UNIDIR

# Neurotechnology in the Military Domain: A Primer

FEDERICO MANTELLASSI • EDWARD MADZIWA

## Acknowledgements

Support from UNIDIR funders provides the foundation for all of the Institute's activities. This study was produced by UNIDIR's Security and Technology Programme (SECTEC), which is supported by Czechia, Germany, Italy, the Netherlands, Norway, the Republic of Korea, Switzerland and Microsoft.

The authors would like to extend their sincere thanks to Ioana Puscas, Sarah Grand-Clément, Dr Giacomo Persi Paoli, Gosia Loj, Dr Łukasz Kamieński and Dr Renaud Jolivet for their thoughtful comments on previous versions of this paper.

## About UNIDIR

The United Nations Institute for Disarmament Research (UNIDIR) is a voluntarily funded, autonomous institute within the United Nations. One of the few policy institutes worldwide focusing on disarmament, UNIDIR generates knowledge and promotes dialogue and action on disarmament and security. It is based in Geneva and assists the international community in developing the practical, innovative ideas needed to find solutions to critical security problems.

## About the Security and Technology Programme

Contemporary developments in science and technology present new opportunities for, as well as challenges to, international security and disarmament. UNIDIR's Security and Technology Programme aims to build knowledge and awareness about the international security implications and risks of specific technological innovations and convenes stakeholders to explore ideas and develop new thinking on ways to address them.



## Citation

Federico Mantellassi and Edward Madziwa, *Neurotechnology in the Military Domain: A Primer* (Geneva: UNIDIR, 2025)

## Authors

**Federico Mantellassi** is a Researcher in the Security and Technology Programme at UNIDIR.

**Edward Madziwa** is a Programme Assistant in the Security and Technology Programme at UNIDIR.

---

**Cover image:** Warfighter profile with glowing digital brain visualization and neural pathways (generated with AI). Credit: Adobe Stock / Domingo.

# Acronyms & Abbreviations

| | |
|---|---|
| **AI** | Artificial intelligence |
| **BBI** | Brain-to-brain interface |
| **BCI** | Brain–computer interface |
| **BWC** | Biological Weapons Convention |
| **CWC** | Chemical Weapons Convention |
| **DBS** | Deep brain stimulation |
| **EEG** | Electroencephalogram |
| **FMRI** | Functional magnetic resonance imaging |
| **ICT** | Information and communications technologies |
| **MRI** | Magnetic resonance imaging |
| **PET** | Positron emission tomography |
| **PTSD** | Post-traumatic stress disorder |
| **TBS** | Transcranial brain stimulation |

# Contents

# Introduction

Neurotechnology[1] is an emerging but rapidly advancing field that offers significant promise across various domains, while also posing considerable risks. These risks have prompted an emerging discussion over the need for governance to ensure that the technology is developed in ways that are ethical, safe and secure.[2] In particular, the dual-use nature of neurotechnologies raises the potential for them to become disruptive military technologies. Militaries worldwide have explored the integration of a wide suite of neurotechnologies into the military domain throughout the 21st century, with some initiatives dating back to the late 20th century.[3] Recent advances in various scientific and technological fields have rendered the integration of neurotechnology into military contexts increasingly likely to become a reality in the near future. In contrast to civilian neurotechnology, this trend has received comparatively less attention, while carrying with it significant potential risks for international peace and security. A preliminary mapping of the potential risks, challenges and opportunities specifically associated with the militarization of neurotechnology is therefore both timely and necessary.

This primer has four sections. Section 1 briefly introduces neurotechnology, providing a description of what it does and how. Section 2 provides an overview of potential military applications of various neurotechnologies for various functions: battlefield applications, support functions (i.e., training, recruitment and personnel screening), military healthcare, intelligence, interrogation and counterintelligence. It also exposes the drivers behind the increasing desire to adopt neurotechnology in the military domain. Section 3 then provides a preliminary risk mapping linked to the militarization of neurotechnology. Due to the complexity of the technology, and its early stages of development and deployment in the military domain, an in-depth risk assessment is beyond the scope of this primer. Rather, it gives a general overview of the potential military uses of neurotechnology, highlighting possible categories of risk linked to its militarization. This may serve as a springboard for a future, more detailed analysis as the technology matures. Finally, Section 4 sets out an initial overview of ways in which neurotechnologies may intersect with disarmament and arms control, both due to their accelerating development and deployment in the military domain and due to their commercial proliferation.

---

1 The term “neurotechnology” in this Primer refers to the general field pertaining to the technologies that monitor, interact with or alter the nervous system, while the term “neurotechnologies” describes the different tools, devices and applications developed (e.g., neural implants, brain computer interfaces and neuromodulation devices).

2 UNESCO, “First draft of a Recommendation on the Ethics of Neurotechnology (revised version)”, Working document as of 27 August 2024, https://unesdoc.unesco.org/ark:/48223/pf0000391074.

3 Jonathan Moreno, *Mind Wars: Brain Science and the Military in the 21st Century* (Bellevue Literary Press, 2012).

# 1. What is neurotechnology?

Neurotechnology encompasses a wide range of technologies and techniques aimed at accessing, monitoring, investigating, assessing, manipulating or stimulating the structure and function of the nervous system, including the brain, the spinal cord and nerves.[4] These technologies are designed to do at least one of the following:

**a.** To record brain signals and "translate" them into technical commands to control external devices

**b.** To monitor neural activity through brain imaging or recording electrodes

**c.** To manipulate brain activity through the application of electrical, optical, ultrasound or magnetic stimuli[5]

Neurotechnologies were first designed and deployed in the medical field, which remains their primary field of application. These capabilities have unlocked treatment options for neurodevelopmental, neurodegenerative and mental health conditions (e.g., Parkinson's disease or post-traumatic stress disorder, (PTSD)), as well as physical disorders through interfacing with such external devices as prosthetics or computers.[6] Today, neurotechnology is increasingly making inroads into consumer markets, driven by a growing desire for wearables, digital biometrics and consumer electronics.[7]

Indeed, while standard wearables like smartwatches already track heart rate, sleep or activity levels, neurotechnologies designed to record, monitor or manipulate the brain and the nervous system have advanced the scope of what wearables can do.[8] Consumer neurotechnology now includes, for example, applications as varied as wellness monitoring and cognitive enhancement, immersive entertainment, and brain–computer interaction among others.[9] Neurotechnology wearables not only gather neural data (i.e., data related to neural activity and the quantitative measurement of the structure, activity and function of the nervous system)

---

[4] UNESCO, *The Risks and Challenges of Neurotechnologies for Human Rights* (Paris: UNESCO, 2023), https://unesdoc.unesco.org/ark:/48223/pf0000384185; Organisation for Economic Co-operation and Development (OECD), "Recommendation on Responsible Innovation in Neurotechnology", 2019, https://legalinstruments.oecd.org/api/print?ids=658&Lang=en; Healthdirect, "Nervous System", n.d., https://www.healthdirect.gov.au/nervous-system.

[5] UNESCO, "Report of the International Bioethics Committee of UNESCO (IBC) on the Ethical Issues of Neurotechnology", 15 December 2021, https://unesdoc.unesco.org/ark:/48223/pf0000378724.

[6] Ricardo Chavarriaga, Jean-Marc Rickli and Federico Mantellassi, *Neurotechnologies: The New Frontier for International Governance*, Strategic Security Analysis no. 29 (Geneva: Geneva Centre for Security Policy, 2023), https://www.gcsp.ch/sites/default/files/2024-12/ssa-2023-issue29.pdf.

[7] Centre for Future Generations, "Neurotech Consumer Market Atlas: How the sector is making moves into the mainstream", 16 June 2025, https://cfg.eu/neurotech-market-atlas/; Rolfe Winker, "Apple to Support Brain-Implant Control of its Devices", *Wall Street Journal*, 13 May 2025, https://www.wsj.com/tech/apple-brain-computer-interface-9ec69919.

[8] Nuno Gomes et al., "A Survey on Wearable Sensors for Mental Health Monitoring", *Sensors*, vol. 23, no. 3 (2023).

[9] Centre for Future Generations, "Neurotech Consumer Market Atlas".

but also influence cognition and mental states.[10] Examples include electroencephalogram (EEG) headbands such as Muse and Emotiv, which monitor brainwave activity in real time and provide feedback to improve focus, reduce stress or support meditation practices.[11] Most recently, Meta launched augmented reality glasses, the features of which can be controlled by a neural interface called the "Neural Band".[12]

Neurotechnology is inextricably linked to other converging technological fields, such as artificial intelligence (AI) and biotechnology, with advances in all fields influencing one another.[13] AI, for example, has enhanced the ability to map the brain, decipher brain signals, improve the analysis of these signals and neural data, as well as mediate their translation into specific outputs.[14] Developments in biotechnology, for their part, have improved the capacity to access the brain, with genetic editing technologies (e.g., CRISPR-Cas9) that will continue to accelerate this convergence and enable novel devices, techniques and treatments.[15] These technological convergences have thus contributed to enabling significant progress in neurotechnology in recent years. AI, biotechnology and access to vast quantities of computing power have played a key role in the growing transition of advancements from research laboratories to clinical applications and viable consumer applications. These have revolutionized treatment options and broadened prospects for brain health, rehabilitation and human–computer interaction.

Neurotechnologies can be broadly categorized based on their level of invasiveness and their primary function.[16]

## Level of invasiveness:

- **Invasive** methods involve inserting electrodes or implants into the brain to modify the neural system.[17] Deep brain stimulation (DBS) is one such example. Although these systems pose risks and complexities for the user, they are essential for applications that demand precise

---

[10] Patrick Magee, Marcello Ienca and Nita Farahany, "Beyond Neural Data: Cognitive Biometrics and Mental Privacy", *Neuron*, vol. 11, no. 18 (2024).

