doi.org/10.1038/s41378-022-00479-8.

[57] Zhang, E et al., 'Magnetoelectric Nanoparticle-Based Wireless Brain–Computer Interface: Underlying Physics and Projected Technology Pathway' (2026) *Advanced Science* e24329 https://doi.org/10.1002/advs.202524329.

[58] MIT Media Lab, 'Autonomous and Surgery-Free Brain-Computer Interface (BCI)' (MIT Media Lab 2025) https://www.media.mit.edu/projects/autonomous-and-surgery-free-brain-computer-interface-bci/overview/ (accessed 31 July 2026).

[59] Mitchell, P et al., 'Assessment of Safety of a Fully Implanted Endovascular Brain-Computer Interface for Severe Paralysis in 4 Patients: The Stentrode Withwith Thought-Controlled Digital Switch (SWITCH) Study' (2023) 80(3) *JAMA Neurology* 270 https://doi.org/10.1001/jamaneurol.2022.4847.

Table 3. Examples of augmentation-relevant capabilities enabled by brain-computer interfaces. These examples are intended to illustrate the current state of the field and potential trajectories for BCI development rather than provide a comprehensive review. They should not be interpreted as evidence of generalisable, scalable, or deployment-ready technology.

Domain	Examples	Augmentation relevance	Translation signal
Speech and communication	• ECoG neuroprosthesis decoding attempted speech (78 words/min) with avatar animation and personalised synthesised voice.[60] • Intracortical recordings decode imagined (inner) speech directly from the motor cortex without attempted vocalisation.[61] • Brain activity recorded using MEG was used to decode typed sentences without implanted electrodes.[62]	Examples demonstrate that neural activity can be translated into language, enabling communication with people, computers or AI without speaking. Progression from attempted speech to imagined speech, and advances in non-invasive decoding, suggest that increasingly forms of neural communication may become feasible without motor commands or implanted devices.	Neuralink's VOICE clinical trial and Paradromics' Connect-One Early Feasibility Study are evaluating implanted BCIs for speech restoration in people with severe speech impairment. Their progression into clinical trials provides an important market signal that speech BCIs are moving beyond proof-of-concept towards translation and commercial development.

[60] Metzger, SL et al., 'A High-Performance Neuroprosthesis for Speech Decoding and Avatar Control' (2023) 620(7976) *Nature* 1037 https://doi.org/10.1038/s41586-023-06443-4.

[61] Kunz, EM et al., 'Inner Speech in Motor Cortex and Implications for Speech Neuroprostheses' (2025) 188(17) *Cell* 4658 https://doi.org/10.1016/j.cell.2025.06.015.

[62] Lévy, J et al., 'Noninvasive Decoding of Typed Sentences from Human Brain Activity' (2026) *Nature Neuroscience* https://doi.org/10.1038/s41593-026-02303-2.

Domain	Examples	Augmentation relevance	Translation signal
Motor extension	• Training with a robotic third thumb induced cortical incorporation of a supernumerary limb without disrupting existing hand representations. [63] • Intracortical BCIs have enabled people with paralysis to control robotic arms with multiple degrees of freedom and interact with computers through neural decoding. [64] • China's regulator approved Neuracle's minimally invasive brain implant, which pairs with a robotic glove to help people with spinal cord injuries grasp objects. It is the world's first commercial approval of an implanted BCI. [65]	Shows that the adult brain can both incorporate the representation of additional effectors and control external devices through neural activity, providing the biological and technological foundations for motor augmentation. Together, these studies suggest that future BCIs could enable intuitive control of supernumerary robotic limbs, exoskeletons or other external devices beyond the natural body.	Clinical translation of motor BCIs to restore lost function is accelerating. Synchron is conducting the COMMAND [66] and INTENT [67] trials, while Blackrock Neurotech, CorTec, INBRAIN Neuroelectronics, and Neuralink are also evaluating implanted neurotechnologies in humans. These studies indicate increasing technological maturity and commercial interest in motor BCIs.

[63] Kieliba, P et al., 'Robotic Hand Augmentation Drives Changes in Neural Body Representation' (2021) *Science Robotics* https://doi.org/10.1126/scirobotics.abd7935.

[64] Nuyujukian, P et al., 'Cortical Control of a Tablet Computer by People with Paralysis' (2018) PLOS ONE https://doi.org/10.1371/journal.pone.0204566.

[65] Fieldhouse, R and You, X, 'China Approves Brain Chip to Treat Paralysis — A World First' (2026) 651 Nature 865 https://doi.org/10.1038/d41586-026-00849-6.

[66] He, Q et al., 'The Brain Nebula: Minimally Invasive Brain–Computer Interface by Endovascular Neural Recording and Stimulation' (2024) *Journal of Neurointerventional Surgery* https://doi.org/10.1136/jnis-2023-021296.

[67] Synchron, Inc., 'INdependence Through Endovascular Neuroprosthetic Technology (INTENT): An Early Feasibility Study' (NCT07543367, ClinicalTrials.gov 2026) https://clinicaltrials.gov/study/NCT07543367.

Domain	Examples	Augmentation relevance	Translation signal
Sensory addition	• Rats learned to use infrared information delivered to the somatosensory cortex through intracortical stimulation. [68] • Intracortical microstimulation in humans has restored artificial touch sensations that improve prosthetic control and object discrimination. [69,70] • Dynamic electrical stimulation of the visual cortex generated coherent visual forms that could be recognised by both sighted and blind participants. [71]	Demonstrates that the brain can interpret artificial sensory signals and integrate new streams of information, supporting the possibility of adding novel sensory capabilities beyond natural human perception. Extension to infrared, ultraviolet or magnetic-field perception remains speculative but is mechanistically coherent.	Artificial sensory stimulation is progressing towards restorative applications. If these approaches prove safe and effective, they would establish that targeted cortical stimulation can reliably generate meaningful artificial percepts in humans, providing an important translational pathway towards future sensory augmentation. The Orion visual cortical prosthesis , [72] for example, is being evaluated in an early feasibility study.
Memory and learning	• tDCS has improved attention, motor skill acquisition, and numerical competence across multiple sessions in healthy individuals. [73] • Optogenetic manipulation of hippocampal memory engrams demonstrated that specific memories are encoded in identifiable neuronal populations that can be selectively reactivated, suppressed or associated with new experiences. [74]	Demonstrates that memory processes can be influenced through neuromodulation. Human studies suggest that adaptive stimulation can modestly improve memory performance, while animal studies show that specific memories can be reactivated, suppressed or artificially associated with new experiences. Although highly speculative in humans, these findings establish a mechanistic basis for future forms of memory augmentation or modification.	Clinical studies are increasingly investigating adaptive neuromodulation for memory disorders, but no technology has yet demonstrated reliable, generalisable memory augmentation in healthy individuals. Translation of optogenetic approaches to the human brain remains unlikely in the near term because they require genetic modification of neurons.

[68] Thomson, EE et al., 'Perceiving Invisible Light through a Somatosensory Cortical Prosthesis' (2013) Nature Communications https://doi.org/10.1038/ncomms2497.

[69] Flesher, SN et al., 'A Brain-Computer Interface that Evokes Tactile Sensations Improves Robotic Arm Control' (2021) 372(6544) *Science* 831 https://doi.org/10.1126/science.abd0380.

[70] Chandrasekaran, S et al., 'A Neuroprosthesis for Restoring Hand Movement and Sensation in a Person with Complete Tetraplegia' (2026) Nature Medicine https://doi.org/10.1038/s41591-026-04498-0.

[71] Beauchamp, MS et al., 'Dynamic Stimulation of Visual Cortex Produces Form Vision in Sighted and Blind Humans' (2020) *Cell* https://doi.org/10.1016/j.cell.2020.04.033.

[72] Second Sight Medical Products, 'Early Feasibility Study of the Orion Visual Cortical Prosthesis System' (NCT03344848, UCLA Clinical Trials 2025) https://ucla.clinicaltrials.researcherprofiles.org/trial/NCT03344848.

[73] Qi, S et al., 'Effects of Transcranial Direct Current Stimulation on Motor Skills Learning in Healthy Adults through the Activation of Different Brain Regions: A Systematic Review' (2022) *Frontiers in Human Neuroscience* https://doi.org/10.3389/fnhum.2022.1021375.

[74] Liu, X et al., 'Optogenetic Stimulation of a Hippocampal Engram Activates Fear Memory Recall' (2012) *Nature* https://doi.org/10.1038/nature11028.

