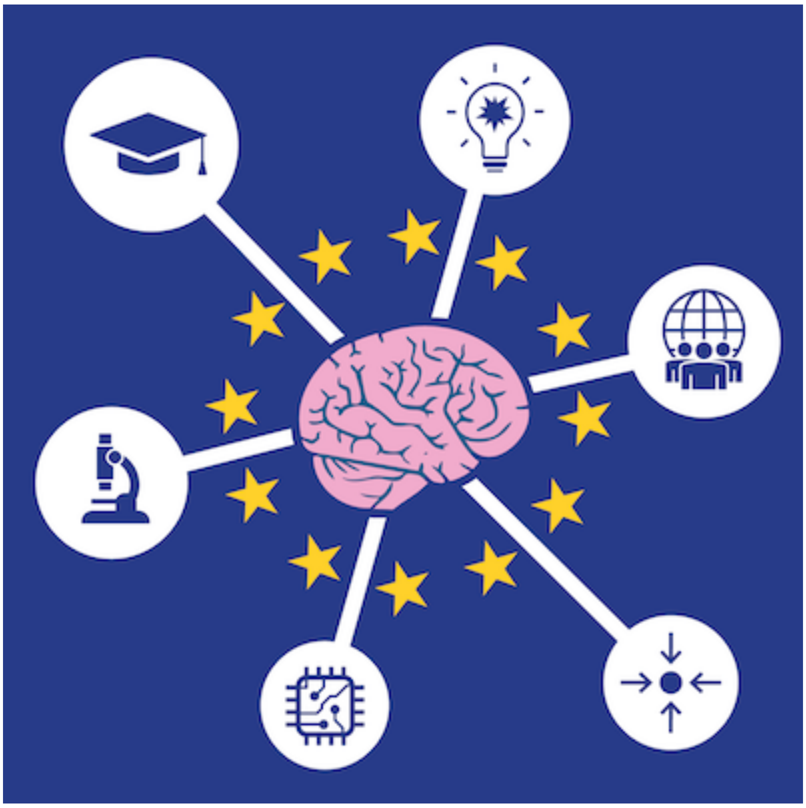
Neurotech^{EU}

The European University of Brain and Technology



D4.2
NeurotechEU Graduate School (GS)

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1.1	Updated draft based on input from all NTEU partners	16/02/2023
1.2	Updated draft based on discussions regarding joint scientific meetings	21/03/2023
1.3	Final version	29/03/2023
1.4	Final version after internal review	13/04/2023

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1. Introduction

1.1. Purpose of this document

The purpose of this document is to define the goals and scope of the **Graduate School (GS) of the NeurotechEU Alliance (NTEU)** and to provide the framework for its implementation. The latter includes a structured outline of past, current, and planned activities towards developing the GS. The document will be updated as new activities are planned and implemented. It will also serve as an overview for reporting NTEU activities to funders.

1.2. Goals of the Graduate School (GS)

As defined in the grant application, the NTEU GS has several goals. Primarily, the GS will train students in multidisciplinary, international and intersectoral settings. Students will focus on one or several current challenges, i.e., challenges that can be met by neuroscientific or neurotechnological research and approaches. Upon graduation each student will have an intersectoral experience with a strong multidisciplinary research background.

1.3. Scientific scope of the GS

The focus of NTEU are the scientific fields of research related to the function of the brain and the methods, concepts, artificial systems, and technologies that aim to understand, interact with, repair, enhance, and directly influence the brain and behaviour. Mapping this complex field of science can be achieved by visualising the various dimensions that play a role (**Fig. 1**, Appendix 1 by Paul Verschure). All NTEU content can be localised along these dimensions, and we will use them to structure and group content and to navigate it.