[11] Muse, https://eu.choosemuse.com/; Emotiv, https://www.emotiv.com/.

[12] Meta, "Meta Ray-Ban Display: AI Glasses with an EMG Wristband", 17 September 2025, https://about.fb.com/news/2025/09/meta-ray-ban-display-ai-glasses-emg-wristband/.

[13] Sara Berger and Francesca Rossi, "AI and Neurotechnology: Learning from AI Ethics to Address an Expanded Landscape", *Communications of the ACM*, vol. 66, no. 3 (2023), https://doi.org/10.1145/3529088; Dirk Helbing and Marcello Ienca, "Why Converging Technologies Need Converging International Regulation", *Ethics and Information Technology*, vol. 26, no. 15 (2024), https://link.springer.com/article/10.1007/s10676-024-09756-8.

[14] Chavarriaga et al., Neurotechnologies.

[15] Helbing and Ienca, "Why Converging Technologies Need Converging International Regulation".

[16] Timo Istace and Milena Costas Trascasas, "Between Science-Fact and Science-Fiction: Innovation and Ethics in Neurotechnology", *Geneva Academy of International Humanitarian Law and Human Rights Research Brief*, 2024, https://www.adh-geneve.ch/joomlatools-files/docman-files/Between Science-Fact and Science-Fiction Innovation and Ethics in Neurotechnology.pdf; Jakob Hensing and Andreas Faika, *Neurotechnology: A New Frontier for Prosperity and Security in Germany and Europe* (Berlin: GPPI, 2025), https://gppi.net/2025/03/27/neurotechnology-a-new-frontier-for-prosperity-and-security-in-germany-and-europe.

[17] Hensing and Faika, Neurotechnology.

control (e.g., the restoration of movement or communication in individuals with severe paralysis).[18]

- **Non-invasive** techniques communicate with the neurological system without implants, penetration or surgery.[19]
- **Partially invasive** techniques use implants that require minimal surgery or pre-existing medical technologies (e.g., stents and catheters) to insert electrodes close to the brain without open surgery.[20]

### Primary function:

- **Sensing** entails the identification and documentation of brain activity by acquiring metabolic, chemical or electrical signals from the brain or nervous system, such as through **neuroimaging** methods or recording electrodes.[21]
- **Stimulation** entails the delivery of targeted energy – which can be either electrical, optical, ultrasound or magnetic – to the neural tissue to regulate its activity, through for example **neuromodulation** techniques.[22]
- **Interfacing** is the process of making a direct operational link between the nervous system and external devices or systems, for example, through **brain–computer interfaces** (BCIs).[23]

The three examples of neurotechnologies methods mentioned above – neuroimaging, neuromodulation and Interfacing – are explained further below, before the section turns to challenges and limitations.

---

18 Jeremy Y. Ng, "Exploring the Intersection of Brain–Computer Interfaces and Traditional Complementary and Integrative Medicine", *Integrative Medicine Research*, vol 14, no. 2 (2025), **https://www.sciencedirect.com/science/article/pii/S2213422025000228**; Analysis and Research Team, "From Vision to Reality: Promises and Risks of Brain Computer Interfaces", *Council of the European Union General Secretariat*, 2024, **https://www.consilium.europa.eu/media/fh4fw3fn/art_braincomputerinterfaces_2024_web.pdf**.

19 Brandan Alison et al., "Future Directions in Brain/Neuronal Computer Interaction (Future BNCI)", Conference Paper, BCI Meeting 2010, Asilomar, California, **http://bcimeeting.org/2010/poster_abstracts.shtml#S2**.

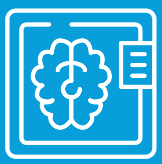
20 Matthew Sample et al., "Do Publics Share Experts' Concerns about Brain–Computer Interfaces? A Trinational Survey on the Ethics of Neural Technology", *Science, Technology, & Human Values*, vol. 45, no. 1 (2020), **https://doi.org/10.1177/0162243919879220**.

21 Glenn J.M. van der Lande et al., "Brain State Identification and Neuromodulation to Promote the Recovery of Consciousness", *Brain Communications*, vol. 6, no. 5 (2024), **https://doi.org/10.1093/braincomms/fcae362**.

22 Hayoung Song et al., "Neuromodulation of the Peripheral Nervous System: Bioelectronic Technology and Prospective Developments", *BMEMat*, vol. 2, no. 1 (2023), **https://doi.org/10.1002/bmm2.12048**.

23 Hongyu Zhang et al., "Brain–Computer Interfaces: The Innovative Key to Unlocking Neurological Conditions", *International Journal of Surgery*, vol. 110, no. 9 (2024), **https://doi.org/10.1097/js9.0000000000002022**.

## NEUROIMAGING



Neuroimaging refers to various techniques used to visualize, monitor and record the structure and functioning of the brain and central nervous system. It is a key enabler of neurotechnology applications such as BCIs and brain decoding.[24]

Examples of non-invasive methods include EEG, magnetic resonance imaging (MRI), functional MRI (fMRI), computed tomography (CT) and positron emission tomography (PET).[25]

Invasive methods include electrocorticography (ECoG), which requires the placement of electrodes directly on the brain's surface and provides more accurate temporal readings of neural activity patterns (i.e., when things happen in the brain). Even greater precision can be achieved with penetrating electrodes implanted directly into the brain tissue.[26]

## NEUROMODULATION

Neuromodulation[27] denotes the modification of neuronal activity (i.e., the electrical and chemical signals produced and transmitted by neurons in the brain) through various approaches.[28] Broadly speaking, these include DBS and transcranial brain stimulation (TBS). TBS delivers stimulation electrically and magnetically through focused ultrasound or through optogenetics (i.e., using light to control cells, typically brain cells, that have previously been genetically modified). Other forms of neuromodulation include pharmacological agents and stimulation of the vagus nerve. These techniques modify, bypass or substitute neuronal structures and processes to influence brain activity. The key objective is to alter the way in which the nervous system transmits messages, which can lead to changes in sensory, motor or cognitive functions.

## INTERFACING

Interfacing refers to the use of physical interfaces between the human brain and external devices. For example, BCIs are systems that convert the activity of the central nervous system into an artificial output that replaces, restores, enhances, supplements or improves the system's natural output. BCIs thereby alter the interactions between the central nervous system and its external or internal environment.[29] These technologies enable direct communication between the brain and external devices such as computers.

Given that BCIs rely mainly on the transmission of data between the brain and a computer, they can be divided according to the direction of information flow: unidirectional or bidirectional. Unidirectional BCIs either receive signals from the brain or send signals to it, while bidirectional BCIs allow for information exchange in both directions.[30]

---

24 Chaihui Yen, Chia-Li Lin and Ming-Chang Chiang, "Exploring the Frontiers of Neuroimaging: A Review of Recent Advances in Understanding Brain Functioning and Disorders", *Life (Basel)*, vol. 13, no. 7 (2023), https://doi.org/10.3390/life13071472; Istace and Costas Trascasas, "Between Science-Fact and Science-Fiction".

25 Istace and Costas Trascasas, "Between Science-Fact and Science-Fiction". EEG monitors electrical currents in various brain regions, fMRI infers brain activity from blood oxygen levels, and PET uses administered radioactive substances for imaging.

26 Istace and Costas Trascasas, "Between Science-Fact and Science-Fiction".

27 It must be noted that, in basic physiology, the term neuromodulation carries a slightly different meaning and denotes the process by which neurons regulate the activity of other neurons through chemical releases.

28 Hayoung Song et al.,"Neurmodulation of the Peripheral Nervous System".

29 Jonathan R. Wolpaw, "Brain Computer Interfaces", in *Handbook of Clinical Neurology*, ed. Michale P. Barnes and David C. Good (Amsterdam: Elsevier, 2013), https://www.sciencedirect.com/science/article/abs/pii/B978044452901500006X.

30 Janis Peksa and Dmytro Mamchur, "State-of-the-Art on Brain-Computer Interface Technology", *Sensors*, vol. 23, no. 13 (2023), https://www.mdpi.com/1424-8220/23/13/6001.

Close-up of neurological MRI scan (generated with AI). Credit: Adobe Stock / quanlu.

## 1.1. Fundamental challenges and current limitations

While significant progress has been made in the development and application of neurotechnologies, particularly in the health sector, substantial challenges remain. These can be broadly divided into three interrelated categories:

- **a.** Technological: limitations in the current state of the art in the component technologies,
- **b.** Biological: issues related to the degradation of components or signals due to the biology of the human brain,[31]
- **c.** Neurological: problems linked to the still incomplete understanding of the human brain.[32]

These challenges will continue to hamper the reliable utilization of advanced types of neurotechnologies in both the civilian and military domains.

---

[31] Maddison A. Spenrath, Margaret E. Clarke and Stanley Kutcher, "The Science of Brain and Biological Development: Implications for Mental Health Research, Practice and Policy", *Journal of the Canadian Academy of Child and Adolescent Psychiatry*, vol. 20, no. 4 (2011), **https://pmc.ncbi.nlm.nih.gov/articles/PMC3222573/**.

[32] Jing Reng and Feng Xia, "Brain-inspired Artificial Intelligence: A Comprehensive Review", arXiv preprint, 2024, **https://arxiv.org/html/2408.14811v1**.