Domain	Examples	Augmentation relevance	Translation signal
Neuroadaptive systems (human-machine teaming)	• Closed-loop BCIs have used EEG and other physiological signals to detect cognitive states such as workload, fatigue, attention and error recognition, allowing systems to adapt task allocation or interface behaviour in real time. • Neuroadaptive systems combining EEG with large language models have demonstrated that AI assistants can adjust their responses according to a user's cognitive engagement and uncertainty in real time. [75]	Demonstrates that augmentation does not necessarily require directly modifying brain activity. Instead, neural signals can be used to continuously infer cognitive states such as attention, workload, fatigue or uncertainty, allowing AI systems and other technologies to adapt their behaviour in real time. This creates a form of augmentation in which performance emerges from the interaction between the user and an adaptive machine.	Neuroadaptive technologies are being actively developed for aviation, transportation, defence and industrial operations, where monitoring cognitive states such as workload, fatigue and uncertainty could improve safety and human performance. Advances in AI, particularly large language models capable of adapting their behaviour in response to neural signals, provide an additional translation pathway by integrating BCIs into widely used digital systems without requiring invasive neural interfaces.

[75] Baradari, D et al., 'NeuroChat: A Neuroadaptive AI Chatbot for Customizing Learning Experiences' (arXiv 2025) https://doi.org/10.48550/arXiv.2503.07599.

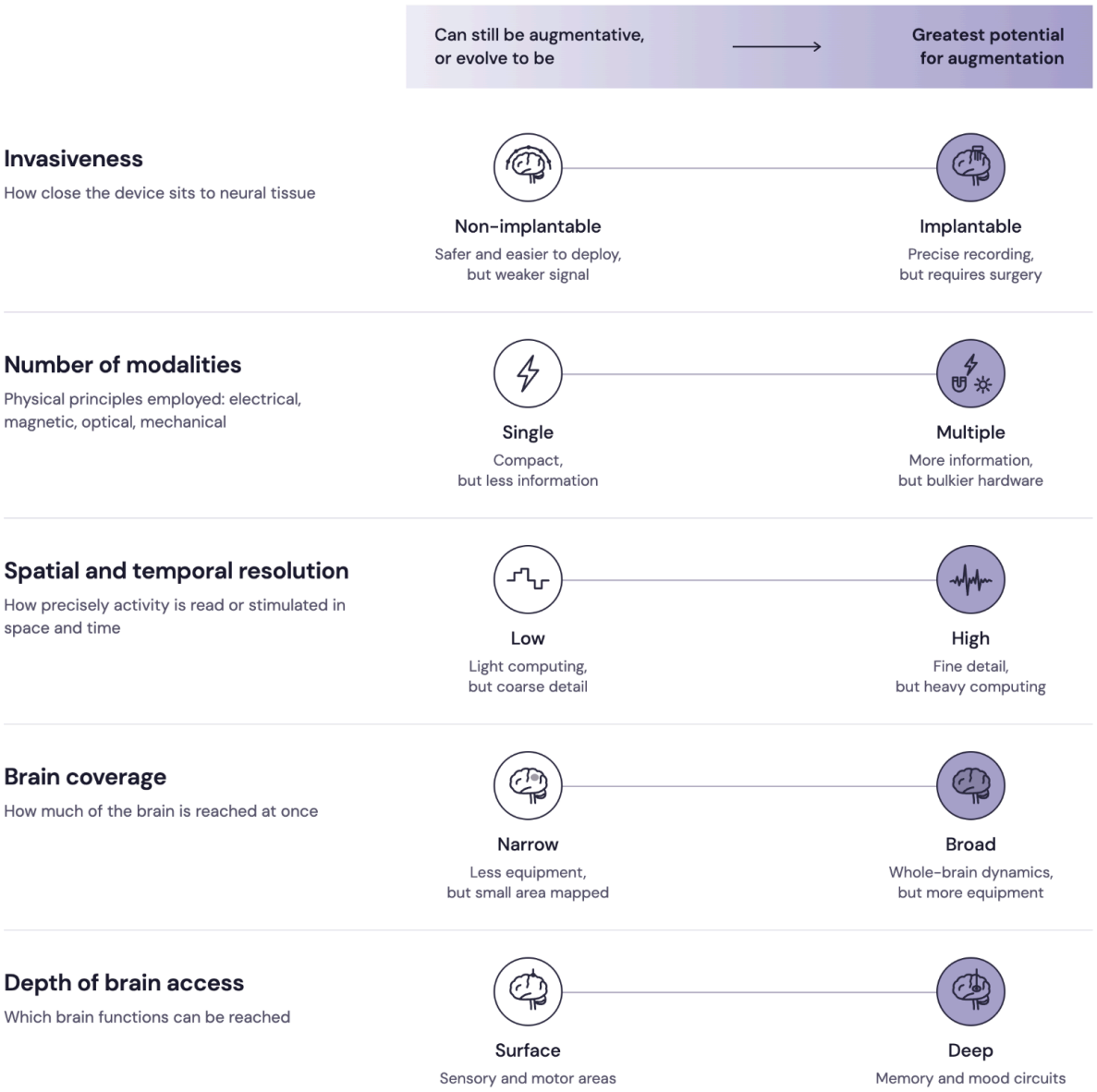


Figure 4. Five technological axes of BCIs. Each axis is a trade-off: both ends have strengths, and moving right, towards the greatest potential for augmentation, comes at a price in safety, portability, computing power or local detail. The axes are linked but do not all move together: more invasive devices tend to reach deeper and record finer detail, but cover less of the brain, while combining modalities usually needs hardware too bulky to implant or wear. No current technology sits at the right-hand end of every axis.

Likely constraints on augmentation using BCIs

While BCIs hold technological potential, current technical and biological constraints restrict their development and use for augmentation.[76]

Technological bottlenecks

Engineering constraints currently limit what BCIs can achieve. Specific areas highlighted in expert interviews include:

- **Chronic implant stability**: Once invasive BCIs have been placed in the brain, immune responses including gliosis, electrode drift due to motion, and the corrosive ionic environment of the brain raise the impedance of the electrode-tissue interface. This leads to signal degradation and limits how long implants can operate reliably.
- **Decoder generalisation**: Algorithms trained on one individual's neural signals, or on one session transfer poorly to another individual or another day, requiring frequent recalibration. Training using large datasets of neural activity is showing promising results,[77] but using data at scale is not always an option.
- **Stimulation and recording specificity**: No clinically or commercially available technology can selectively target specific neuronal types (e.g. inhibitory or excitatory neurons) or isolated circuits, confining stimulation approaches to broad modulation of neural circuits. Optogenetics (Table S2, **Annex 2**) is the only approach that may confer specificity, but it is limited to animal research and requires genetic modification of neurons.
- **Depth and breadth of access**: Subcortical structures relevant to memory, emotion, and motivation (e.g. hippocampus, amygdala) are largely inaccessible to non-invasive methods and to invasive implants placed on the cortex. Focused ultrasound is the main exception (Table S2, **Annex 2**), and even that carries resolution and hardware constraints.
- **Power delivery and battery constraints: Although wireless power transfer** methods such as inductive and ultrasound-based charging are reducing reliance on implanted batteries for BCIs,[78,79] long-term continuous operation is still limited by power transfer efficiency, heat dissipation, and device miniaturization.
- **Bandwidth**: The rate at which neural data can be transmitted off-device is a limiting factor.

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[76] Science and Technology Organization, *Neuroenhancement in Military Personnel: Conceptual and Methodological Promises and Challenges* (NATO n.d.) https://www.sto.nato.int/document/neuroenhancement-in-military-personnel-conceptual-and-methodological-promises-and-challenges-report/ (accessed 27 July 2026).

[77] Boccato, T et al., 'Cross-Subject Decoding of Human Neural Data for Speech Brain Computer Interfaces' (2026) 23(4) *Journal of Neural Engineering* https://doi.org/10.1088/1741-2552/ae8576.

[78] Neuralink, 'Technology' (Neuralink n.d.) https://neuralink.com/technology/ (accessed 31 July 2026).

[79] Seo, D et al., 'Wireless Recording in the Peripheral Nervous System with Ultrasonic Neural Dust' (2016) 91(3) *Neuron* 529 https://doi.org/10.1016/j.neuron.2016.06.034.

- **Miniaturisation**: Current systems capable of high-fidelity recording or stimulation are often bulky (helmets, external hardware), limiting everyday use or making their implantation into the body challenging.
- **Surgical precision and personnel**: Invasive implantation currently depends on a limited pool of neurosurgeons trained for precise electrode placement, constraining the scale at which invasive BCIs can be deployed even where the devices themselves are ready. Robotic-assisted implantation is being developed to address this challenge, with companies such as Neuralink pioneering such approaches.[80] However, these technologies are not yet widely adopted in clinical practice.