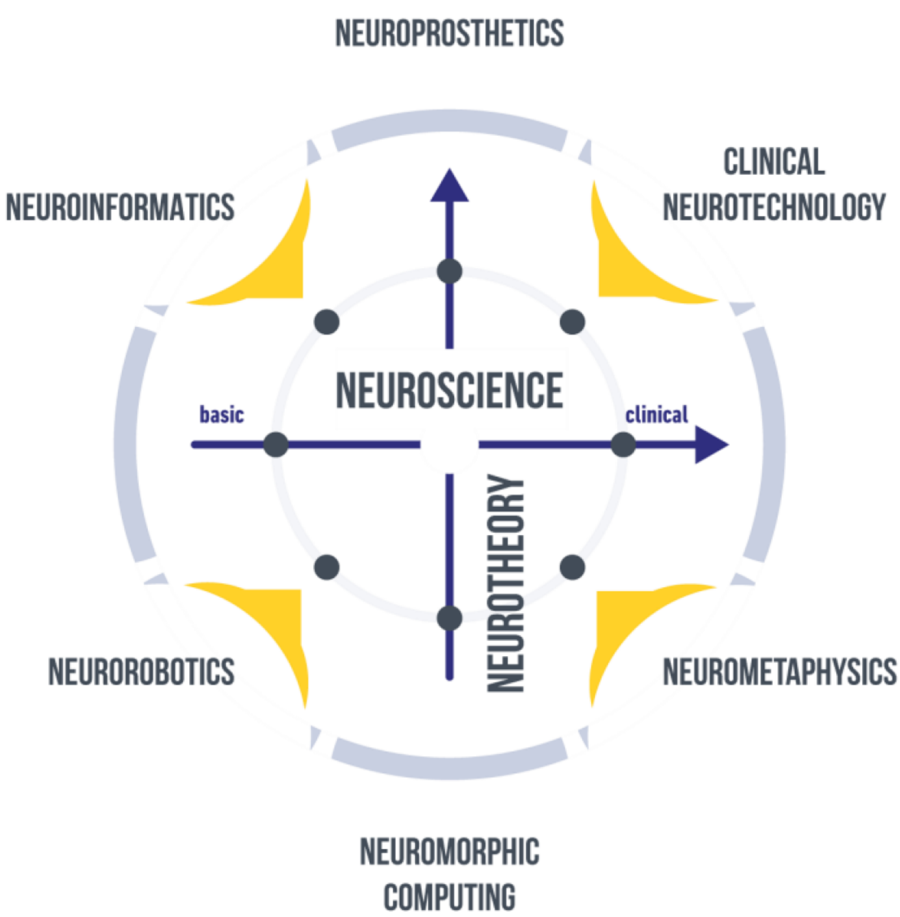

Figure 1 (adopted from Appendix 1, Paul Verschure): At the core of brain-related sciences and technologies is a firm understanding of the functioning of the nervous system in healthy individuals (basic neuroscience) and its alterations in brain diseases (clinical neuroscience) together with well-formulated theories of brain operation. Building on this foundation are sciences like neuroprosthetics and clinical neurotechnology that solve problems related to clinical neuroscience using technology. Similarly, neuroinformatics, neurorobotics and neuromorphic computing can be viewed as technology development inspired by neuroscience and neurotechnology. Please see Appendix 1 for a full explanation.

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1.4. Target Group of the GS

The level of education of students enrolling in local graduate school at the NTEU partners varies depending primarily on country specific regulations for higher education. For the NTEU GS, it was decided to focus on doctoral students especially during the initial setup phase of the GS. Nonetheless, content will be made available to master students and master-level students provided there is sufficient capacity (e.g., number of participants for hands-on classes).

1.5. Development phases of the GS

There are short-term and long-term goals in the development of the NTEU GS. In the initial phase, the NTEU GS will serve as an umbrella structure for existing graduate schools (see below for a list of existing graduate schools) and educational opportunities. The aim is to enable student access to partners, to promote awareness of research topics and techniques across partners and to promote scientific collaborations. See chapter 2 for more details.

In a second phase (i.e., in the NTEU second phase starting 2023), we plan to equip the GS with scholarships for students and projects, which will be awarded in a competitive and centrally organised selection process to students. Their projects will match the scientific goals of the NTEU GS and foster collaboration across NTEU partners. These students will be advised by mentors from NTEU partners and from industrial or societal partners. The NTEU GS will offer a structured programme providing education across the various dimensions of science in NeurotechEU to the enrolled students. See chapter 3 for further information.

1.6. Web platform and announcements of the GS

For the time being, any content related to the GS will be made visible through the NTEU website. The announcements (e.g., for talks or courses) will be made available via the usual NTEU channels (e.g., Twitter) and by the partners at the local level.