# 2. Neurotechnology in the military domain

While the development of neurotechnology is primarily driven by civilian applications, it is inherently a dual-use technology, and military research has played an important role in its advancement since the late 20th century.[33] Indeed, military research institutions, such as the US Defense Advanced Research Projects Agency (DARPA), have long invested in neurotechnology projects and have produced breakthrough innovations in the field.[34] These institutions (e.g., in China and the United States) have also been key beneficiaries of national efforts directed at advancing research into neuroscience and neurotechnology, such as the US BRAIN initiative, or China Brain Project.[35]

The military potential of many of the capabilities emerging from this field means that they are of significant interest to armed forces. For example, experts have identified applications of dual-use neurotechnologies, such as brain–computer interfaces, neurotechnologies for warfighter enhancement, and neurotechnological systems for deception, detection and interrogation.[36]

The desire to leverage the augmentative possibilities of neurotechnologies in the military domain can be considered within the broader context of human enhancement or augmentation technologies. Human enhancement has a long history in the military domain, not limited to neurotechnology but encompassing a wide array of other physical, chemical and biological augmentations.[37] In its broadest sense, augmentation refers to the application of science and technology for the cognitive and physical enhancements of soldiers beyond what is needed to be healthy.[38]

The military application of neurotechnology is still in its very early stages – it is less developed than its civilian counterpart and much of the current research is confined to laboratories in a limited number of countries.[39] Nevertheless, it is a rapidly evolving domain that is attracting

---

33 US Defense Advanced Research Projects Agency, "Six Paths to the Nonsurgical Future of Brain–Machine Interfaces", 20 May 2019, https://www.darpa.mil/news/2019/nonsurgical-brain-machine-interfaces; Robin A. Miranda et al., "DARPA-Funded Efforts in the Development of Novel Brain–Computer Interface Technologies", *Journal of Neuroscience Methods*, vol. 244 (2015), https://doi.org/10.1016/j.jneumeth.2014.07.019.

34 Miranda et al., "DARPA-Funded Efforts".

35 Margaret Kosal and Joy Putney, "Neurotechnology and International Security: Predicting Commercial and Military Adoption of Brain–Computer Interfaces (BCIs) in the United Sates and China", *Politics Life Sciences*, vol. 42, no. 1 (2023), https://doi.org/10.1017/pls.2022.2.

36 Michael N. Tennison and Jonathan D. Moreno, "Neuroscience, Ethics and National Security: The State of the Art", *PLoS Biology*, vol. 10, no. 3 (2012), https://doi.org/10.1371/journal.pbio.1001289.

37 British Ministry of Defence, *Human Augmentation – The Dawn of a New Paradigm: A Strategic Implications Project* (London: Ministry of Defence, 2021), https://www.gov.uk/government/publications/human-augmentation-the-dawn-of-a-new-paradigm; Łukasz Kamieński, "Military Neuroenhancement", in *Routledge Handbook of the Future of Warfare*, ed. Artur Gruszczak and Sebastian Kaempf (London: Routledge, 2021).

38 Joachim Klerx, "The Future of Human Enhancement in the Military Domain", in *Icarius' Wings: Navigating Human Enhancement*, Schriftenreihe der Landesverteidigungsakademie no. 3/2025, ed. Anton Dengg (Vienna: Landesverteidigungsakademie, 2025), https://www.bmlv.gv.at/pdf_pool/publikationen/book_icarus_wings_04_klerx_technology.pdf.

39 Kosal and Putney, "Neurotechnology and International Security".

growing attention and investment, with potential profound implications for warfare. A number of potential military applications of neurotechnology (including both combat and non-combat-related applications as well as both restorative and augmentative applications), while largely still in an early research and development phase, feature prominently in expert discourse (see Table 1 for a non-exhaustive list). Others lie further in the future (see Box 1).

The growing interest in neurotechnology in the military domain is the result of the convergence between human augmentation with the parallel trend of human–machine integration. Advances in human–machine integration are, for their part, related to the growing military roles of AI, uncrewed systems and robotics. Indeed, the proliferation of AI-enabled capabilities, digital systems, sensors and connected devices has led to an explosion of data produced by modern battlefields. It has also created a need to collect, analyse and act upon insights gained from an ever growing number of data streams at ever faster speed.[40] This has compressed decision-making timelines, increased the cognitive workload of soldiers and created incentives to further rely on AI capabilities to coordinate a growing number of systems and to assist in command and control.[41] Some have argued that, in this context, humans – who increasingly have to partner with a growing array of intelligent systems operating at machine speed – have become the most inefficient element in this system.[42] This has resulted in a desire to increasingly integrate humans with military technological systems and to develop technologies that facilitate this integration and allow for a smoother teaming between humans and computational systems.[43] Neurotechnologies represent one of the possible ways in which this interfacing could take place, allowing soldiers to remain cognitively engaged and to cope with the increased demands, complexity and accelerated decision-making speeds of modern battlefields.[44] Such augmentation has the potential to improve, among other things, cognitive processing, reaction time, memory, and resilience to fatigue and stress, as well as neural interfacing with autonomous systems.[45]

It must be noted, however, that military interest in neurotechnology stems not only from the field's augmentative potential, but also from its restorative potential. Indeed, members of

---

[40] Ruben Stewart, "The Shifting Battlefield: Technology, Tactics and the Risk of Blurring Lines in Warfare", *ICRC Humanitarian Law and Policy Blog*, 22 May 2025, **https://blogs.icrc.org/law-and-policy/2025/05/22/the-shifting-battlefield-technology-tactics-and-the-risk-of-blurring-lines-of-warfare/**.

[41] Sahar Latheef, "Brain to Brain Interfaces (BBIs) in Future Military Operations; Blurring the Boundaries of Individual Responsibility", *Monash Bioethics Review*, vol. 41, no. 1 (2023), **https://doi.org/10.1007/s40592-022-00171-7**.

[42] Kamieński, "Military Neuroenhancement".

[43] Anika Binnendijk, Timothy Marler and Elizabeth M. Bartels, "Brain–Computer Interfaces: U.S. Military Applications and Implications – An Initial Assessment", RAND Corporation, 2020, **https://www.rand.org/content/dam/rand/pubs/research_reports/RR2900/RR2996/RAND_RR2996.pdf**; Marina Favaro and Elke Schwarz, "Human Augmentation and Nuclear Risk: The Value of a Few Seconds", *Arms Control Today*, March 2022, **https://www.armscontrol.org/act/2022-03/features/human-augmentation-and-nuclear-risk-value-few-seconds**.

[44] Binnendijk et al., "Brain–Computer Interfaces".

[45] Imre Négyesi, "Opportunities for the Development of Military Cognitive Skills II (Practical Approach)", *Scientific Bulletin*, vol. 29, no. 1 (2024), **https://doi.org/10.2478/bsaft-2024-0009**; Klerx, "The Future of Human Enhancement in the Military Domain"; Tad T. Brunyé et al., "Neuroenhancement in Military Personnel: Conceptual and Methodological Promises and Challenges", STO Technical Report TR-HFM-311, NATO, 2024, **https://ris.utwente.nl/ws/portalfiles/portal/293569323/AD1159590.pdf**.

armed forces suffer from the types of injuries, both physical and psychological, for which neurotechnology holds much promise, such as lost mobility, loss of limbs, PTSD or traumatic brain injury (TBI).[46]

TABLE 1.

## Potential applications of neurotechnologies in the military domain

| POTENTIAL MILITARY USES | NEURO-TECHNOLOGY | EXPLANATION |
|---|---|---|
| **BATTLEFIELD APPLICATIONS** | | |
| Cognitive enhancement and battlefield network integration | BCIs | BCIs could further integrate humans within human–machine teams by allowing direct neural interfacing with other networked battlefield capabilities, information networks and AI-enabled battlefield-awareness systems (e.g., uncrewed systems, ground sensors, satellites and other decision-support tools).[47] This meshing of human and machine intelligence could provide soldiers with higher levels of situational awareness as they could receive, process and analyze a growing array of information from those sources faster and more efficiently.[48] This in turn would assist in the identification of threats or in the navigation of unfamiliar terrain.[49] |
| | Neuromodulation | Neuromodulation could improve some cognitive functions that are important to decision-making (e.g., alertness, concentration or memory).[50] This has potential to accelerate the skill acquisition of personnel and to enhance their performance and abilities in combat.[51] |
| Operation of uncrewed systems | BCIs | BCIs could enable soldiers to remotely control uncrewed vehicles directly through neural commands, eliminating the need for physical interfaces such as keyboards, joysticks or |

46 Michael J. Young, David J. Lin and Leigh R. Hochberg, "Brain–Computer Interfaces in Neurorecovery and Neurorehabilitation", *Semin Neurology*, vol. 41, no. 2 (2021), https://doi.org/10.1055/s-0041-1725137.

47 Stewart, "The Shifting Battlefield"; KPMG, "Artificial Intelligence (AI) in Defence Modernisation", 23 June 2025, https://kpmg.com/in/en/blogs/2025/06/artificial-intelligence-in-defence-modernisation.html.

48 Kamieński, "Military Neuroenhancement".

49 Jonathan P. Wong et al., One Team, One Fight, Vol. I, *Insights on Human Machine Integration for the U.S. Army* (Santa Monica, CA: RAND Corporation, 2025), https://www.rand.org/pubs/research_reports/RRA2764-1.html.