Many of these engineering constraints are potentially tractable challenges. Sustained progress across these areas would provide a technical signal of increasing augmentative capability.

Biological constraints

Beyond the technological bottlenecks above, experts noted that the brain itself, and our knowledge of it, can impose constraints on augmentation that are likely to present challenges to any efforts at augmentation. These include:

- **Knowledge of brain function remains limited**, particularly at the level of detail that augmentation would require, from basic mechanisms of learning and memory consolidation, to the neural correlates of consciousness, identity, mood, and perception. Importantly, these limitations hinder the development of effective BCIs, but BCI research is itself generating new insights into brain function.
- **Unpredictable, long-term and variable effects.** The brain is an interconnected system, which makes it hard to predict its dynamics upon stimulation. Even in highly controlled animal experiments using optogenetics, which are designed to causally isolate specific circuit functions, brain activity can be altered in unintended ways.
- **Temporal constraints of neural processing**. The brain is a sequential, rate-limited system. Synaptic plasticity, memory consolidation, behaviour,[81] and the propagation of signals across circuits and regions all unfold on biologically fixed timescales that cannot be arbitrarily accelerated.
- **The brain does not function in isolation**. There is a tendency to focus narrowly on the brain in isolation when discussing augmentation. However, cognitive and affective functions are shaped by continuous interaction with the rest of the body (e.g. hormonal, immune), by an individual's model of the world and their expectations, and by the social and physical context in which a person operates.
- **The brain changes and varies**. The brain changes over the course of a person's life through development, experience, and ageing, and brain structure and function vary between individuals. The same function can be mapped in different areas across individuals or remapped during the course of a lifetime. This makes generalisation

[80] Neuralink, 'An Integrated Brain–Machine Interface Platform with Thousands of Channels' (2019) 21(10) *Journal of Medical Internet Research* e16194 https://doi.org/10.2196/16194.

[81] Zheng, J and Meister, M, 'The Unbearable Slowness of Being: Why Do We Live at 10 Bits/s?' (2025) 113(2) *Neuron* 192 https://doi.org/10.1016/j.neuron.2024.11.008.

difficult at every level: decoding algorithms trained on one person's neural signals transfer poorly to another's, and a model calibrated to an individual at one point in time may not hold months or years later as that person's brain continues to change.

Signals and phases of augmentation development

The bottlenecks highlighted above, and the dimensions of technical development across which they impact provide the basis for identifying development signals that might indicate that augmentation is becoming more feasible. These signals matter because they may make it easier for technologies to move between therapy, optimisation and augmentation as they become more reliable, portable, affordable and embedded in everyday settings. As such, they can act to highlight emerging needs for governance action.

Four areas are potentially significant here, and are summarised in **Table 4**. These signals should be read collectively rather than individually. No single development would show that augmentative BCIs are imminent. The more important warning sign is progress across signals: when technical performance improves, products become easier to deploy, commercial incentives strengthen and social resistance falls.

Different augmentation pathways will require different combinations of these signals. Motor control and communication may become plausible through better decoding, durability and integration with external devices. Cognitive or affective augmentation is likely to require deeper progress in neuroscience, stimulation specificity and predictive modelling. Sensory addition may depend on new modalities capable of delivering interpretable signals to the brain safely and reliably.

Table 4: Signals of augmentation potential

Area	Why it matters	Signals
Neuroscience maturity	Augmentation depends on whether neural activity can be decoded or influenced reliably across people, tasks and contexts. Cognitive augmentation is especially challenging because attention, memory, decision-making and emotion depend on distributed, dynamic neural networks.	Better mechanistic understanding of higher cognitive functions; predictive models of stimulation effects; evidence that effects generalise across users and settings; clearer understanding of unintended or compensatory effects.
Technical performance	BCIs become more relevant to augmentation when they are accurate, durable, responsive and usable outside controlled clinical or laboratory settings.	Advances to extend usable device lifespan and reduce revision surgeries; progress in cross-subject and cross-session generalisation to enable scalable augmentation; novel targeted delivery methods to enable more precise interventions; non-invasive deep-brain access; gains in energy density or wireless power transfer to

		enable persistent, less obtrusive use; improvements in wireless data transfer and signal compression; miniaturisation driven by advances in chip design and microfabrication.
Interoperability and data infrastructure	Neural signals are not yet a standard input. Augmentation becomes more scalable if BCIs can connect reliably with wider digital ecosystems.	Common neural-data formats; interoperability standards; integration with operating systems, AI assistants and connected devices; privacy-preserving neural-data infrastructure; secure data-sharing and auditing mechanisms.
Deployment and markets	Augmentation becomes a governance issue when systems move from specialist research or clinical settings into consumer, workplace, educational, defence or other institutional uses.	Wearable BCIs embedded in earbuds, glasses or headsets; minimally invasive implantation pathways; reduced dependence on specialist personnel; investment by major technology firms; commercial partnerships; procurement or trials in workplaces, schools, defence or safety-critical settings.
New modalities	New forms of recording, stimulation or delivery could expand what BCIs can do.	Non-invasive deep-brain access; multimodal sensing; closed-loop stimulation; injectable, biohybrid or multi-region interfaces; movement from animal or experimental studies into human trials

The ethics and governance of augmentation

The technical features and signals of augmentation identified in the previous chapter create a need for governance intervention. That need is driven by a set of ethical concerns that recur across the literature on BCIs and human augmentation. This section introduces those concerns, maps them onto a structured framework, and considers how similar challenges are addressed in other domains where augmentation is at issue.

Dimensions of ethical concern

Concerns about BCI use for augmentation converge around autonomy and coercion, equity, risk and intrusiveness. Specific considerations related to reversibility and vulnerability are prominent where interventions involve children or dependent populations, invasive technologies or potentially permanent effects. Uses outside therapeutic settings and interventions that affect cognition or decision-making are consistent triggers for heightened scrutiny.

Table 5 defines these dimensions and considers how **their significance changes** across the spectrum from repair to augmentation. It shows how the need for governance intervention varies as applications move along that spectrum, even when the underlying technology remains the same.

A need for governance intervention may arise in two ways. The first is when a single dimension raises a serious concern on its own: an elective intervention that carries a high risk of irreversible harm, a technology used by people who cannot freely consent, or a setting in which refusal is not realistically possible. The second is convergence, where moderate concerns across several dimensions combine to create a more significant governance challenge. A technology that presents only moderate risks may warrant closer scrutiny if it is used in a coercive environment or targeted at a vulnerable group.

Identifying these concerns does not mean that augmentation is inherently unacceptable. Individuals may decide that benefits outweigh risks. Companies may pursue augmentation for competitive advantage, and states may see it as strategically important. The point is to identify a need for appropriate governance. The experience of other domains, including gene editing, cognitive enhancement drugs and cosmetic surgery, suggests a range of relevant approaches, introduced below.

Table 5. Dimensions that underpin ethical assessment and governance of augmentative BCIs