1.7. Members of the GS task group

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2. GS Development in NTEU Phase One

The funding available for GS development is limited. Therefore, we focus initially on low-threshold activities and measures to provide additional education for students at the partner universities, to improve awareness of research topics and methods at partner universities and to enable mutual access to modules and courses between the partners. In parallel, we are in the process of securing additional funding for NTEU-related research that will become part of the GS.

2.1. Existing NT-related GS at partners

Existing NTEU-related graduate schools at the NTEU partners:

Donders Graduate School (RU): https://www.ru.nl/donders/talent-education/graduate-school/
BIGS Neuroscience (UBO): https://bigs-neuroscience.de/
Bogazici University Graduate Programs (BOUN): https://bme.boun.edu.tr/, https://iesc.boun.edu.tr/, http://www.fbe.boun.edu.tr/fbe/?q=en/mainpage, http://www.sbe.boun.edu.tr/

Further content for the target group of the NTEU GS:

Congreso Estudiantes Doctorado (UMH): https://congresoestudiantesdoctorado.umh.es/en/

2.2. Lecture Series: Current Methods in Neurotechnology

This is an online lecture series highlighting specific expertise of individual researchers and laboratories of the partners or at the partner universities. They are made available via the online platform LearnGala (https://www.learngala.com/catalog/libraries/neurotecheu) and provided along with additional material (e.g. suggested reading, discussion and reflections, handouts) and further NTEU-specific courses. The lectures themselves are also available on YouTube (https://www.youtube.com/playlist?list=PLSrV8056EZgAjupemhRT5CsK_op9ihXKK).

This is an ongoing activity. We intend to expand the lecture series over time. The long-term plan is to integrate them into the NTEU content delivery platform.

2.3. Lecture Series: Current Research on Brain and Technology

Selected scientists from partners present their current research in general lectures. The target audience of these lectures are graduate students and scientists. There are lecture series organised by the student council of NTEU. In addition, NTEU partners and their local organisations such as the Bonn International Graduate School (BIGS) for Neuroscience (University of Bonn) are organising lecture series in cooperation with NTEU. Lectures take place online and are advertised via neurotalk (Email-List UBO), Bonn Center of Neuroscience, BIGS Neuroscience, Bonn NTEU website and official NTEU website (https://theneurotech.eu/news/).

Past and future lectures in the series:

Date	Lecturer	Topic

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16.02.2022	Martin Fuhrmann, Prof. Dr.	Neuronal network disturbances associated with memory impairment in a mouse model of Alzheimer's disease
06.04.2022	Anja Schneider, Prof. Dr.	Biomarkers in neurodegenerative diseases
15:06.2022	Tobias Rose, Prof. Dr.	Stability and plasticity in the visual system and beyond
11.08.2022	Domenico Azarnia Tehran, Dr.	Neuronal communication in the healthy and aging brain
13.09.2022	Bettina Schnell, Prof. Dr.	Neural circuits underlying the control of steering maneuvers during flight in Drosophila.
20.10.2022	Dominik Bach, Prof. Dr.	Algorithms for survival - computing adaptive behaviour.
30.11.2022	Carmen Ruiz de Almodovar, Prof. Dr.	Vascular control of neurodevelopment
07.12.2022	Margret Bülow, PD Dr. sc.	Organelle contact sites in axons and their role in neuron differentiation and function

This is ongoing and will be updated as new lectures take place/are planned.

2.4. NTEU Summer Schools and Courses

All partners already organise summer schools, modules, and courses for local PhD students with great success. All partners have agreed to make these available to doctoral students from partner universities.

Past, current, and planned modules specifically opened or organised for NeurotechEU with NeurotechEU student participation are in the table below.