50 Kamieński, "Military Neuroenhancement".

51 Emily Waltz, "DARPA to Use Electrical Stimulation to Enhance Military Training", 26 April 2017, https://spectrum.ieee.org/darpa-to-use-electrical-stimulation-to-improve-military-training; Gary Sheftick, "Army Researchers Looking to Neurostimulation to Enhance, Accelerate Soldiers' Abilities", 14 June 2018, https://www.army.mil/article/206197/army_researchers_looking_to_neurostimulation_to_enhance_accelerate_soldiers_abilities.

| | | |
|---|---|---|
| | | touchscreens.[52] This is one of the most probable and possible military uses of BCIs, and it is a key rationale behind the development of military neurotechnology as a whole. It is also one of the most disruptive capabilities. For example, BCIs are expected to allow the operation of swarms of uncrewed vehicles in the near future.[53] |
| Cognitive strain detection | Neuroimaging | Neuroimaging techniques may be utilized in the evaluation and assessment of cognitive, emotional or behavioural states.[54] For example, continuous neuroimaging may detect when a soldier's focus wanes or when cognitive or emotional strain occurs. This would allow for timely interventions (e.g., rest, stimulation or task reassignment) before performance declines.[55] It is important to note that these methods remain expensive and not easily portable, limiting their operational potential and usefulness at present stages of development. |
| Real-time control of personnel | BCIs | The connection of soldiers to BCIs could allow commanders to remotely manipulate some aspects of their behaviour on the battlefield. Commanders could issue orders directly to the brain of a soldier and manipulate neural implants in a way that could influence behaviour or regulate emotional states and decision-making through chemical releases or stimulation of brain functions.[56] It is important to note that this remains one of the more speculative applications of military neurotechnology. |
| **SUPPORT FUNCTIONS (TRAINING, RECRUITMENT, SCREENING)** | | |
| Training optimization | BCIs | BCIs could assist in the creation of immersive battlefield scenarios or the personalization of training regimes.[57] Militaries have also shown interest in the ability of BCIs to help accelerate complex skill acquisition (e.g. foreign language acquisition, marksmanship, cryptography |

---

52 Zhuming Bi et al., "Brain Computer Interface for Shared Controls of Unmanned Aerial Vehicles", *IEEE Transactions on Aerospace and Electronic Systems*, 2024, https://doi.org/10.1109/TAES.2024.3368402; Ivan S. Kotchetkov et al., "Brain–Computer Interfaces: Military, Neurosurgical and Ethical Perspective", *Neurosurg Focus*, vol. 28, no. 5 (2010), https://pubmed.ncbi.nlm.nih.gov/20568942/; Jo Best, "Mind-Controlled Drones and Robots: How Thought-Reading Tech Will Change the Face of Warfare", ZDNet, 28 July 2020, https://www.zdnet.com/article/mind-reading-particles-for-the-military-the-bcis-that-enable-soliders-to-fly-planes-with-their-thoughts-alone/; Binnendijk et al., "Brain–Computer Interfaces".

53 Kamieński, "Military Neuroenhancement".

54 John A. Cadwell, Jennifer K. Smith and J. Lynn Cadwell, "Functional Magnetic Resonance Imaging Shows Potential for Predicting Individual Differences in Fatigue Vulnerability", United States Airforce Research Laboratory, 2004, https://www.researchgate.net/publication/235041369_Functional_Magnetic_Resonance_Imaging_Shows_Potential_for_Predicting_Individual_Differences_in_Fatigue_Vulnerability; Kamieński, "Military Neuroenhancement".

55 Brunyé et al., "Neuroenhancement in Military Personnel".

56 Wong et al., *One Team, One Fight.*

57 Anna M. Gielas, "Soldier Enhancement through Brain-Computer Interfaces: The Risks of Changing the Human Condition", *RUSI Journal*, vol. 170, no. 1 (2025), https://www.researchgate.net/publication/389127194_Soldier_Enhancement_through_Brain-Computer_Interfaces_The_Risks_of_Changing_the_Human_Condition.

| | | |
|---|---|---|
| | | and target discrimination), thereby shortening the time, resources and investment required for combat preparation.[58] |
| | Neuroimaging | Neuroimaging techniques may be used in the context of military training by providing armed forces with insights into the cognitive and functional status of individual soldiers. This may help them assess the training status of individual soldiers and so allow them to optimize and personalize training and to assign soldiers with roles that align with their strengths.[59] |
| Recruitment and task assignment | Neuroimaging | Neuronal profiling may provide reliable methods to identify the most appropriate candidates for service, assign them to specific branches and delegate the most suitable tasks.[60] For example, fMRI allows the detection of individuals who are quick learners, more willing to take risks, resilient to mental stress or tolerant to sleep deprivation. |
| Personnel monitoring | BCIs, neuroimaging | Brain and body functions of military personnel could be continuously monitored by relevant specialized units or commanders.[61] This could assist commanders in tailoring troop deployment, mission tasks and unit composition based on the physical and cognitive condition of personnel – finding the soldiers with the optimal conditions for a specific mission or task.[62] Real-time warnings about any negative psychological and physical condition of personnel could allow commanders to take preventive action that could contribute to positive mission outcomes. |
| **MILITARY HEALTHCARE AND REHABILITATION** | | |
| Mental health treatment and rehabilitation | Neuromodulation | By offering specialized therapies to alter brain circuits involved in processing memories, anxiety and fear, various neuromodulation techniques could be utilized in the prevention and treatment of PTSD.[63] |

58 Binnendijk et al., "Brain–Computer Interfaces".

59 Carolina Diaz-Piedra, Maria Victoria Sebastián and Leandro L. di Stasi, "EEG Theta Power Activity Reflect Workload among Army Combat Drivers: An Experimental Study", *Brain Sciences*, vol. 10, no. 199 (2020), https://pmc.ncbi.nlm.nih.gov/articles/PMC7226148/; Brunyé et al., "Neuroenhancement in Military Personnel"; US National Research Council, Committee on Opportunities in Neuroscience for Future Army Applications, "Opportunities for Future Army Applications, 3 Training and Learning", 2009, https://www.ncbi.nlm.nih.gov/books/NBK207966/; Yen et al., "Exploring the Frontiers of Neuroimaging".

60 US National Research Council, "Opportunities for Future Army Applications".

61 Noam Lubell and Katya Al-Khateeb, "Cyborg Soldiers: Military Use of Brain-Computer Interfaces and the Law of Armed Conflict." In *Big Data and Armed Conflict: Legal Issues Above and Below the Armed Conflict Threshold*, ed. Laura A. Dickinson and Edward W. Berg (Oxford: Oxford University Press, 2022), https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4160967.

62 Lubell and Al-Khateeb, "Cyborg Soldiers".

63 Felicia Manocchio et al., "Neuromodulation as a Therapeutic Approach for Post-Traumatic Stress Disorder: The Evidence to Date", *Expert Review of Neurotherapeutics*, vol. 25, no. 8 (2024), https://pubmed.ncbi.nlm.nih.gov/39704493/; Vlada Novakovic et al., "Brain Stimulation in Posttraumatic Stress Disorder", *European Journal of Psychotraumatology*, vol. 2 (2011), https://pubmed.ncbi.nlm.nih.gov/22893803/.

| | | |
|---|---|---|
| | | Neuromodulation may further assist military personnel in managing stress or recovering from mental exhaustion.[64] |
| Control of artificial or digital devices post injury | BCIs | BCIs also have myriad medical applications for personnel who have sustained injuries such as loss of limbs or paralysis, providing them with a higher quality of life and independence post-deployment. BCIs can enable soldiers to control devices such as prosthetics or robotic devices that replace lost limbs by conveying their intent without engaging the peripheral nerves or muscles.[65] Existing applications further show that BCIs can enable paralyzed patients to navigate digital environments using only their thoughts.[66] |
| **INTELLIGENCE, INTERROGATION AND COUNTERINTELLIGENCE** | | |
| Security screening and detection | BCIs | BCIs could be used in intelligence, surveillance and reconnaissance, as well as for various monitoring operations, helping to improve threat-detection abilities. By leveraging their potential for direct data transmission between computers and the human brain, operators could use BCIs to analyze surveillance data with greater speed and efficiency.[67] |
| Manipulation and deception | Neuromodulation | Researchers have demonstrated an emerging "memory engineering" ability, creating several techniques to selectively boost or erase memories from a person's mind.[68] While useful in certain clinical conditions, this ability could be weaponized and could enable new opportunities for mental manipulation, both for state actors and malicious non-state actors.[69] |
| | Neuroimaging | Neuroimaging techniques, particularly fMRI, may hold potential for lie detection.[70] For example, recent studies suggest that fMRI can identify specific brain activity linked to deception.[71] This may make such neurotechnologies attractive for the purposes of interrogation, intelligence and counter-intelligence operations. |

64 Xiaolong Sun and Hua Yuan, "Promising Applications of Non-Invasive Brain Stimulation on Military Cognitive Enhancement: A Long Way to Go", *General Psychiatry*, vol. 36, no. 5 (2023), https://pmc.ncbi.nlm.nih.gov/articles/PMC10618962/.

65 Dennis J. Mcfarland and Jonathan R. Wolpaw, "Brain–Computer Interfaces for the Operation of Robotic and Prosthetic Devices", *Advances in Computers*, vol. 79 (2010), https://www.sciencedirect.com/science/article/abs/pii/S0065245810790045.

66 Antonio Regalado, "Brain–Computer Interfaces Face a Critical Test", *MIT Technology Review*, 1 April 2025, https://www.technologyreview.com/2025/04/01/1114009/brain-computer-interfaces-10-breakthrough-technologies-2025/; Clive Cookson and Richard Walters, "The Transformative Potential of Computerised Brain Implants", *Financial Times*, 3 June 2025, https://www.ft.com/content/f4cd1130-6adc-4dbd-b74b-9813ae008166.