Dimension	Definition and Scope	At repair / treat	At augment	Key governance challenges
Risk	The probability and severity of harm, including uncertainty about long-term effects. Concern increases where effects are difficult to predict, monitor or reverse. In military applications risks may persist after service and affect post-service identity, responsibility and reintegration.	Higher risk acceptable where proportionate to clinical benefit.	Low tolerance: no clinical need offsets the harm.	The likelihood and severity of harm relative to benefit; the extent of uncertainty about long-term or irreversible effects.
Autonomy and coercion	The capacity to set one's own goals and decide freely. Augmentation may undermine agency directly (through modulation of cognition, emotion or behaviour) or indirectly through social, institutional or competitive pressures that make adoption difficult to refuse. Autonomy may also be eroded by social or institutional pressure to adopt.	Free and informed consent is fundamental; clinical need may bear on how voluntary consent really is.	Close scrutiny: exceeding baselines may drive arms-race dynamics, and power imbalances may make adoption hard to refuse.	Whether refusal is genuinely possible; whether the intervention alters agency directly; pressures to adopt arising from the surrounding context.
Vulnerability	Characteristics affecting capacity to consent and exposure to harm: age, cognitive status, health condition, institutional dependency and constraints on freedom of choice.	Clinical safeguards are clear and established.	Protections may not extend beyond healthcare.	Whether users can freely consent; whether safeguards designed for clinical settings extend to the actual context of use.
Equity	The distribution of access and the potential to entrench advantage. Augmentation is repeatedly linked to unequal access, unfair advantage, discrimination and the emergence of augmented versus non-augmented groups.	Clinical need is the primary determinant of access, although affected by health system inequities.	Risk of stratification and exclusion between augmented and non-augmented people. Exacerbated by concerns about competitive pressures and cumulative social inequalities.	How access is allocated; whether it confers competitive advantage outside clinical need; cumulative effects on existing inequalities.
Reversibility	Whether effects can be undone technically, functionally, and psychologically. A device may be removable yet leave lasting traces. Irreversible augmentation is generally considered more ethically problematic and in need of stronger oversight.	Irreversibility may be acceptable where alternatives are exhausted.	Should be exceptional and require strong safeguards.	Whether effects are durable or permanent; whether removal genuinely restores the prior baseline; the stakes of elective irreversibility.
Intrusive-ness	Concerns relating to bodily integrity, mental integrity and neural data. Greater intrusiveness, whether biological or informational, is generally associated with a stronger case for oversight.	Invasive methods justified by therapeutic necessity.	Hard to justify for elective use, especially where it affects mental rather than bodily function.	The degree of biological and informational intrusion; whether it is proportionate to the purpose; its interaction with the functional domain targeted.
Capability	The capability targeted: physical, sensory, cognitive, or affective. Augmented cognitive, affective and decision-making capabilities attract particular scrutiny because they relate closely to identity, agency, authenticity and moral responsibility. Augmentative BCIs may raise questions of authenticity: whether capabilities enabled by neural interfaces are experienced as genuine, or as shaped by a device, platform or institution	Determined by pathology.	Cognitive or affective modification attracts heightened scrutiny.	Whether cognitive, affective, or moral functions are targeted; how this sharpens concerns about risk, intrusiveness, and reversibility.

Dimension	Definition and Scope	At repair / treat	At augment	Key governance challenges
Setting	Clinical, consumer, workplace, educational, or military. Context reflects power relations and shapes how voluntary adoption really is.	Established oversight of clinical context.	Consumer, workplace, and military settings may lack adequate governance.	The power relations of the setting; the adequacy of existing oversight; whether the context itself constrains genuine refusal.

Governance considerations for human augmentation technologies

Risk

Existing medical device frameworks in the EU, UK and US set safety requirements that help manage many of the risks associated with BCIs. In the EU, all transcranial brain stimulation devices are now classified as medical devices and must undergo full Notified Body review, even when no therapeutic claim is made.[82,83] However, medical device regulation focuses primarily on benefit to risk ratio,[84] whether a product is safe, and that it performs as intended. It says much less about how a technology should be used once it moves into workplaces, schools or military settings, or how safety is established where use may have long-term and unintended consequences. A parallel may be drawn with post-market surveillance and monitoring of technologies such as AI, pharmaceuticals and medical devices, or gene editing.[85] In the case of gene editing, for example, FDA guidance on therapeutic genome editing emphasises the lack of knowledge about off-target effects and the need for long-term follow-up.[86] Similar evidence gaps exist for BCIs. For adaptive BCIs, the EU Product Liability Directive (2024), which explicitly covers software and AI-enabled products, may apply, but its application to cognitive or emotional harms has yet to be tested and liability remains uncertain.

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[82] Bublitz, C and Ligthart, S, 'The New Regulation of Non-Medical Neurotechnologies in the European Union: Overview and Reflection' (2024) 11(2) *Journal of Law and the Biosciences* lsae021 https://doi.org/10.1093/jlb/lsae021.

[83] Regulatory Horizons Council, *Neurotechnology Regulation* (Regulatory Horizons Council 2022) https://www.gov.uk/government/publications/regulatory-horizons-council-the-regulation-of-neurotechnology (accessed 31 July 2026).

[84] Chen, R, 'Benefit-Risk Analysis for Medical Devices: FDA, EU MDR, and ISO 14971 Decision Framework' (MedDeviceGuide 24 April 2026) https://meddeviceguide.com/blog/benefit-risk-analysis-medical-device-fda-eu-mdr-iso-14971-guide (accessed 31 July 2026).

[85] Clark, M, 'Post-Market Monitoring for AI Systems: Obligations, Architecture, and Implementation under the EU AI Act' (SSRN Scholarly Paper No 6773119, Social Science Research Network 2026) https://doi.org/10.2139/ssrn.6773119.

[86] Center for Biologics Evaluation and Research, 'Long-Term Follow-up AfterUp after Administration of Human Gene Therapy Products' (Food and Drug Administration 30 January 2020) https://www.fda.gov/regulatory-information/search-fda-guidance-documents/long-term-follow-after-administration-human-gene-therapy-products (accessed 31 July 2026). See also Tavridou, A et al., 'Genome-Editing Medicinal Products: The EMA Perspective'. Nature Reviews Drug Discovery 23, no. 4 (2024): 242–43. https://doi.org/10.1038/d41573-024-00050-2.

Autonomy and coercion

Pressures to use BCI augmentation technologies may emerge in education, employment and the military.[87] In workplaces, these pressures may be reinforced by employer monitoring and surveillance, performance-management systems or expectations that workers use BCI tools to improve productivity, attention or fatigue management. Even where adoption is voluntary, employees may feel unable to refuse if non-use is perceived as a lack of commitment or as a competitive disadvantage. Research ethics protections apply during development,[88] and professional guidance highlights how competitive environments can limit genuine freedom of choice.[89,90] Peer pressure may arise where classmates, colleagues or unit members adopt enhancement technologies, creating informal norms that make refusal socially or professionally costly. Human rights frameworks focused on human dignity are essential to support both the freedom to adopt and the freedom to refuse augmentation technologies.[91,92] For BCI technologies, this concern may be heightened where data feedback, neurostimulation or adaptive systems are used not only to measure performance but to shape attention, mood or behaviour, raising risks of behavioural manipulation as well as coercive uptake.

Equity

Equity concerns emerge across technologies with augmentation potential. Human gene editing has prompted concerns about unequal access to desirable traits and new forms of social stratification. Cosmetic surgery raises related questions about social pressure and commercial incentives that may encourage modification in order to remain competitive or accepted. Unequal access may arise from for different reasons, including costs, insurance coverage, geographical availability, infrastructure, disability status, regulatory approval pathways, and

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[87] Andorno, R, Analysis of the Existing European Human Rights Framework Concerning the Human Rights Issues Raised by Neurotechnologies and Their Applications (Steering Committee for Human Rights in the Fields of Biomedicine and Health 2025) https://www.ibme.uzh.ch/dam/jcr:db1d094c-3023-46bb-bb16-d8da649510ff/2025-11%20Andorno%20CDBIO(2025)16REV_Report_Neurotechnologies_Andorno_E1.pdf (accessed 31 July 2026).

[88] Klein, E and Ojemann, J, 'Informed Consent in Implantable BCI Research: Identification of Research Risks and Recommendations for Development of Best Practices' (2016) 13(4) *Journal of Neural Engineering* 043001 https://doi.org/10.1088/1741-2560/13/4/043001.

[89] Agid, Y et al., *The Use of Biomedical Techniques for "Neuroenhancement" in Healthy Individuals: Ethical Issues* (Comité Consultatif d'Ethique 2024).

[90] Nicholson, P et al., *Cognitive Enhancing Drugs and the Workplace* (British Medical Association 2015) https://www.bma.org.uk/media/agcf0ol3/bma_cognitive_enhancing_drugs_and_the_workplace_oct_2019.pdf (accessed 31 July 2026).

[91] Parliamentary Assembly of the Council of Europe, *The BCI: New Rights or New Threats to Fundamental Freedoms?* (Resolution 2344, 2020) https://www.europeanrights.eu/public/atti/Resolution_2344_(2020)_ENG.pdf (accessed 31 July 2026).

[92] Andorno, R, Analysis of the Existing European Human Rights Framework Concerningconcerning the Human Rights Issues Raised by Neurotechnologies and Their Applications (Steering Committee for Human Rights in the Fields of Biomedicine and Health 2025) https://www.ibme.uzh.ch/dam/jcr:db1d094c-3023-46bb-bb16-d8da649510ff/2025-11%20Andorno%20CDBIO(2025)16REV_Report_Neurotechnologies_Andorno_E1.pdf (accessed 31 July 2026).

difference in employer or institutional support. These concerns may become particularly important if augmentative BCIs begin to influence performance expectations in workplaces or education. Employment and equality laws, including the Employment Equality Directive and the International Covenant on Economic, Social and Cultural Rights, may help protect people from disadvantages where technology use becomes an implicit requirement.[93] However, existing anti-discrimination frameworks do not explicitly address differences between augmented and non-augmented individuals. Cross-border regulation may also become important if BCI devices, data services or enhancement procedures are offered in jurisdictions with weaker safeguards, creating risks of regulatory arbitrage and uneven protection. At a global level, unequal access may reinforce existing disparities between high- and low-resource settings, such that any benefits of augmentation accumulate among already advantaged groups while others face exclusion or dependency on important technologies.