Date	Module/Course/Event name	Location (and URL if available)
Oct 2021, Mar 2022, Sept 2022	Basic and Intensive Language Courses	UBO Organiser: Uta Brus
July 2022	Summer School of Quantitative Electroencephalography (Blended Intensive Programme)	UMF Organiser: Dafin Muresanu
Aug 2022	Bonn International Graduate School of Neuroscience Summer School (10 days)	UBO (https://bigs-neuroscience.de/summer-schools/) Organiser: Gaia Tavosanis, Martin Fuhrmann

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Sep 2022	Donders Cognition Brain and Technology summer school (two weeks)	RU (https://bcbt.specs-lab.com/bcbt22/ Organiser: Paul Verschure
Sep 2022	European Summer School on Eye Movements (ESSEM)	UBO (https://www.essem.info/) Organiser: Ulrich Ettinger
Feb 13 2023	Mini Symposium Implicit Bias	UBO, iBehave Organiser: Ilona Grunwald
May 8-17 2023	Bonn International Graduate School of Neuroscience Summer School (10 days)	UBO (https://bigs-neuroscience.de/summer-schools/) Organiser: Martin Fuhrmann, BIGS Neuroscience
May 29-30 2023	StratNeuro Retreat Yearly organised by KI, where key scientists are invited to present.	KI Organiser: TBA
May 31-June01 2023	Hackathon This will be organised by KI as a consortium-wide event, which will be planned in parallel to the BoR meeting at Karolinska.	KI Organiser: TBA
July 17-22 2023	Electron Microscopy Sample Preparation *The course is split into an online part, in which tutors from UD and other partners from the NeurotechEU will provide the theoretical background, and a second five-day-long practical course, which will be held in the Electron Microscopy Laboratory of the Department of Anatomy, Histology and Embryology (UD).*	UD Organiser: Peter Szucs
September 2023	Donders Brain, Cognition, and Technology Summer School	RU Organiser: TBA
17-21 Dez 2023	Preclinical Magnetic Resonance Imaging *This course is intended to give a complete overview on preclinical Magnetic Resonance Imaging techniques. It will cover the theoretical bases of MRI and the most used MRI techniques (relaxometry, diffusion-based, functional), their main biomedical and neuroscientific applications, and a real hand-on session with MRI data acquisition and analysis.*	UMH Organiser: Santiago Canals and Juana Gallar

This is ongoing. Participation is/should be organised by the international offices of the NTEU partners. Depending on the format, financial support could be available via the Blended-Intensive-Programmes

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(BIPs) of the Erasmus+ programme. All partners actively advertise these opportunities for exchange. A strategy for accreditation needs to be developed (e.g., transcripts, certificates, microcredentials).

2.5. Scientific meeting in the NTEU GS

Scientists connect by talking about research. They also network and collaborate to access research methods that are not directly available to them. Scientific meetings related to NTEU seem ideal to get this conversation going. Instead of organizing such meetings centrally, NTEU will support partners if they wish to set up NTEU symposia/sessions/meetings (e.g., within their scientific events or attached to international conferences). The idea is to lower the threshold for organizing such NTEU events by embedding them into existing meeting series or graduate schools.

There are many examples of meetings organized by NTEU partners into which such NTEU sessions could be integrated (e.g., BIGS Neuroscience Summer School at UBO, BonnBrain3 meetings at UBO, Donders Summer School by RU, StratNeuro retreat by KI). To obtain NTEU financial support, NTEU partners should submit a one-page proposal to the programme committee (see below) with details on the planned event. In that proposal, the scientific programme and its alignment with NTEU should be presented (see **Fig. 1**). It should further explain how the event is particularly import for the target group of the NTEU GS and how strong student participation will be ensured. The preliminary structure/schedule of the event and requested funding should be included.

The programme committee will advise organizers, evaluate proposals, and recommend them to the NTEU project office/board of governors. Its members will also act as contact points for identifying potential speakers/participants for the events.

Programme committee

- RU: Paul Verschure (paul.verschure@donders.ru.nl, cc/alternatively Wim Scheenen (wim.scheenen@ru.nl)
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- UMF: Dafin Muresanu (office@ssnn.ro), cc/alternatively Stefan Strilciuc (stefan.strilciuc@ssnn.ro)
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- UD: Péter Szücs (szucs.peter@med.unideb.hu)
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- UL: Sophie Halliez (sophie.halliez@inserm.fr)
- KI: Joana Pereira (joana.pereira@ki.se)
- HR: Paolo Gargiulo (paolo@ru.is), Kamilla Rún Jóhannsdóttir (kamilla@ru.is)

3. GS Development in NTEU Phase Two

We will concentrate on two main goals: 1) Obtaining funding for dedicated doctoral networks with NTEU-related topics, and 2) Developing common MSc./PhD degree programmes across NTEU.