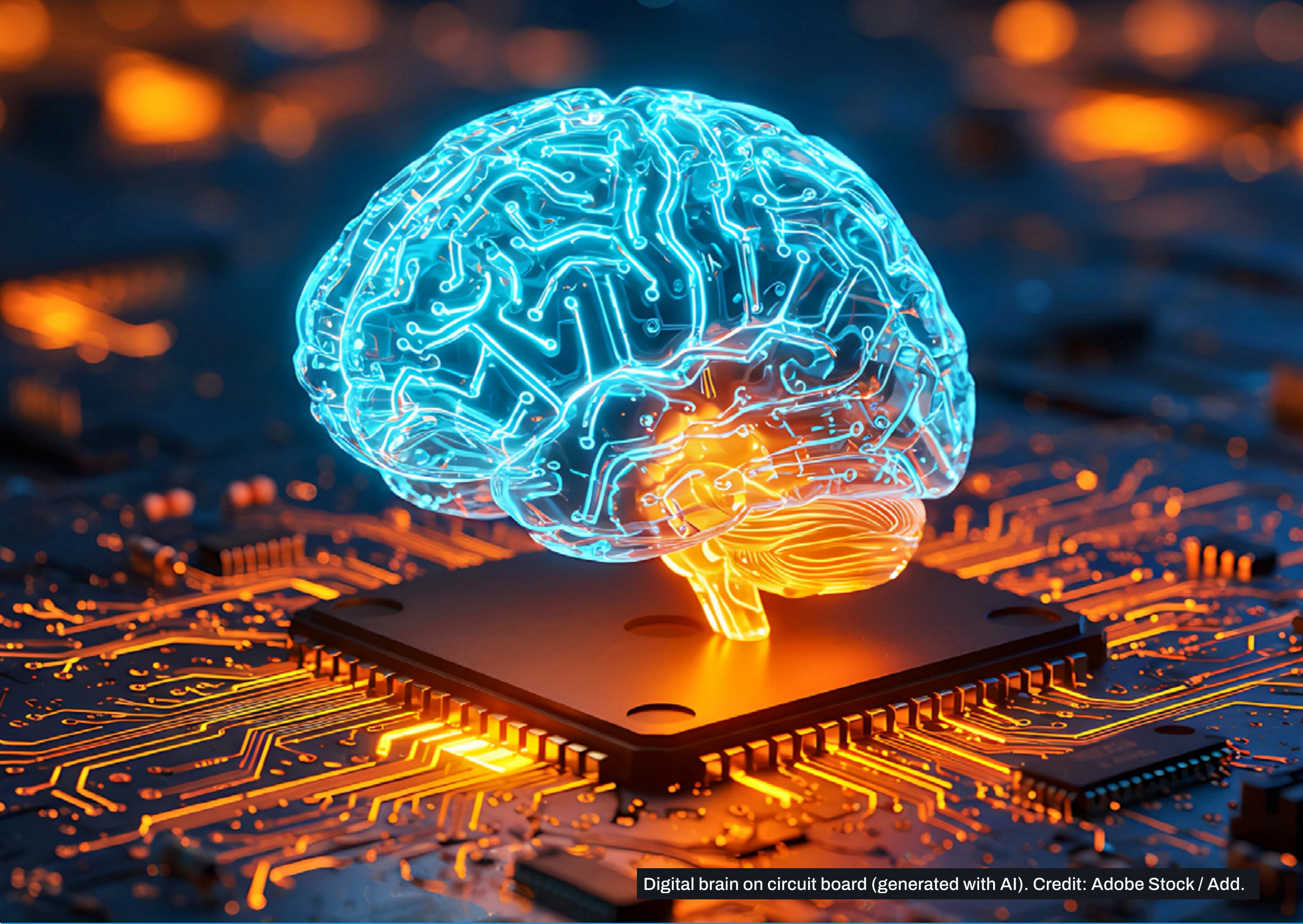
67 Analysis and Research Team, "From Vision to Reality".

68 Marcello Ienca and Roberto Andorno, "Towards New Human Rights in the Age of Neuroscience and Neurotechnology", *Life Sciences, Society and Policy*, vol. 13, no. 5 (2017), https://lsspjournal.biomedcentral.com/articles/10.1186/s40504-017-0050-1.

69 Ienca and Andorno, "Towards New Human Rights in the Age of Neuroscience and Neurotechnology".

70 Tennison and Moreno, "Neuroscience, Ethics and National Security".

71 Calvin J. Kraft and James Giordano, "Integrating Brain Science and Law: Neuroscientific Evidence and Legal Perspectives on Protecting Individual Liberties", *Frontiers in Neuroscience*, vol. 11 (2017), https://www.frontiersin.org/journals/neuroscience/articles/10.3389/fnins.2017.00621/full.



Digital brain on circuit board (generated with AI). Credit: Adobe Stock / Add.

BOX 1.

## Further into the future: Brain-to-brain interfaces

Researchers have demonstrated the first ability for direct brain-to-brain communication enabled by brain-to-brain interfaces (BBIs).[72] While this remains a proof of concept that faces significant challenges, and it lies at an extreme frontier of the technology, experts have already begun to explore its military potential and implications.[73] BBIs could, for example, enable "silent talk" – allowing users to communicate directly through neural signals transmitted via the interfaces.[74] This may have myriad applications both in active combat, where verbal commands may be lost or misunderstood, or during covert operations, where audible commands may not be issued.

[72] Latheef, "Brain to Brain Interfaces (BBIs) in Future Military Operations".

[73] Latheef, "Brain to Brain Interfaces (BBIs) in Future Military Operations".

[74] Binnendijk et al., "Brain-Computer Interfaces".

# 3. Risks of neurotechnology in the military domain

While neurotechnologies present armed forces with various opportunities and use cases, their integration in the military domain comes with considerable risks, ranging from safety and security concerns to legal and ethical challenges. It also raises important questions linked to surveillance and manipulation, while also having implications for the proliferation of the technology among states and non-state actors and the weaponization of commercial neurotechnology. Some of these risks relate solely to the use of neurotechnologies, while others have substantial overlap with international security risks of adjacent fields, such as AI and cybersecurity. As neurotechnology further converges with other technological fields, the intersections may amplify existing risks and create novel, hard-to-anticipate threats, further complicating effective mitigation measures. This section sets out an initial, non-exhaustive overview of some potential risks linked to the development and use of neurotechnologies in the military domain (see Table 2 for a summary and Box 2 on terminology).

TABLE 2.

## Summary of risks

| RISK | SUMMARY EXPLANATION |
|---|---|
| Safety and security | ▸ Creation of novel cyber vulnerabilities<br>▸ Extraction of sensitive neural data, signal spoofing and device manipulation<br>▸ Physical harm to operators, disruption of military operations and raising legal and ethical concerns in accordance with international humanitarian law |
| Human control over weapon systems | ▸ Blurred line between human judgement and machine input in military decision-making<br>▸ Reduced space for human cognitive input and control |
| Surveillance, cognitive warfare and disinformation | ▸ Intrusive monitoring and behavioural manipulation<br>▸ Exacerbated impact of disinformation campaigns |
| Legal implications | ▸ Challenges core rules of international humanitarian law<br>▸ Blurred distinction between human cognition and AI input complicating attribution of responsibility |
| Human rights, ethics and privacy | ▸ Surveillance, privacy breaches and discrimination<br>▸ Unclear long-term psychological and physical effects on soldiers |
| Neurotechnology–AI convergence | ▸ Spillover of AI-related risks in military neurotechnology<br>▸ Responsible military neurotechnology a function of responsible military AI |
| Neurotechnology “arms-race” | ▸ Potential for “enhancement race”<br>▸ Accelerated weaponization, risky developments and deployments with fewer safeguards |
| Proliferation to non-state actors and weaponization | ▸ Commercial proliferation raises risk of misuse by malicious non-state actors<br>▸ Risks to national and international peace and security, hampering regulatory efforts |

## 3.1. Safety and security

As connected devices, neurotechnologies may increase the surface area for cyberattacks by creating novel vulnerabilities.[75] Potential cyberattacks may put neurotechnologies, their operators, and the data utilized and created by using the technology at risk.

It is expected that connected neurotechnologies will produce troves of data that is extremely sensitive in nature and that must be stored and protected. Researchers have demonstrated the vulnerability of network-connected BCIs to potential cyberattacks. By exploiting vulnerabilities to extract data generated through various neurotechnologies, attackers could, for example, disclose extremely sensitive information about the neural activity of military personnel. Researchers have also shown that cyberattacks could aim to introduce spoofed signals or modified data, which may lead to unwanted BCI-mediated movement and altered behaviour in users.[76] Lastly, cyberattacks or electronic warfare could directly seek to render neural devices unusable. If connected neurotechnologies are compromised, this could have operational and tactical consequences on the battlefield, such as uncrewed systems being lost or co-opted or the loss of communication between human operators and command-and-control systems.[77]

Targeting BCI systems might also have unpredictable physical consequences for operators, some of which might be considered excessively injurious, or which might affect soldiers not actively participating in hostilities.[78]

## 3.2. Human control over weapon systems

Human control over AI-enabled systems in the military domain is already a fraught issue, and a key factor in the safe and legal development and use of military AI capabilities.[79] Even more complex considerations arise with respect to human control over AI-enabled systems if used in conjunction with neurotechnologies.[80]

For example, neurotechnologies that lead to the integration of humans and machines could obscure where machine input ends and human judgement starts.[81] Accelerating the transfer of information between humans and AI systems and reducing friction in doing so might further accelerate decision-making, reduce the time for human cognitive input and increase the influence of algorithmic decisions.[82]

---

75 Hensing and Andreas, Neurotechnology.

76 Tyler Schroder et al., “Cyber Risks to Next-Gen Brain-Computer Interfaces: Analysis and Recommendations”, 2025, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5138265.

77 Gielas, “Soldier Enhancement through Brain–Computer Interfaces”.

78 Lubell and Al-Khateeb, “Cyborg Soldiers”.

79 Ingvild Bode, “Human–Machine Interaction and Human Agency in the Military Domain”, Policy Brief no. 193, Centre for International Governance and Innovation, 2025, https://www.cigionline.org/publications/human-machine-interaction-and-human-agency-in-the-military-domain/.

80 Yasmin Afina, “Human Control is Essential to the Responsible Use of Military Neurotechnology”, 8 August 2019, https://www.chathamhouse.org/2019/08/human-control-essential-responsible-use-military-neurotechnology.