Vulnerability

Concerns about autonomy and coercion become acute when users are less able to understand risks, protect their interests or freely refuse an intervention. Vulnerability may arise not only from age, but also from mental fitness, cognitive impairment, economic insecurity, disability, dependency on institution, or circumstance in which access to care, education, and employment or promotion is controlled by others. Professional guidance from bodies such as the American Academy of Neurology, for example, recommends against neuroenhancement in people under 18 .[94] Several jurisdictions, including the UK, Australia and Italy, place age restrictions on certain cosmetic interventions. The underlying principle is that especially vulnerable individuals require additional safeguards before undergoing elective interventions with risks or long-term consequences. For augmentative BCI's, similar concerns may arise where users have reduced decision-making capacity, face financial or institutional pressure, or are dependent on employers, scholars, clinicians, careers or military authorities.

Reversibility

Guidance used in EU research ethics reviews highlights the importance of considering whether an intervention can be reversed and whether less permanent alternatives are available.[95] Cosmetic surgery often produces lasting changes, which is why professional guidance emphasises informed consent, cooling-off periods and realistic expectations.[96] Germline gene editing is tightly restricted in part because its effects are heritable and cannot be reversed for

[93] Warso, Z and Gaskell, S, *SIENNA D3.2: Analysis of the Legal and Human Rights Requirements for Human Enhancement Technologies in and outside the EU* (Version V2.0, Zenodo 2019) https://doi.org/10.5281/zenodo.4066617.

[94] Tambornino, L and Lanzerath, D, *SIENNA D3.3: Survey of REC Approaches and Codes for Human Enhancement* (Version V3.0, Zenodo 2019) https://doi.org/10.5281/zenodo.4066874.

[95] Erden, YJ and Brey, PAE, 'Ethics Guidelines for Human Enhancement R&D' (2022) 378 *Science* 835 https://doi.org/10.1126/science.add9079.

[96] Tambornino, L and Lanzerath, D, *SIENNA D3.3: Survey of REC Approaches and Codes for Human Enhancement* (Version V3.0, Zenodo 2019) https://doi.org/10.5281/zenodo.4066874.

future generations.[97] DARPA's PREPARE programme requires that any protective gene-activation effects are temporary and do not permanently alter the host genome.[98] Reversibility also matters for legal responsibility: product liability regimes are less effective at addressing harms that are difficult or impossible to undo, and removing implanted devices may itself carry significant risks.

Intrusiveness

Across augmentation technologies, greater intrusiveness is generally associated with stronger oversight and safeguards.[99,100] Cosmetic surgery, for example, is more tightly regulated than ordinary beauty products because it is invasive, often permanent and carries medical risks. BCI-enabled intrusiveness can vary significantly: physical intrusiveness, where devices require implantation or bodily intervention; psychological intrusiveness, where system affect cognition, emotion, attention or self-understanding; social intrusiveness, where use exposes individuals to monitoring or pressure in workplaces, education or military setting; and information intrusiveness, where neural or behavioural data are collected, inferred or shared. Even small amounts of neural data may be sufficient to identify individuals.[101,102] As a result, the use of BCIs for augmentation may engage the right to privacy protected under the European Convention on Human Rights, and through EU and UK GDPR protections.[103] However, neural data presents challenges for existing data governance frameworks.[104,105] Concerns may be acute in consumer

[97] Juengst, ET et al., 'Preventive Human Genome Editing and Enhancement: Candidate Criteria for Governance' (2024) 54(5) *Hastings Center Report* 14 https://doi.org/10.1002/hast.4913.

[98] DARPA, 'Dialing Up the Body's Defenses Against Public Health and National Security Threats' (DARPA 2018) https://www.darpa.mil/news/2018/bodys-defenses-public-health-threats (accessed 31 July 2026).

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[101] Silva Castanheira, Jd et al., 'Brief Segments of Neurophysiological Activity Enable Individual Differentiation' (2021) 12(1) *Nature Communications* 5713 https://doi.org/10.1038/s41467-021-25895-8.

[102] Nougrères, AB, *Foundations and Principles for the Regulation of Neurotechnologies and the Processing of Neurodata from the Perspective of the Right to Privacy: Report of the Special Rapporteur on the Right to Privacy* (UN Human Rights Council 2025) https://www.ohchr.org/en/documents/thematic-reports/ahrc5858-foundations-and-principles-regulation-neurotechnologies-and

[103] Andorno, R, *Analysis of the Existing European Human Rights Framework Concerning the Human Rights Issues Raised by Neurotechnologies and Their Applications* (Steering Committee for Human Rights in the Fields of Biomedicine and Health 2025). https://www.ibme.uzh.ch/dam/jcr:db1d094c-3023-46bb-bb16-d8da649510ff/2025-11%20Andorno%20CDBIO(2025)16REV_Report_Neurotechnologies_Andorno_E1.pdf (accessed 31 July 2026).

[104] Information Commissioner's Office, *ICO Tech Futures: Neurotechnology* (Information Commissioner's Office 2023) https://ico.org.uk/media2/about-the-ico/research-and-reports/ico-tech-futures-neurotechnology-0-1.pdf (accessed 31 July 2026).

[105] United States Government Accountability Office, *Brain-Computer Interfaces: Applications, Challenges, and Policy Options* (United States Government Accountability Office 2024) https://www.gao.gov/assets/gao-25-106952.pdf (accessed 31 July 2026).

markets, where companies may seek to aggregate, analyse and monetise anonymised neural data collected from users.[106]

Capability

Different augmentation technologies affect different human capabilities, and this shapes how they are governed. Gene editing may target physical and cognitive traits. Nootropic drugs tend to focus on attention, alertness and memory. BCIs could affect a much broader range: communication, attention, memory, emotion, sensory perception and decision-making. Technologies that affect cognition, emotion or agency deserve particular attention because they operate close to an individual's mental life, encompassing inner conscious and subconscious individual experience. Their use may engage rights protected under frameworks such as the European Convention on Human Rights, the Human Rights Act 1998 and the EU Charter of Fundamental Rights. For BCIs, this means governance cannot treat all applications in the same way.

Setting

The governance of other augmentation domains illustrates why context matters. A nootropic drug may be prescribed to treat ADHD, used by students to improve exam performance, or adopted by shift workers to maintain concentration. Cosmetic surgery can be framed as healthcare, a consumer service or a commercial beauty practice depending on who provides it and how it is marketed. For BCIs, medical device regulation and clinical ethics play a central role in healthcare settings. Outside healthcare, oversight is often more limited. By positioning products as wellness or lifestyle technologies rather than medical devices, companies may currently be able to avoid stricter forms of regulatory scrutiny.

Implications for the governance of BCI augmentation

This overview highlights that engaging with augmentation concerns may require coordination of governance mechanisms across multiple regulatory regimes.[107] While the potential for augmentation is recognised as an issue meriting dedicated attention in research (notably in the EU's Horizon programme), outside of research there is no single regulatory framework for human augmentation that covers the full range of ethical concern. Governing augmentation will require bringing different approaches together: product regulation, professional oversight and standards, data and AI governance, human rights protections and sector-specific safeguards, while identifying areas where existing rules leave gaps. The next section draws on a series of scenarios exploring potential future technological developments to test the challenges and possibilities associated with such an approach.

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[106] European Parliamentary Research Service, *The Protection of Mental Privacy in the Area of Neuroscience: Societal, Legal and Ethical Challenges* (European Parliament 2024) https://doi.org/10.2861/869928.

[107] UNESCO. 'Recommendation on the Ethics of Neurotechnology'. (UNESCO, 2026). https://unesdoc.unesco.org/ark:/48223/pf0000394866. (accessed 31 July 2026).

Future governance challenges for augmentative BCIs

This section draws on an expert workshop held in June 2026 in which participants used a set of hypothetical scenarios to test the augmentation taxonomy and explore its governance implications. The scenarios, summarised in Box 1 and detailed in Annex 3, were designed to cover the augmentation types introduced earlier (personal-referent A1, population-referent A2 and extrinsic B) across healthcare, finance, education, emergency response and defence. The scenarios are summarised in box 1, and full details are provided in Annex 3.