3.1. Doctoral networks

The long-term goal of NTEU is to train students across disciplines. In the context of the NTEU GS, this will be implemented in the form of interdisciplinary PhD student projects. These will involve collaborative research of at least two NTEU partners aligned with the overall concept of NTEU (see **Fig. 1**) and focused on one of the NTEU challenges (as discussed for instance at the NTEU summit 12-13 Sep 2022). The following points have been discussed as cornerstones of such NTEU GS student projects:

- A competitive selection procedure of PhD students should be established.
- The allocation of students/studentships to interdisciplinary projects should be done in a thematically and geographically balanced way (i.e., across partners and NTEU dimensions).
- Student education should be such that they understand the basic concepts and challenges of the NTEU dimensions. This will enable them to understand and to connect to specialists working in these fields.
- The interdisciplinary nature should be reflected in the thesis advisory committee. It should be composed of representatives of different disciplines and NTEU partners. In addition, there should be an advisor from a closely related private business or with direct business experience.
- Annual scientific meetings (e.g., in parallel or interwoven with the NTEU scientific meeting, see above) should be held to promote scientific collaboration among students and NTEU partners.
- A mentoring system should be in place that can also help with the NTEU-specific aspects (e.g., diversity of involved institutions and academic traditions/procedures, interdisciplinarity, geographically distributed projects).

A main challenge is to obtain sufficient funding for both the PhD student salaries and additional costs (e.g. consumables). Such initial funding will be obtained by suitable funding schemes at the national and EU level (e.g. MSCA Doctoral Networks).
In a first step, representatives of NTEU and associated partners have proposed to establish a doctoral school called the “NeurotechEU Network” (NTN) to bring together leading institutions for a European Training Network. We will have ten Early-Stage Researchers (ESRs), who will focus on themes across the dimension of NTEU (see above). The proposal is currently under revision.

3.2. Joint MSc./PhD degree programmes

We are in the planning phase of joint MSc./PhD programmes in the fields of neurotechnology and neuroengineering. The goal is to develop programmes with the following features and fulfilling the following criteria: MSc. level programmes with a fast track MSc.-PhD option, fully developed curriculum for both phases, specified guidelines for content creation, complementary to existing programmes, maximum structural compatibility with existing programmes at NTEU partners to allow mobility/exchange between programmes, involvement of companies and industry at every level, option of split industry/academia positions.

3.3. Benefit survey

Structured education of PhD students has become the standard at partner universities to broaden their expertise and skillset and to further their conceptual knowledge and awareness for other fields. Therefore, the target group of the NTEU GS is most likely already enrolled in a local programme. For this reason, the content offered by NTEU needs to have an added value beyond such local programmes. Besides the wider focus (**Fig. 1**), we want to find out what such added value could be in stage 1. A questionnaire will be prepared that should be filled in primarily by PhD students, which will inform us about gaps in the offered material and events that the NTEU GS can fill. It will also guide the definition of new programmes for students in phase two of the NTEU GS.

3.4. NTEU Thesis Award

An annual award could honour the most outstanding doctoral thesis successfully defended by a NTEU student in a given year. We are currently exploring funding options. The current plan is that the winner

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receives appropriate prize money, a certificate, and will be given the possibility to present their thesis at a NTEU scientific meeting (see above).

Rules and guidelines for the submission of entries:

- The doctoral thesis must have been successfully defended between January 1st and December 31st of the preceding year.
- The student must have fully completed a local graduate school curriculum at the partner university or, in the future, of NTEU.
- The candidate must be nominated by a PI of NTEU. Each PI may nominate one student per year. The submission must comprise a letter of support by the thesis supervisor (2 pages max), short summary of the thesis and the CV of student (2 pages max), a copy of the certificate of successful defense of the doctoral thesis, PDF of the thesis (or download link if the file size exceeds 10 MB).
- The documents should be submitted as a single PDF. The deadline for the call could be July 31st each year. Members of the NTEU GS task force (excluding the nominating PI) will act as the jury and select the winner. If none of the nominations are outstanding, the jury may decide to not award the prize.