81 Favaro and Schwarz, “Human Augmentation and Nuclear Risk”.

82 Ibid.

BOX 2.

# On “brain hacking”

The term “brain hacking” (sometimes “mind hacking” or “neuro hacking”) is often used in neurotechnology policy literature as well as popular discourse to refer to the risks of neurotechnology. However, it is a nebulous term that lacks a clear definition – it refers to and encapsulates a multitude of distinct activities and risks.[83] This primer refrains from using the term in order to avoid confusion about the risks that “brain hacking” specifically refers to.

## In the context of cyberattacks

“Brain hacking” is at times used to denote the risk of cyberattacks on connected neurotechnologies such as BCIs. In this context, the terminology inaccurately represents the threat. Adversarial cyber activities in this context aim to extract data from neurotechnologies, to impede their functioning or to introduce spoofed signals. What is therefore taking place is the – rather traditional – hacking of a connected device, not the brain itself.

## Cognitive control and external influence

The risk of brain hacking is also used to denote the risk of manipulation and behavioural and cognitive modification through external influence or through the use of neurotechnologies. Utilizing the term “hacking” to denote external influence over an individual’s behaviour and cognition lacks conceptual clarity and is a loose interpretation of an originally ICT-related term which refers to the unauthorized access to a computer network.

## Self-improvement and influence on neuronal activity

“Brain hacking” is also used to refer to self-administered techniques for self-improvement of various aspects of cognition or mental health. Additionally, “brain hacking” is sometimes used to denote any change to brain function (even positive and intended) that is achieved through the means of neurotechnology. In this case, “brain hacking” is used to denote the primary purpose of neurotechnologies and not hacking in any negative sense.

## The need for accurate terminology

Precise terminology is key in the context of risk mapping and policy discussions to assess and manage the risks of neurotechnologies, but the above ambiguities show that the term “brain hacking” lacks precision. Not only does the term refer simultaneously to too many risks and neurotechnology enabled activities, but it may also encourage inaccurate popular representations of the risks linked to neurotechnologies. This may hamper the development of appropriate safeguards and policies to mitigate those risks.

---

83 Marcello Ienca and James Scheibner, “What is Neurohacking? Defining the Conceptual, Ethical and Legal Boundaries”, *Developments in Neuroethics and Bioethics*, vol. 3 (2020), **https://doi.org/10.1016/bs.dnb.2020.03.008**; Shujhat Khan and Tipu Aziz, “Transcending the Brain: Is There a Cost to Hacking the Nervous System?”, *Brain Communications*, vol. 1, no. 1 (2019), **https://doi.org/10.1093/braincomms/fcz015**.

This would make discussions surrounding the place of human operators in AI-enabled military systems, and the level of control they exert over these systems, more complex.

## 3.3. Surveillance, cognitive warfare, disinformation and manipulation

The commercial proliferation of neurotechnology and the large-scale neural data collection it enables could exacerbate ubiquitous surveillance and disinformation and influence campaigns.[84] Neurotechnology enables the use of neural and other biometric data to make inferences about the mental states of users and to gain valuable personal insights about them.[85] Coupled with the dynamics which enable AI and social media technologies to be vectors of behavioural modification, neurotechnology could further exacerbate the impact and scope of state-sponsored disinformation and influence campaigns.[86] This could render influence campaigns more targeted and personalized, potentially making them more effective.

In the military domain, neurotechnologies could enable undue surveillance and monitoring of personnel and the use of this data for behavioural-modification and manipulation purposes.

## 3.4. Legal implications

Due to the novelty of the technology, its legal implications in the military domain remain theoretical for now. However, scholars have already begun to identify some key legal issues.[87] The use of neurotechnologies in the military domain may indeed challenge key legal concepts linked to the law of armed conflict (international humanitarian law) with respect to targeting, distinction and proportionality, as well as the protection of persons *hors de combat*, among other issues.[88] Furthermore, the ability for commanders to directly interface with – and influence – soldier's

---

84 Camilla Cavendish, "Humanity is Sleepwalking into a Neurotech Disaster", *Financial Times*, 4 March 2023, https://www.ft.com/content/e30d7c75-90a3-4980-ac71-61520504753b; Jean-Marc Rickli, Federico Mantellassi and Gwyn Glasser, "Peace of Mind: Cognitive Warfare and the Governance of Subversion in the 21st Century", GCSP Policy Brief No. 9, Geneva Centre for Security Policy, August 2023, https://dam.gcsp.ch/files/misc/pb-9-rickli-mantellassi; Nita A. Farahany, *The Battle for Your Brain: Defending the Right to Think Freely in the Age of Neurotechnology* (New York: St Martin's Press, 2023).

85 Farahany, The Battle for Your Brain.

86 Miah Hammond-Errey and Tom Barrett, "The Only Privacy We Have Left is What's in Our Heads, and That Will Soon be Public", *Sunday Morning Herald*, 1 February 2024, https://www.ussc.edu.au/the-only-privacy-we-have-left-is-what-s-in-our-heads-and-that-will-soon-be-public.

87 Rain Liivoja, "Being More than You Can Be: Enhancement of Warfighters and the Law of Armed Conflict", in *The Future of the Law of Armed Conflict*, ed. Matthew Waxman and Thomas W. Oaxley (Oxford: Oxford University Press, 2021); Denise Koecke, "Merging Man and Machine: A Legal Assessment of Brain–Computer Interfaces in Armed Conflict", *International Review of the Red Cross*, vol. 107, no. 928 (2025), https://international-review.icrc.org/articles/merging-man-and-machine-a-legal-assessment-of-brain-computer-interfaces-in-armed-conflict-928; Lubell and Al-Khateeb, "Cyborg Soldiers"; Latheef, "Brain to Brain Interfaces (BBIs) in Future Military Operations".

88 For a comprehensive overview of legal challenges linked to BCI, see Lubell and Al-Khateeb, "Cyborg Soldiers".

brains and behaviours raises serious legal and ethical concerns.[89] Debates have additionally explored the legal implications of blurring the line between human and machine with respect to the legal status of neurotechnology-enhanced soldiers.[90]

Additionally, a constant flow of data between human brains and machines can make it difficult to differentiate between human thought processes and AI-enabled calculations and inputs. This is exacerbated by the possibility that, in the case of neurotechnology, machine inputs may be subconscious and the operator themself may no longer be able to distinguish them from their own thoughts.[91] In the case of BCI-connected soldiers, this could make it increasingly difficult to attribute responsibility for an action taken. This entails further complexity in existing concerns over human control, legal responsibility and accountability for decisions made and actions taken in conjunction with AI systems.[92] Possible malfunctions and adversarial manipulations add a further layer of complexity to the picture.

## 3.5. Human rights, ethics and privacy[93]

Human rights, ethical and privacy implications are some of the most important risks linked to neurotechnology and are a key element of governance discussions in the civilian domain.[94] Neurotechnology may, for example, have an impact on rights such as the protection against discrimination, freedom of thought, privacy, criminal justice system-related rights, mental and bodily integrity, or workplace rights.[95]

The same risks manifest themselves in the use of military neurotechnologies. This entails that their development must therefore be similarly guided by the key emerging principles and practices that seek to minimize these risks in the civilian domain.

For example, ethical questions about informed consent of soldiers over neurotechnology enhancements and their right and ability to refuse enhancement are critical.[96] Soldiers utilizing neurotechnologies may be subject to undue surveillance, privacy breaches and discriminations based on neural data collection and inferences made from such data. Additionally, the

---

89 Lubell and Al-Khateeb, “Cyborg Soldiers”.

90 Analysis and Research Team, “From Vision to Reality”.

91 Koecke, “Merging Man and Machine”; Lubell and Al-Khateeb, “Cyborg Soldiers”.

92 Lubell and Al-Khateeb, “Cyborg Soldiers”; Latheef, “Brain to Brain Interfaces (BBIs) in Future Military Operations”.

93 This section is intentionally brief, as the human rights implications of neurotechnologies are a complex and critical topic whose detailed examination falls beyond the scope of this paper. For a comprehensive analysis, see Erica Harper and Timo Istace, “Neurotechnology and Human Rights: An Audit of Risks, Regulatory Challenges, and Opportunities”, Research Brief, Geneva Academy of International Humanitarian Law and Human Rights, 2024, https://www.geneva-academy.ch/joomlatools-files/docman-files/Neurotechnology and Human Rights - An Audit of Risks Regulatory Challenges and Opportunities.pdf.

94 Office of the High Commissioner for Human Rights (OHCHR), “UN Expert Calls for Regulation of Neurotechnologies to Protect Right to Privacy”, 12 March 2025, https://www.ohchr.org/en/press-releases/2025/03/un-expert-calls-regulation-neurotechnologies-protect-right-privacy.

95 Ibid.

96 Tennison and Moreno, “Neuroscience, Ethics and National Security”.

long-term psychological and physical effects linked to neurotechnology and the transition back to a "non-enhanced" status must be further understood.[97]

## 3.6. Neurotechnology–AI convergence

Given the role of AI in enabling modern neurotechnology, the risks linked to the convergence between the two technological fields must be duly explored.

While this convergence enables neurotechnology to benefit from opportunities linked to AI, it also entails that the risks linked to one technology spill over to the other.[98] For example, as AI algorithms assist in decoding and interpreting neural signals, questions over algorithmic bias, the representativeness and quality of training data and algorithmic hallucinations among others become relevant for neurotechnology. The use of military neurotechnology will therefore also be plagued by the still-emerging risks linked to the use of AI in the military domain.

Therefore, the responsible development and operationalization of neurotechnology in the military domain is also a function of the responsible development and operationalization of AI in the military domain.