Summary of scenarios

1. **The Returning Surgeon:** A neurosurgeon rehabilitating from a stroke opts for a BCI system featuring motor extension and sensory addition capabilities. Through repeated closed-loop training, the surgeon enhances her movement precision beyond pre-stroke baselines.
2. **The Financial Trading Floor:** An investment firm adopts a neuroadaptive system to enhance attention and rapid decision-making during periods of market volatility.
3. **The Emergency Response Network:** First responders adopt a network-based neuroadaptive system designed to coordinate attention and emotional regulation across an entire team during natural disasters.
4. **The Adaptive Classroom:** A secondary school pilots a neuroadaptive learning environment to enhance memory and learning. Students wear EEG headbands during lessons which monitor attentional engagement, cognitive load and fatigue.
5. **The Silent Operator:** A defense agency deploys a subvocal speech and communication interface to special operations units. This system can be integrated with an AI co-pilot for real-time tactical analysis, shortening decision loops by detecting and acting on pre-articulatory neural signals and enabling covert communication.
6. **The Rehabilitating Veteran:** An injectable neural implant receives approval for stroke and traumatic brain injury (TBI) rehabilitation and shows potential for enhancing memory and learning.
7. **The Electromagnetic Reader:** A university spin-out develops a wearable focused ultrasound cap that detects ambient electromagnetic fields. As a form of sensory addition, the system allows users to perceive (previously) invisible signals.

Classifying augmentation in practice

The scenarios confirmed that classification is difficult but also showed where the taxonomy has traction and where it does not.

The *Electromagnetic Reader* was the clearest case: it introduced a sensory capability humans do not naturally possess and aligned straightforwardly with extrinsic augmentation (B). The *Silent Operator* was contested. Participants disagreed on whether subvocal communication represented a genuinely new capability or simply made existing communication more efficient. The *Adaptive Classroom* and *Financial Trading Floor* were harder still. Some participants viewed the trading-floor system as augmentative because it appeared to push attention and decision-making beyond normal levels; others saw it as optimisation no different in kind from caffeine or pharmaceuticals. The classroom scenario was read as assistive for students with attention difficulties and potentially augmentative for already high-performing students. In the *Returning Surgeon* scenario, participants noted that for individuals already operating at the upper end of human capability, the line between personal-referent and population-referent augmentation becomes almost impossible to draw.

These disagreements were not failures of the taxonomy. They reflected genuine ambiguity in the technology, and participants were transparent about where that ambiguity sat. What mattered more, as the following sections show, was that disagreement about classification rarely translated into disagreement about governance needs.

Setting, not capability, drove governance concern

The workshop's most consistent finding was that participants' concerns were shaped more by where and how a technology was deployed than by what it could do.

The *Silent Operator* illustrates this clearly. A system enabling rapid non-verbal communication raised relatively limited concern as a general proposition, but took on a different character in operational military environments where silence, speed and communication through physical barriers have strategic value. Participants identified a common cluster of concerns (privacy, data governance, the implications of detecting pre-verbal intention) but these were activated by the deployment context, not by the technical specification alone.

The *Adaptive Classroom* generated some of the workshop's most sustained discussion, despite being one of the scenarios participants were least likely to classify as augmentation. The concern was not the EEG headband itself but the school setting: children who cannot freely refuse, developmental uncertainty about long-term use or withdrawal, and the prospect that schools would need to manage mixed groups of augmented and non-augmented students with no clear framework for doing so. Participants stressed that a system designed to support a student with attention difficulties looks different from the same system used to extend concentration in an already high-performing student, and that the difference is produced by context, not hardware.

Employment settings generated a parallel set of concerns. In the *Financial Trading Floor* scenario, participants focused less on whether the neuroadaptive system counted as augmentation and more on its likely downstream effects: rising performance expectations, longer working hours, differential treatment of augmented and non-augmented workers, and the risk that a tool introduced to reduce burnout could instead intensify pressure. The *Emergency Response Network* raised the possibility that if a coordination system worked most effectively for people with particular neural or physiological profiles, organisations might favour those

individuals in recruitment and deployment, creating exclusionary effects even where the technology was framed as a team capability rather than individual enhancement.

These discussions converged on a practical point: governance frameworks are likely to be more effective when they focus on the conditions of use (who adopts, who decides, who bears the consequences of refusal) than on resolving whether a given application crosses a definitional threshold into augmentation.

Classification uncertainty does not block governance

The second consistent finding was that participants could identify governance needs without first resolving classification disputes.

In the *Financial Trading Floor* scenario, participants who classified the system as optimisation and those who saw it as augmentation identified the same concerns: pressure on workers' autonomy, the erosion of meaningful choice in competitive environments, and the inadequacy of existing employment frameworks to address technologies that reshape performance expectations. In the *Silent Operator* scenario, disagreement about whether subvocal communication was a new capability or an extension of existing communication did not prevent agreement that the system raised serious questions about neural data, the detection of pre-verbal intention, and accountability within command structures.

This pattern repeated across the workshop. Participants treated classification as analytically useful (it helped structure discussion and surface the right questions) but did not treat it as a precondition for identifying what governance should do. An important implication for policy is that regulators should not wait for definitional consensus before acting. The question is not "is this augmentation?" but "what concern does this trigger?": risk, coercion, unfair advantage, effects on agency, or changes to the social practice in which the technology is used.

Gaps highlighted by the workshop

While participants drew on the ethical dimensions and existing governance frameworks introduced in the previous chapter, several areas emerged where existing governance frameworks appear underdeveloped.

Neural data governance

Participants consistently returned to three questions: who can access neural data, how it is protected, and who is responsible when protections fail. Concern was greatest when technologies moved beyond conventional device interaction into the detection, interpretation or transmission of mental states. The *Emergency Response Network* scenario raised the possibility that coordination systems might require access to neural or physiological profiles (so-called "brain fingerprints"), creating sensitive data that existing privacy and data protection frameworks were not designed to address. Participants questioned whether current legal protections are sufficient for technologies that can infer attention, fatigue, intention, emotion or identity from neural signals.

Lifecycle accountability

The *Rehabilitating Veteran* scenario highlighted risks that extend well beyond initial product approval: dependency on a device whose manufacturer might exit the market, the difficulty of removing or maintaining implanted systems, and the possibility that effects persist or change after use ends. Participants drew a distinction between restoring a person to their previous level of functioning and enhancing them beyond that baseline, but noted that either trajectory creates obligations that current regulatory frameworks do not reliably assign, particularly for long-term monitoring, post-trial access, cybersecurity and support for orphaned devices.

The coercion-in-practice problem.

Existing consent frameworks assume that individuals can freely choose whether to adopt a technology. Participants repeatedly questioned whether this assumption holds in education, employment and defence. In the *Emergency Response Network* scenario, they asked whether first responders could ever give fully voluntary consent to interventions whose effects remain uncertain and whose refusal might carry professional consequences. The underlying problem (that social, institutional and competitive pressures can make adoption a practical requirement even when it remains formally voluntary) is not unique to BCIs, but participants noted that no existing regulatory regime addresses it adequately.

Reversibility as necessary but not sufficient

Participants considered reversibility an important factor in assessing the stakes of an intervention, but emphasised that the possibility of reversal should not, by itself, justify approval or reduce the need for safeguards. A reversible intervention may still create dependency, competitive pressure or institutional expectations to adopt. In education, participants raised the possibility that withdrawal from long-term use could itself have consequences. Reversibility mitigates some risks but does not remove the need to assess vulnerability, consent and the pathway by which a therapeutic device may become an augmentative product.

Lessons for governance

The workshop reinforced three conclusions. First, governance challenges posed by augmentative BCIs depend primarily on how and where technology is used, what expectations it creates, and how adoption distributes risk, control and opportunity, not on resolving whether a particular application qualifies as augmentation. Second, existing governance frameworks provide meaningful points of intervention, but no single regime is sufficient; effective governance will require coordination across health regulation, data protection, consumer protection, employment and equality law, defence oversight and standards bodies. Third, some issues (particularly coercion in competitive settings, neural data governance and lifecycle accountability) do not fit neatly within any current regulatory framework and will require dedicated attention.

Governing augmentative BCIs

Brain–computer interfaces are not yet enabling augmentation, and significant biological and engineering constraints cap how BCIs can be used. However, advances in neural recording, stimulation, AI-enabled decoding, and miniaturisation could make augmentative uses possible sooner than regulatory systems expect. The policy challenge is therefore to anticipate and prepare for foreseeable uses of technologies already moving through clinical, consumer, workplace and defence pathways.

Existing governance is fragmented. Medical device regulation, consumer protection, data protection, employment law, human rights frameworks and sector-specific rules each address part of the problem. None provides a complete framework for augmentation applications of BCIs.