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4. Appendix 1: The NTEU Content Space

The Neurotech[EU] Content Space: An initial sketch
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Department of Science and Technology
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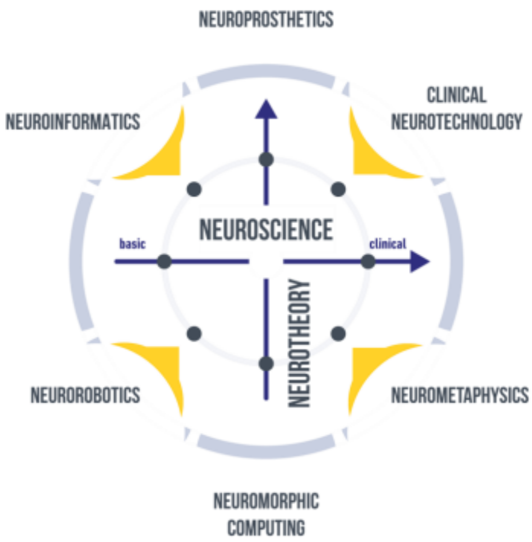
20220703

Neurotechnology (NT) focuses on the realization of a broad set of methods, concepts, artificial systems and technologies that aim to understand, interact with, repair, enhance, and directly influence the brain and behaviour. In other words: technology *from* the brain, *for* the brain and *with* the brain. NT provides strategic bridges between various disciplines, including neuroscience, medicine, engineering, artificial intelligence, cognitive science, and robotics. In addition, it links to philosophy, design, ethics and law. NT takes on a special status with respect to the explanation of the structure and function of the brain because it emphasizes the role of synthesis in understanding nature or following the 18th-century scholar Giambatista Vico: the truth and the made are reversible ("factum et Verum convertuntur")[1]. In other words, the impact of neurotechnology is twofold. On the one hand, it transforms our understanding of the brain into technology relevant to a broad range of application areas, including neuroscience itself, on the other, it is a distinct methodology to advance our understanding of the fundamental principles underlying mind and brain[2].



[1] G Vico, *Scienza Nuova Seconda, The New Science of Giambattista Vico, Revised Translation of the Third Edition by Thomas Goddard Bergin and Max Harold Fisch* (Ithaca: Cornell University Press, 1948; Cornell Paperbacks, 1976., 1730).
[2] Paul F M J Verschure and Tony J Prescott, "A Living Machines Approach to the Sciences of Mind and Brain," *Living Machines: A Handbook of Research in Biomimetics and Biohybrid Systems*, 2018, 15.

Figure 1: The Neurotech[EU] Content Space: See text for further explanation.

The specific expressions of NT can take many forms, including bioelectronics, brain-computer interfaces, neuromodulation methods using an electrical, chemical, optical or sound-based coupling, implantable devices, neuromorphic hardware and control, wearables, neurofeedback systems, neuroprosthetics, non-invasive modulation using AR/VR/XR methods and methods for cognitive augmentation[3]. To advance this panoply of possibilities we should define the map on which they are placed. NeurotechEU posits an eight-dimensional space that defines the envelope of current and future research, education, and application of neurotechnology: 1) empirical and clinical neuroscience; 2) theoretical neuroscience; 3) neuromorphic computing; 4) neuromorphic control /neurorobotics; 5) neuroinformatics; 6) neuroprosthetics; 7) clinical neurotechnology; 8) neurometaphysics (neurophilosophy, neurolaw, neuroethics, neuroaesthetics, neurodesign). These dimensions will be described below.

Empirical and clinical neuroscience: neurotechnology is predicted on progress in neuroscience, an exponentially growing field. Neuroscience comprises many methods and technologies driving progress in the field, leading to a doubling period of the data generated every 7 years[4]. This technology-oriented approach toward science has defined a distinct development of neuroscience where the correlations between specific manipulations and observed brain states are the reporting standard rather than the strong inference over hypotheses on principles of brain organization. Indeed, it has been shown that the same data analysis approach towards deciphering the operations performed by a Commodore 64 processor fails to decode its algorithm or functions [5]. This challenge to empirical neuroscience is further illustrated by the lack of progress in diagnosing and treating leading neurological diseases such as stroke, addiction, and dementia. A noticeable exception is the field of Parkinson's disease (PD), where deep brain stimulation (DBS) has become a standard treatment method, especially for patients where pharmacological interventions have ceased to be effective, i.e. a prime example of neurotechnology as a game-changer in the clinic [6]. Neurotechnology is both based on empirical and clinical neuroscience while providing enablers for progress in both domains;