## 3.7. Neurotechnology "arms race"

As a disruptive set of dual-use technologies, neurotechnologies are increasingly moving out of the laboratory and into the real world. In this context, states may succumb to competitive pressures and, out of fear of falling behind competitors, be driven to develop and adopt military applications of neurotechnologies. This dynamic has the potential to create a race to the bottom in the deployment of military neurotechnologies.[99]

As stated by some experts, "governments increasingly see the best means of protecting their citizens from weaponized neurotechnology to be developing it themselves".[100] This could create an "enhancement race", with incentives to out-enhance competing states.[101] This could lead states to forgo ethical, legal and normative guardrails and could result in riskier

---

97 Heather A. Harrison Dinniss and Jann K. Kleffner, "Soldier 2.0: Military Human Enhancement and International Law", *International Law Studies*, vol. 92 (2016), **https://digital-commons.usnwc.edu/cgi/viewcontent.cgi?article=1695&context=ils**; Łukasz Kamieński, "Soldiers or Weapons? The Ethical Dilemma and Consequences of the Status for Super Soldier Veterans", *AJOB Neuroscience*, vol. 18, no. 1 (2025), **https://doi.org/10.1080/21507740.2025.2530956**; Vincent Guerin, "Veteran and Brain–Computer Interfaces: The Duty to Care", *AJOB Neuroscience*, vol. 18, no. 1 (2025), **https://pubmed.ncbi.nlm.nih.gov/40694026/**.

98 Chavarriaga et al., Neurotechnologies.

99 Erica Harper and Allan McCay, "Neurotechnology – Integrating Human Rights in Regulation", Research Brief, Geneva Academy and the University of Sydney, 2025, **https://www.geneva-academy.ch/joomlatools-files/docman-files/Neurotechnology - Integrating Human Rights in Regulation.pdf**.

100 Erica Harper "The Evolving Neurotechnology Landscape: Examining the Role and Importance of Human Rights in Regulation", Geneva Academy, 2023, **https://www.geneva-academy.ch/joomlatools-files/docman-files/The Evolving Neurotechnology Landscape.pdf**.

101 Favaro and Schwarz, "Human Augmentation and Nuclear Risk".

neurotechnologies. With ongoing competitive pressures in military AI, the incentive for riskier neurotechnologies could be further exacerbated should they prove to be useful in the context of human–machine teaming with AI systems.

## 3.8. Proliferation to non-state actors and weaponization

Due to the dual-use nature of neurotechnologies, their proliferation is not only a function of state adoption for military purposes. The acceleration of commercial developments means that proliferation among non-state actors such as organized crime or terrorist organizations remains a possibility.[102] This could lead to the weaponization of some commercially available neurotechnologies or to the malicious intervention and manipulation of the data, connectivity or functionality of neurotechnologies. Such acts could potentially undermine national and international peace and security. Proliferation to, and use by, malicious non-state actors would significantly complicate regulatory and normative efforts aimed at ensuring safe, secure and responsible neurotechnologies.

[102] Marcello Ienca, Fabrice Jotterand and Bernice S. Elger, "From Healthcare to Warfare and Reverse: How Should We Regulate Dual-Use Neurotechnology?", *Neuron*, vol. 97, no. 2 (2018), **https://pubmed.ncbi.nlm.nih.gov/29346750/**.

Soldiers and AI systems managing a drone fleet (generated with AI). Credit: Adobe Stock / Artinun.

# 4. Possible implications of neurotechnology for arms control, disarmament and non-proliferation

At the United Nations, multilateral discussions surrounding neurotechnology, its governance and the management of related risks have so far mostly been concentrated in two main forums: the Human Rights Council, which is investigating the human rights implications of neurotechnology; and the United Nations Educational, Scientific and Cultural Organization (UNESCO), which is focusing its efforts on the ethics of neurotechnology.[103] Outside the United Nations, a multitude of efforts have proliferated, led for example by the Organisation for Economic Co-operation and Development (OECD) or by professional organizations such as the Institute of Electrical and Electronics Engineers (IEEE).[104] Discussion of neurotechnology in disarmament and international peace and security forums has so far been limited, an exception being a short appearance as part of a briefing for the United Nations Security Council organized by

---

[103] United Nations, Human Rights Council, "Impact, Opportunities and Challenges of Neurotechnology with Regard to the Promotion and Protection of all Human Rights", Report of the Human Rights Advisory Council, A/HRC/57/61, 8 August 2024, https://docs.un.org/en/A/HRC/57/61; UNESCO, "Ethics of Neurotechnology", 15 September 2025, https://www.unesco.org/en/ethics-neurotech?hub=83294.

[104] Organisation for Economic Co-operation and Development (OECD), *Neurotechnology Toolkit* (Paris: OECD, 2025), https://www.oecd.org/content/dam/oecd/en/topics/policy-sub-issues/emerging-technologies/neurotech-toolkit.pdf; IEEE, "IEEE Neuroethics Framework", n.d., https://brain.ieee.org/publications/ieee-neuroethics-framework/.

Switzerland in 2024.[105] Considerations surrounding advances in and weaponization of neuroscience more broadly have received some attention in forums such as the Biological Weapons Convention (BWC) and the Chemical Weapons Convention (CWC).[106]

However, military developments in neurotechnology (as described in Section 2) could quickly result in a need to better understand the implications of these developments for the disarmament machinery. This may both require integrating neurotechnology related considerations into existing disarmament and arms control processes and frameworks, or considering the need for novel approaches to mitigate the international security risks linked to the use of neurotechnology in the military domain.

The following four subsections therefore provide an anticipatory overview of potential areas where the growing development and deployment of neurotechnology could come to intersect with disarmament processes and efforts and so require the attention of the disarmament community. The areas are ordered based on the level of urgency, starting with issues that are likely to materialize in the nearer term.

## 4.1. Export controls

The commercial proliferation of neurotechnology has already begun and is likely to continue before the common use of the technology in the military domain. However, as a dual-use technology (and as mentioned in Subsection 3.8), the proliferation of commercial neurotechnology might lead to easier access by malicious actors, both state and non-state. Commercial proliferation could also result in faster adoption by armed forces. It must therefore be a key policy goal to explore which neurotechnologies (or component technologies that are not already controlled) should be subject to export controls because of their strong civilian–military overlap or because they pose a greater risk.

Complex questions linked to this dual-use nature will need to be tackled. Similarly to AI, neurotechnology is an umbrella term used for a wide array of tools, techniques and technologies (as highlighted in Section 2). It will therefore be necessary to capture exactly which of these should be subject to control. Additionally, since the applications of neurotechnologies are primarily medical, particular care should be taken not to hinder the development and distribution of beneficial medical innovations.

---

105 United Nations, Security Council, "Briefing: Anticipating the Impact of Scientific Developments on International Peace and Security", Statement by Switzerland, 21 October 2024, https://www.aplusforpeace.ch/briefing-anticipating-impact-scientific-developments-international-peace-and-security.

106 BWC, 8th Review Conference, "Review of Developments in Science and Technology", Working paper submitted by the United Kingdom, BWC/CONF.VIII/WP.17, 1 November 2016, https://docs.un.org/BWC/CONF.VIII/WP.17; BWC, Meeting of States Parties, "The Convergence of Chemistry and Biology: Implications of Developments in Neurosciences", Working paper submitted by the United Kingdom, BWC/MSP/2012/MX/WP.1, 12 July 2012, https://docs.un.org/BWC/MSP/2012/MX/WP.1; BWC, 7th Review Conference, "New Scientific and Technological Developments Relevant to the Convention", BWC/CONF.VII/INF.3/Add.1, 23 November 2011, https://docs.un.org/BWC/CONF.VII/INF.3/Add.1; CWC, Conference of the States Parties, "Understanding Regarding the Aerosolised Use of Central Nervous System-Acting Chemicals for Law Enforcement Purposes", Decision C-26/DEC.10, 1 December 2021, https://www.opcw.org/sites/default/files/documents/2021/12/c26dec10(e).pdf.

While still in preliminary stages, efforts by the Bureau of Industry and Security (BIS) of the United States Department of Commerce to solicit industry opinions on export controls on BCI technology, as well as efforts by the European Union to develop neurotechnology-specific export controls suggest a growing recognition of the importance of such controls.[107]

## 4.2. Information and communications technologies

Neurotechnology and information and communications technologies (ICTs) are becoming increasingly intertwined, with ICTs enabling neurotechnology to gather, analyse and transmit neural data in an unprecedented manner. The proliferation of commercial neurotechnology may thus usher in a new era of digital connectivity.[108] As explored in Subsection 3.1, networking and connectivity that directly integrate humans create novel vulnerabilities, threats and attack vectors as well as potentially novel impacts on, and consequences for, both individuals and society. As neurotechnology devices become targets of malicious cyber activity, they could enable novel forms of espionage, sabotage, disinformation, attacks and other acts of hostile interference.[109]

Some aspects of this (e.g., the collection and processing of neural data) have been the focus of governance discussions linked to the ethics and human rights implications of neurotechnology. However, there has been no exploration of the cybersecurity of neurotechnology as it relates to malicious cyber activities, international security and broader international ICT governance discussions. As commercial neurotechnology proliferates and becomes increasingly integrated into everyday life, including critical sectors, and as it becomes growingly utilized in the military domain, the disarmament community may need to begin to consider measures to respond to these novel threats.

## 4.3. Conventional weapons, lethal autonomous weapon systems and AI in the military domain

As mentioned in Section 2, one likely military application of neurotechnology is its use for the control of weapon systems, as well as to interface with autonomous weapon systems and other AI-enabled capabilities such as decision-support systems. This, coupled with the technology's overall convergence with AI, might have an impact on ongoing disarmament efforts and broader international security and governance conversations relating to AI in the military domain.