Governance of augmentation should focus on purpose, effect and context of use. The same BCI may restore function in one setting, optimise performance in another and augment capability in a third. Regulators should monitor not only devices, but also markets, claims, deployment settings and institutional incentives. This should be coordinated across health, data protection, consumer protection, employment, education, defence and standards bodies.

Classification will often be contested. Policymakers should not wait for perfect agreement on whether a BCI use case involves augmentation before acting. The workshop scenarios showed that experts could disagree about classification. Rather than making governance depend on whether a BCI can be definitively classified as augmentation, regulators should ask what concern is triggered: risk, coercion, unfair advantage, loss of authenticity, effects on agency, or changes to the social practice in which the technology is used

In order to effectively enable governance, we need to build the capacity to detect, assess and respond to augmentative uses before they become embedded in markets or institutions.

Key priorities are:

1. Regulate by use case, not just by technology. Oversight should examine what capability is affected, who uses the system, who benefits, who bears the risks and whether refusal is genuinely possible. Particular scrutiny is needed in settings marked by dependency or power imbalance, notably schools, workplaces, and defence.

2. Protect the right to refuse. Augmentative BCIs could become de facto requirements in competitive environments. Policymakers should consider safeguards against coercive or indirectly mandatory use, especially where adoption may affect employment, education, military service, access to services or professional advancement.

3. Address equity early. BCIs, because they may confer advantages in learning, work, communication or decision-making, could deepen existing inequalities if access is uneven. Governance should address access, and how augmented and non-augmented people are treated in shared settings, including potential discrimination.

4. Protect neural data. BCI governance should address data governance issues associated with the use of neural signals to infer attention, fatigue, intention, emotion, identity or vulnerability.

5. Promote reversibility. Governance requirements should be substantially higher for potential BCI applications that are likely to be irreversible or difficult to reverse. However, reversibility should not be treated as sufficient on its own to justify approval or reduce safeguards; even reversible systems may create dependency, institutional expectations or pressure to adopt, and should still be assessed for risks related to consent, vulnerability, and long-term effects.

6. Require lifecycle accountability. Safety should cover more than initial product approval. Regulators should require clear responsibilities for long-term monitoring and updates, removal, post-trial access, cybersecurity and support if a company exits the market.

7. Coordinate regulators nationally and internationally. No single regulatory regime will be sufficient. Effective governance will require coordination between health regulators, data protection authorities, consumer protection bodies, employment and equality regulators, defence oversight bodies and standards organisations. To be effective, this will require international coordination and cooperation.

8. Monitor technology development. Governments should monitor technical and market signals that augmentation is becoming more feasible: improved understanding of brain functions and neural correlates of cognitive, emotion and behaviour, improved decoder generalisation, durable implants, non-invasive deep-brain access, wearable consumer BCIs, integration with AI assistants, investment by major technology firms, and marketing claims that suggest performance advantage.

9. Consider social acceptability. Public attitudes towards modifying or enhancing the brain vary considerably across countries, cultures, and applications, and are shaped by factors such as perceived risks and benefits, trust in technology developers and regulators, ethical concerns, and broader beliefs about human augmentation.[108,109] While we have not considered societal acceptance of augmentation in this report, it is an important factor of which policy makers should be aware and which requires further attention.[110]

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[108] Sattler, S and Pietralla, D, 'Public Attitudes towards Neurotechnology: Findings from Two Experiments Concerning Brain Stimulation Devices (BSDs) and Brain-Computer Interfaces (BCIs)' (2022) 17(11) *PLOS ONE* e0275454 https://doi.org/10.1371/journal.pone.0275454.

[109] Prudhomme, M, *SIENNA D3.5: Public Views of Human Enhancement Technologies in 11 EU and Non-EU Countries* (Version V4, Zenodo 2020) https://doi.org/10.5281/zenodo.4068194.

[110] Dijkstra, AM and Schuijff, M, 'Public Opinions about Human Enhancement Can Enhance the Expert-Only Debate: A Review Study' (2016) 25(5) *Public Understanding of Science* 588 https://doi.org/10.1177/0963662514566748.

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Annex 1 Literature reviewed and interviews

Interviewee expertise

To capture a range of perspectives on the current and potential augmentative capacity of BCIs, we conducted 9 structured interviews with a selected panel of experts spanning both academic and industry settings. The panel included researchers affiliated with universities and research institutes as well as professionals from BCI companies, seeking a balance between fundamental scientific and engineering perspectives and applied perspectives on the real-world deployment and augmentation potential of BCIs. Participants were based across multiple countries, including Germany, the United States, the United Kingdom, Sweden, and Spain.

Interview plans were reviewed and granted approval by the RAND Europe Research Ethics Committee.

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Annex 2: Recording and Stimulation Technologies

Table S1. Recording technologies, their key characteristics, and relevance to augmentation

Technology	Physical principle	Invasiveness	Deep brain access	Resolution	Brain coverage	Augmentation relevance
Electroencephalography (**EEG**)	**Electrical**: detects electrical fields generated by neuronal activity through electrodes placed on the scalp.	Non-invasive	Primarily cortical	Low spatial; high temporal (~ms)	Depends on the number of electrodes; can cover the entire scalp	**Supports continuous, non-invasive decoding of broad cognitive states and simple motor intentions, supporting adaptive interfaces and brain-computer control.** Detects macroscopic brain states (e.g. arousal, fatigue, attention, sleep) with useful accuracy. Advances in sensors and AI have enabled non-invasive control of external devices such as computer cursors, prostheses and drones. Its portability, low cost, and compatibility with consumer devices (helmets, headphones, glasses, VR headsets) make it the recording technology with the greatest near-term deployment potential.
Functional near-infrared spectroscopy (**fNIRS**)	**Optical:** uses near-infrared light to measure haemodynamic changes associated with neuronal activity.	Non-invasive	Primarily cortical	Moderate spatial; low temporal (~s)	Partial cortical coverage or whole scalp, depending on sensor configuration.	**Provides continuous monitoring of sustained cognitive states, supporting adaptive human-computer interaction based on mental workload and cognitive effort.** Measures haemodynamic responses associated with attention, workload, fatigue and stress. Limited temporal resolution restricts rapid closed-loop control but makes it suitable for long-duration monitoring. Frequently combined with EEG to improve robustness.

Technology	Physical principle	Invasiveness	Deep brain access	Resolution	Brain coverage	Augmentation relevance
Magnetoence phalography (**MEG**)	**Magnetic**: detects magnetic fields generated by neuronal electrical activity.	Non-invasive	Primarily cortical; limited sensitivity to deep sources	Moderate-to -high spatial; high temporal (~ms)	Whole brain	**Offers high-fidelity, non-invasive decoding of cortical activity, supporting more precise reconstruction of motor, and speech-related neural processes than EEG.** Combines millisecond temporal resolution with better spatial localisation (magnetic fields are less distorted by the skull). Recent work combining MEG and EEG has demonstrated increasingly accurate non-invasive speech decoding. Conventional systems require specialised infrastructure, although the first wearable form factors are already used in research contexts.
Electrocortico graphy (**ECoG**)	**Electrical**: records electrical activity directly from the cortical surface.	Minimally invasive (electrodes placed beneath the skull on the cortical surface, not inside the brain)	Cortical	High spatial; high temporal (~ms)	Limited to the implanted cortical area	**Provides high-performance decoding of complex neural signals, including speech, movement and sensorimotor activity, with substantially higher fidelity than non-invasive methods.** Electrodes placed directly on the cortical surface provide high spatial and temporal resolution without penetrating brain tissue. Represents an intermediate trade-off between recording quality and invasiveness. Clinical trials are evaluating chronic implants for restorative BCIs, with potential future applications in augmentation.

Technology	Physical principle	Invasiveness	Deep brain access	Resolution	Brain coverage	Augmentation relevance
Intracortical neural implants	**Electrical**: record extracellular action potentials from neurons using penetrating microelectrodes.	Invasive	Cortical (deep cortical layers); limited access to subcortical structures depending on implantation site	Very high spatial (single-neuron); high temporal (~ms)	Limited to the implanted region	**Enables the highest-fidelity recording of neural activity currently available, supporting fine-grained decoding of motor intentions, speech and sensory representations for high-performance brain-computer interfaces.** Record action potentials from individual neurons or small neuronal populations, providing the highest information bandwidth among current recording technologies. They underpin state-of-the-art neuroprosthetic demonstrations but require invasive neurosurgery and face challenges related to long-term safety, durability and security.