Theoretical neuroscience: the development and deployment of technology require specifications of sufficient detail. For neurotechnology, these are derived from our understanding of the principles of organization of mind and brain. For instance, DBS is only viable because there is a mechanistic understanding of the symptomatology of PD, which includes over-inhibition of the subthalamic nucleus (STN), leading to a disruption of the recurrent flow of activity in the cortico-basal ganglia circuit. Hence, providing an external pace making of activity of the STN can be predicted to be effective, which has now become a standard of treatment. Hence, the field of theoretical or computational neuroscience

[3] Gray Scott, "The Neurotechnology Revolution Has Arrived," *Futurist* 47, no. 5 (2013): 6–7, https://doi.org/10.1038/464674a.
[4] Ian H Stevenson and Konrad P Kording, "How Advances in Neural Recording Affect Data Analysis.," *Nature Neuroscience* 14, no. 2 (2011): 139–42, https://doi.org/10.1038/nn.2731.
[5] Eric Jonas and Konrad Paul Kording, "Could a Neuroscientist Understand a Microprocessor?," *PLoS Computational Biology* 13, no. 1 (2017): e1005268.
[6] Andres M Lozano et al., "Deep Brain Stimulation for Parkinson's Disease: Disrupting the Disruption," *The Lancet Neurology* 1, no. 4 (2002): 225–31.

provides an interface between empirical neuroscience and technology by articulating principles of neural organization, which lend themselves to further empirical evaluation and technical elaboration [7]. In addition, the linking of neuroscience and artificial intelligence promises to give rise to new brain-based approaches toward specialized and general artificial intelligence beyond current capabilities[8] [9];

3) **Neuromorphic computing**: Since Grey Walters and the early cybernetics movement of the 1940ies, attempts have been made to emulate neuronal circuits and their operations in electronic hardware. This has given rise to the field of neuromorphic computing, which was initiated in the late 1980ies by Carver Mead and Misha Mahowald at Caltech. The need for these alternatives to the standard von Neumann computer architecture is that it promises to achieve high computational density while reducing the power needs[10]. This approach is also seen as an alternative paradigm for computational hardware now that the exponential scaling of transistor density expressed in Moore's law is nearing an asymptote [11]. Neuromorphic hardware will also constitute an enabler for many applications of neurotechnology by providing brain-compatible computation at low power. This field also provides interfaces to material science and computer science;

4) **Neuromorphic control /neurorobotics**: The brain operates as an integrated architecture that is interfaced with the world through sensors and effectors. Indeed, the field of morphological computation posits that the biomechanics of biological bodies provide implicit computation which offloads the central controller, i.e. the brain. The field of Neurorobotics thus combines the power of neuromorphic computation with the constraints of real-world interaction, embodiment, and control. This is of specific relevance to the emerging field of soft robotics, which mimics the compliance and dynamic configuration of biological bodies, enhancing the functionality and safety of robots. This new generation of robots requires new forms of biologically grounded control, requiring advanced in neurorobotics;

5) **Neuroinformatics**[12]: The tools built for studying the brain will converge with those needed to analyze and control artefacts derived from our growing understanding of the brain. For this reason, developing such convergent tools and methods comprises a strategically critical dimension that will enhance the coherence of approaches between neuroscience and neurotechnology and strengthen the synergy between these fields. In addition, given the trend in Neurotechnology toward complete integrated systems as opposed to discrete components, the core challenge of the field is to articulate a multi-scale theory of the brain based on which design decisions can be made, as opposed to being driven by what is