---

[107] Anamaria Corca and Jacob von Hodenberg, "Neurotech & EU Regulation: Innovation Meets Rights", Considerati, 30 April 2025, **https://www.considerati.com/publications/neurotechnology-in-the-eu-balancing-innovation-with-rights-based-regulation/**; Jakob Hensing and Peter Schlecht, "Neurotechnology, Brain–Computer Interfaces and Implications for Germany's and Europe's Foreign and Security Policy", Global Public Policy Institute, 2025, **https://gppi.net/assets/HensingSchlecht_ActionPotentials_2025_Web.pdf**.

[108] Roxana Radu, "Neurotechnologies and the Future of Internet Governance", Issue Brief, European University Institute, 2024, **https://cadmus.eui.eu/bitstreams/edadb24f-813c-58f8-a413-8f0af4814b47/download**.

[109] Hensing and Schlecht, "Neurotechnology, Brain–Computer Interfaces and Implications for Germany's and Europe's Foreign and Security Policy".

The use of neurotechnologies to control weapon systems or in decision-support systems may, for example, have an impact on already complex dimensions of ongoing discussions in the Group of Governmental Expert on Lethal Autonomous Weapons Systems (GGE on LAWS). As noted in Subsection 3.2, neurotechnologies may challenge the general understanding of human control over weapon systems and what represents a meaningful, sufficient or appropriate amount, and it may further complicate questions around legal accountability. It may lead to more complex human–machine interaction more broadly, which could require deeper discussions as to how neurotechnology used in this context affects these key aspects and require a reassessment of collective understandings. In turn, this could necessitate the need to integrate considerations specific to neurotechnologies into discussions surrounding AI in the military domain.

## 4.4. Existing frameworks and new approaches

Lastly, the convergence between neuroscience, neurotechnology, biology and biotechnology may make innovations in this field increasingly relevant for disarmament discussions in the BWC and the CWC.[110] Experts have already posited that state and non-state actors may increasingly be able to develop a wide range of technologies, devices, methods, drugs, or chemical or biological agents intended to degrade the cognitive performance of individuals and groups.[111] At present, the emergence, relevance and threat level of such weapons remains speculative and open to debate.[112] However, experts have noted that the rise in such capabilities could occur in a regulatory vacuum.[113]

Indeed, should armed forces further develop and adopt capabilities at the intersection of neuroscience, neurotechnology, biology and biotechnology that effectively influence the human mind, delivered either through biological or chemical means or through neurotechnologies,

---

[110] Helbing and Ienca, "Why Converging Technologies Need Converging International Regulation"; Malcom Dando, "Advances in Neuroscience and the Biological and Toxin Weapons Convention", Biotechnology Research International, 2011, https://pmc.ncbi.nlm.nih.gov/articles/PMC3042703/.

[111] Katrine Nørgaard and Michael Linden-Vørnle, "Cyborgs, Neuroweapons, and Network Command", *Scandinavian Journal of Military Studies*, vol. 4, n. 1 (2021), https://doi.org/10.31374/sjms.86; Joseph DeFranco, Diane DiEuliis and James Giordano, "Redefining Neuroweapons: Emerging Capabilities in Neuroscience and Neurotechnology", *PRISM*, vol. 3, no. 8 (2020), https://ndupress.ndu.edu/Media/News/News-Article-View/article/2053388/redefining-neuroweapons-emerging-capabilities-in-neuroscience-and-neurotechnolo/; Marcello Ienca and Effy Vayena, "Dual Use in the 21st Century: Emerging Risks and Global Governance", *Swiss Medical Weekly*, 2018, https://smw.ch/index.php/smw/article/view/2545/3991; Ienca et al., "From Healthcare to Warfare and Reverse"; Armin Krishnan, "Attack on the Brain: Neurowars and Neurowarfare", *Space and Defense*, vol. 9 (2016), https://digitalcommons.unomaha.edu/cgi/viewcontent.cgi?article=1110&context=spaceanddefense.

[112] Robert C. Bruner and Filippa Lentzos, "Militarising the Mind: Assessing the Weapons of the Ultimate Battlefield", *BioSocieties*, vol. 14 (2019), https://doi.org/10.1057/s41292-018-0121-4. Sometimes, such capabilities are termed "neuroweapons". This is a broad term, lacking a clear definition that refers to the weaponization of neuroscience. Due to this lack of conceptual clarity and the broad list of techniques and capabilities that "neuroweapons" refers to, they do not feature in their own right as a capability or risk in this primer. The broadness of the term also includes capabilities and techniques that are not strictly neurotechnologies, and therefore fall outside of the scope of this primer. The primer instead focuses on specific capabilities and risks, some of which may be interpreted as "neuroweapons" depending on the definition adopted.

[113] Ienca and Vayena, "Dual Use in the 21st Century".

the disarmament community may need to explore how – and where – to integrate these discussions. Capabilities that intersect closely with biology and chemistry, such as any that may enable the delivery or creation of novel (or known) biological and chemical agents and that successfully weaponize neurobiology, would fall within the purview of the BWC or the CWC.[114] While both of these processes may in theory already encapsulate some of these capabilities, agility should be maintained to potentially incorporate neuro-specific considerations.[115]

Not all neurotechnologies intersect with, or are based on, life sciences. Some neurotechnologies described in this primer could be utilized in an offensive way (i.e., as a weapon) but may perhaps not be considered as a biological or chemical weapon. However, it must be noted that, even in these cases, the broad scopes of the BWC and the CWC mean that these instruments would still encapsulate any capabilities – and their delivery systems – that use toxicity to affect life processes or that have no justification for peaceful, protective or prophylactic purposes. In the case of a capability which may truly fall outside the purview of the BWC or CWC, it would be necessary to first understand whether a capability can be considered as a weapon and, if so, into which other disarmament efforts it could be successfully integrated.

While premature for now, in the longer term the international community may need to consider novel approaches and processes that extend beyond export controls or integration within ongoing discussions on AI in the military domain.[116] Irrespective of the forum, while norms around the development and use of neurotechnology are developing with respect to their civilian application, equivalent norms might become necessary in the context of the use of these technologies in war.

---

[114] DeFranco, DiEuliis and Giordano, "Redefining Neuroweapons"; Ienca et al., "From Healthcare to Warfare and Reverse".

[115] Ienca and Vayena, "Dual Use in the 21st Century; Ienca et al., "From Healthcare to Warfare and Reverse".

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

# Conclusion

While the field of neurotechnology remains in its infancy in the military domain, various neurotechnologies are becoming more commercially viable and military interest is growing. This means that military neurotechnology is on an accelerated path of development. This primer provided an overview of key applications and possible use cases of military neurotechnology and flagged the main areas of risk to international peace and security.

Neurotechnologies such as brain–computer interfaces, neuromodulation and neuroimaging have myriad applications in the military domain, ranging from battlefield applications, via use in support functions and military healthcare, to intelligence, counterintelligence and interrogations. Armed forces could utilize such technologies for cognitive and physical enhancement of soldiers, for the real-time monitoring of and control over cognitive, emotive and physical states. Additionally, neurotechnologies such as BCIs could facilitate more seamless integration between humans and machines and allow direct neural control of uncrewed systems. Similar technologies also have applications for battlefield communications or in military training, as well as having important medical potential.

While neurotechnology offers opportunities, its application to the military domain carries with it important risks to peace and security. This primer provided an overview of some of these potential risks, which include:

- Safety and security risks (both cyber and physical)
- Implications related to human control over weapon systems
- Expanded surveillance, manipulation and disinformation capabilities
- Complex legal risks
- Challenges to human rights, ethics and privacy
- Risks linked to the convergence of neurotechnology with AI
- The risk of a neurotechnology arms race
- The potential proliferation to – and weaponization by – non-state actors

This primer also outlined various ways in which neurotechnology, and the risks linked to its use in the military domain, could come to intersect with disarmament. It showed that neurotechnologies might become increasingly relevant for discussions on AI in the military domain and related disarmament efforts. Growing commercial proliferation might also make these technologies relevant in forums dedicated to protecting ICTs and preventing their malicious use. To prevent the proliferation of dual-use neurotechnologies and their most disruptive risks, the international community should explore the relevance and modalities of export controls on specific neurotechnologies or key component technologies.

Lastly, the growing potential for armed forces to utilize various means enabled by the convergence between neuroscience, neurotechnology, biology and biotechnology to affect the human mind might require understanding of which capabilities could fall within the purview of existing arms control efforts (e.g., the BWC or the CWC). Other capabilities could require development of a novel dedicated neurotechnology effort.

In this context, it is important to further research and to better understand the risks and impacts associated with the militarization of neurotechnology. For example, further research should aim to:

- Further understand the real value of various neurotechnologies in the military domain, to better anticipate which of them hold most value. These would therefore be the most likely to be applied in the military domain and to have the largest impact on it. Research in this area could particularly focus on developing a clearer understanding of the potential of various neurotechnologies for human–machine interaction and integration.
- Develop a comprehensive risk assessment to understand which risks are most likely to materialize and to have the greatest impact. This should aim to develop an understanding of the variables and factors that would lead risks to materialize first and have greater impact.
- Develop a broader understanding of the potential impacts on disarmament and arms control that could arise from the further use of neurotechnologies in the military domain.
- Analyse the increasing convergence of neurotechnologies with other new and emerging technologies (e.g., AI, biotechnology and robotics) and evaluate the potential impacts on the military domain, international security and governance frameworks.

This research would contribute to ensuring the safe, secure and responsible development and deployment of neurotechnology in the military domain and provide initial paths for its effective governance.

@unidir
/unidir
/un_disarmresearch
/unidirgeneva
/unidir

Palais des Nations
1211 Geneva, Switzerland



WWW.UNIDIR.ORG