Table S2. Stimulation technologies, their key characteristics, and relevance to augmentation

Technology	Physical principle	Invasiveness	Deep brain access	Resolution / specificity	Augmentation relevance
Transcranial direct current stimulation (**tDCS**) / Transcranial alternating current stimulation (**tACS**)	**Electrical**: weak electrical currents delivered through scalp electrodes modulate neuronal excitability	Non-invasive	Superficial (effects can propagate indirectly through brain networks)	Low (broad cortical modulation)	**Modulate cortical excitability non-invasively, with the aim of transiently enhancing cognitive, sleep, or motor performance.** Studies have reported short-term improvements in attention, motor learning, working memory and numerical competence in healthy individuals, although effects are generally small, highly variable across individuals, and difficult to reproduce consistently. Their simplicity, low cost and portability have made them the most widely marketed consumer neurostimulation technologies despite limited evidence for durable augmentation . They can be combined with non-invasive recording technologies, such as EEG, for closed-loop stimulation (e.g. sleep enhancement)
Transcranial magnetic stimulation (**TMS**)	**Magnetic**: rapidly changing magnetic fields induce electrical currents in cortical tissue.	Non-invasive	Indirect (cortical target; downstream effects through neural connectivity)	Moderate (focal cortical stimulation, ~1–2 cm)	**Allows non-invasive modulation of cortical function, allowing transient modification of specific neural processes.** Widely used as a research tool to establish causal links between brain regions and behaviour, and clinically approved for disorders including depression, obsessive-compulsive disorder and smoking cessation. Research has explored modulation of attention, perception, learning and self-referential processing, although equipment size, cost and power requirements currently limit portability.

Technology	Physical principle	Invasiveness	Deep brain access	Resolution / specificity	Augmentation relevance
Deep brain stimulation (**DBS**)	**Electrical**: implanted electrodes deliver electrical stimulation to deep brain structures.	Invasive	Yes	High spatial and temporal precision at the stimulation target	**Directly targets deep neural circuits with high precision, allowing modulation of motor, affective and cognitive networks that are inaccessible to non-invasive stimulation.** DBS is the clinical standard for treating movement disorders such as Parkinson's disease and essential tremor, with expanding applications in psychiatric disorders. Documented (unintended) changes in mood, motivation, personality and behaviour in patients treated with this technology illustrate its relevance for future cognitive or affective augmentation.
Cortical **neural implant** (stimulator)	**Electrical**: implanted electrodes stimulate cortical tissue directly.	Invasive	Cortical	High spatial and temporal precision at electrode sites	**Supports precise stimulation of cortical circuits and closed-loop interaction with neural activity, enabling adaptive closed-loop neuromodulation.** Stimulation can be combined with simultaneous recording to create responsive systems that adapt stimulation in real time. Achieving complex cognitive augmentation is expected to require coordinated stimulation across distributed cortical networks.
Focused ultrasound stimulation (**FUS**)	**Mechanical**: focused ultrasound waves modulate neuronal activity through mechanical interactions with neural tissue.	Non-invasive or minimally invasive	Yes	Moderate-to-high (focal targeting of deep brain structures)	**The only technology with the potential to non-invasively stimulate deep brain structures.** Proof-of-concept studies have demonstrated its neuromodulatory capabilities using approaches that involve removal of a section of the skull to optimise ultrasound delivery, while fully transcranial methods remain under development. If these technical barriers are overcome, focused ultrasound could substantially expand opportunities for cognitive and affective neuromodulation without the need for implanted electrodes.

Technology	Physical principle	Invasiveness	Deep brain access	Resolution / specificity	Augmentation relevance
Optogenetics	**Optical**: light activates or inhibits genetically modified neurons expressing light-sensitive ion channels.	Invasive (requires genetic modification and optical access to neural tissue)	Potentially yes	Very high (cell-type and circuit specificity)	**Enables selective stimulation or inhibition of genetically defined neuronal populations with high precision, allowing direct control of specific neural circuits.** Widely used in neuroscience research to establish causal relationships between neural activity and behaviour. Clinical applications remain limited to experimental retinal therapies, while use in the human brain faces major technical, regulatory and ethical barriers due to the need for gene therapy and implanted optical hardware.

Annex 3: Detailed Augmentation Scenarios

#1 The Returning Surgeon

A neurosurgeon (age 52) suffers a mild stroke affecting fine motor control and proprioceptive feedback in their dominant hand. After 6 months of conventional rehabilitation, they regain ~85% function, which is sufficient for most daily activities, but not for performing surgery. The surgeon therefore opts for a BCI system featuring motor extension and sensory addition capabilities: Intracortical recording arrays capture movement-related neural activity from motor cortex, which are decoded using machine-learning algorithms and converted into commands for a prosthetic which can directly interface with robotic surgical instruments. The system also incorporates a closed-loop sensory component: contact sensors on the interface detect pressure and movement, and patterned electrical stimulation is delivered to somatosensory cortex to improve tactile sensation and proprioception. Through repeated closed-loop training, the surgeon enhances her movement precision beyond pre-stroke baselines.

#2 The Financial Trading Floor

An investment firm adopts a neuroadaptive system to enhance attention and rapid decision-making during periods of market volatility. Traders wear non-invasive EEG headbands which track task engagement and fatigue in real-time. These signals are used to adapt the trader's interface dynamically, for instance, by prioritising particular data feeds and promoting sustained engagement through neurofeedback. Additionally, a form of mobile transcranial alternating current stimulation (tACS), delivered through electrodes in frontal and parietal locations on the scalp, entrains task-relevant brain rhythms, supporting attentional control and rapid task-switching. Together, these techniques enable traders to monitor 15–20 data streams at once, recognise patterns in market data around 300 milliseconds faster than unaugmented traders, and sustain attention across trading sessions of six hours or more with markedly reduced cognitive fatigue.

#3 The Emergency Response Network

First responders adopt a network-based neuroadaptive system designed to coordinate attention and emotional regulation across an entire team during natural disasters. Each first responder wears a non-invasive EEG system alongside electrodes measuring physiological responses (e.g. heartbeat, skin conductance). A central platform measures the team's collective state in real-time and coordinates interventions designed to align their affective state - including neurofeedback and stimulation (e.g. mobile tDCS) to align brain rhythms across users, as well as regulating arousal and attention.

#4 The Adaptive Classroom

A secondary school pilots a neuroadaptive learning environment to enhance memory and learning. Students wear EEG headbands during lessons which monitor attentional engagement, cognitive load and fatigue. A software system uses these measures to adjust lesson pacing, task difficulty, and aspects of the classroom environment such as lighting, sound, and temperature. Teachers and parents receive dashboards showing individual and aggregate indicators of focus, stress, and learning efficiency. The edtech company involved also offers neurofeedback and non-invasive transcranial magnetic stimulation (TMS) during study breaks or before exams, intended to improve attentional control, reduce anxiety and

strengthen memory consolidation. Over time, students using the system achieve better academic outcomes, and disparities begin to emerge between adopters and non-adopters within the same year group.
#5 The Silent Operator A defense agency deploys a subvocal speech and communication interface to special operations units. Implanted micro-electrode arrays record neural activity directly from the motor cortex, inferior frontal and premotor areas. Together with electromyographic recordings from the jaw and surrounding musculature, these signals enable the highly precise real-time decoding of silent/imagined speech. Intelligence and tactical commands generated this way are transmitted to team members via bone conduction audio. This system can be integrated with an AI co-pilot for real-time tactical analysis, shortening decision loops by detecting and acting on pre-articulatory neural signals and enabling covert communication.
#6 The Rehabilitating Veteran An injectable neural implant receives approval for stroke and traumatic brain injury (TBI) rehabilitation and shows potential for enhancing memory and learning. Delivered through a minimally invasive procedure and guided into position by an external magnetic field, the bioresorbable device remains active for a defined rehabilitation period before safely degrading in the body. It delivers targeted electrical stimulation intended to improve local perfusion in damaged brain regions, enhancing neuroplasticity in response to rehabilitation and training. Most users (initially, military veterans with combat-related TBI) regain function almost completely, while some report cognitive performance gains beyond their pre-injury levels. As a result, healthy individuals begin seeking access to the same intervention
#7 The Electromagnetic Reader A university spin-out develops a wearable focused ultrasound cap that detects ambient electromagnetic fields (EMF) emitted by power lines, Wi-Fi routers, mobile networks, and electronic devices. The cap translates these signals into dynamic, patterned focused ultrasound delivered across visual cortex, generating faint visual percepts, or phosphenes, that users learn to interpret as a spatial representation of the surrounding electromagnetic environment. As a form of sensory addition, the system does not restore an existing sense but allows users to perceive (previously) invisible signals.

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