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[7] P S Churchland and T J Sejnowski, *The Computational Brain* (MIT Press, 1992); Michael A Arbib and James J Bonaiuto, *From Neuron to Cognition via Computational Neuroscience* (MIT Press, 2016).
[8] Demis Hassabis et al., "Neuroscience-Inspired Artificial Intelligence," *Neuron* 95, no. 2 (2017): 245–58.
[9] Diogo Santos-Pata et al., "Epistemic Autonomy and the Mammalian Hippocampus: Bootstrapping Gradient Descent Learning," *Trends in Cognitive Science*, 2021.
[10] Catherine D Schuman et al., "A Survey of Neuromorphic Computing and Neural Networks in Hardware," *ArXiv Preprint ArXiv:1705.06963*, 2017.
[11] Charles E Leiserson et al., "There's Plenty of Room at the Top: What Will Drive Computer Performance after Moore's Law?," *Science* 368, no. 6495 (2020).
[12] Shun-Ichi Amari et al., "Neuroinformatics: The Integration of Shared Databases and Tools towards Integrative Neuroscience," *Journal of Integrative Neuroscience* 1, no. 2 (December 2002): 117–28, http://www.ncbi.nlm.nih.gov/pubmed/15011281.

technologically opportune. This calls for advancing reference whole-brain models as a core activity in neuroinformatics[13].;

6) **Neuroprosthetics**: In a general sense, neuroprosthetics is a paradigmatic field of neurotechnology since it combines sensing of brain states, their transformation in a functionally appropriate way of this input, and lastly, the functional modulation of brain states as a result of this transformation[14] [15]. Hence, defining a feedback system with distinct stages: input sampling, signal processing, transformation, output preparation, and stimulation, not unlike how the 19th-century Dutch psychologist Franz Donders decomposed mental processes. Each of these stages represents a universe of scientific and engineering challenges, from the design of effective interfaces and the identification of proper representational coding formats (e.g. rate, time, frequency, phase, single-cell, population) to the task-specific transformation of input signals and the drive onto neural and or skeletal-muscle systems to effectuate task-specific change taking into consideration appropriate weight, power, communication, energetic, and biocompatibility constraints. Neuroprosthetics thus builds on advances in the other dimensions of neurotechnology, exercising and testing our understanding of the principles of brain organization in the service of society;

7) **Clinical neurotechnology**: Bringing interventions to patients and health users in the clinic or at home requires embedding specific intervention and monitoring systems in integrated human-in-the-loop digital brain health pipelines [16]. These pipelines must be built and tuned to the specific neurotechnologies they deploy for assessment, diagnostics, and intervention, including advancing patient-specific whole-brain models. The deployment of these systems will radically impact how health care is provided and thus comprises a distinct domain of study and education. The objective of digital brain health must be to realize systems that have relevance in the real world, both given current challenges and future ones. In this effort, the strategic choice would be to link medium- and long-term research and education objectives to fundamental challenges in digital brain health, including education and cognitive augmentation. Digital brain health should be structured along the known challenges society faces in neurological disease and beyond, i.e. in terms of concrete and accepted metrics for the burden of disease to assure impact;

8) **Neurometaphysics** (neurophilosophy, neurolaw, neuroethics, neuroaesthetics, neurodesign): At the heart of advanced research and education are concepts, methods, and skills. These are also predicated on considerations and analyses beyond biological systems' physics and chemistry. For this reason, advances in neurotechnology must be intrinsically coupled to core domains of the humanities. For instance, neuroprosthetics requires detailed neuroethics analyses and guidance, advanced biologically grounded general intelligence requires legal assessment, while the study of consciousness, agency, and volition requires proper philosophical frameworks [17]. As the product of evolution, the brain is marvellously effective in surviving in complex, partially unknown environments. However, currently,

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humanity finds itself in the Anthropocene and limitations of human perception, cognition, action, and experience are becoming one of the main liabilities to finding sustainability of the planet's physical, ecological, social and cultural systems. Neurotechnology is one of the strategic areas which can directly contribute to finding new solutions to augment human mental capability to respond more appropriately to current challenges, such as new sensing capabilities, memory enhancement, optimized decision-making, improved education, etc. Yet, each raises fundamental philosophical and legal challenges that need to be analyzed with care. Conversely, neurotechnology can challenge the humanities to rethink their approaches, for instance, design, as illustrated by the emerging field of neuroarchitecture. Lastly, neuroaesthetics is a new paradigm that has given rise to new art forms capitalizing on autonomy and interaction, providing opportunities for training and research beyond the proximal zone of the known [18].

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