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An application-based taxonomy for brain–computer interfaces

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Naming brain–computer interfaces according to their intended application will assist stakeholders in the evaluation of the benefits and risks of neurotechnologies.

The term 'brain–computer interface' (BCI) is widely used. However, even among experts, its meaning can sometimes be unclear[1–3]. Lack of clarity from the term has real-world implications: it can muddle regulatory guidelines, it may confuse investors, it can affect healthcare-coverage policies and could even make it harder for patients to understand opportunities in clinical trials. Here, we propose a taxonomy to align with public understanding of BCI technology and assist regulators, healthcare providers, patients and other stakeholders. Our goal is to initiate the development of a taxonomy for describing BCIs. And we expect it to be refined into precise technical definitions by professional societies and regulatory agencies according to the needs and perspectives of their stakeholders.

Limitations of current terminology

The terms 'BCI' and 'brain–machine interface' (BMI) have been commonly used to refer to technologies that decode brain signals, with BCI typically referring to non-implantable devices and BMI to implantable technology[3]. But this nomenclature is inconsistent; 'computer' and 'machine' are essentially interchangeable in the context of technology for interfacing with the brain, and the terms distinguish between neither different levels of invasiveness nor function. Also, the modifiers 'non-invasive' and 'invasive' are subjective terms that do not adequately capture nuances in real and perceived risks or those associated with different neurotechnologies.

An application-based taxonomy

We advocate that the term BCI should be used to define any technology that records brain activity and processes it on an electronic device, or any technology that stimulates brain activity based on computations performed on an electronic device, regardless of whether the technology is implanted or not. Furthermore, we propose that BCIs should be categorized on the basis of their primary use (Fig. 1). We put forward

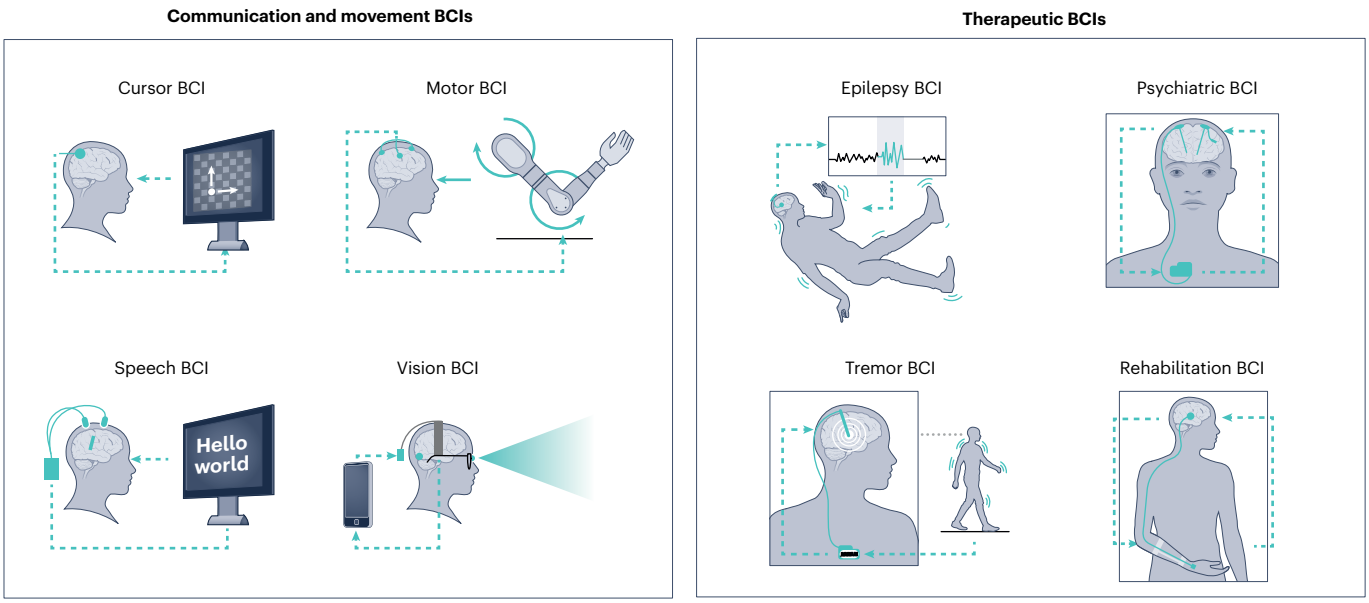

Fig. 1 | Two top-level categories of an application-based taxonomy for BCIs. A category can be subdivided into several applications-based subcategories.

two top-level categories: 'communication and movement BCIs' and 'therapeutic BCIs'.

Communication and movement BCIs should refer to technologies that are primarily intended to transmit information between the brain and a digital or physical device to control it or to receive information. This category is synonymous with 'neural prostheses', and would include sensory, motor and speech BCIs.

Therapeutic BCIs should refer to technologies that are primarily intended to alter brain activity to relieve the symptoms of medical conditions (such as 'epilepsy BCI' or 'psychiatric BCI') or to restore or improve brain function (such as 'rehabilitation BCI'). This category would include traditional neuromodulation technology (such as deep brain stimulators, if the brain stimulation is based on an electronic device that performs computations) yet would not include forms of traditional 'open loop' neuromodulation because they lack a computational step.

Naturally, and regardless of the application, the term 'implanted BCI' should refer to technologies that wholly or partially reside beneath the skin and that require surgical intervention to access brain signals. Implanted BCIs have been defined by the recently formed iBCI Collaborative Community (https://www.ibci-cc.org) as "devices whose recording elements are implanted under the scalp or in the intracranial space, including [devices] with intravascular, epicortical, and/or intraparenchymal electrodes".

Rationale for the taxonomy

Because it is likely that an increasing number of neurotechnologies will be popularly described as BCIs, we are of the opinion that continuing to use the term 'BMI' or any other nomenclature that is at odds with the lay usage of 'BCI' will contribute to the lack of clarity. Instead, classifying BCIs by their application and by whether they require implantation (and, most likely, surgery) captures the most important factors to most stakeholders: benefit and risk. Moreover, adopting an application-based taxonomy will supersede any classification of BCIs on the basis of low-level technical distinctions, and will help regulatory and reimbursement agencies to word guidelines and policies according to specific subsets of BCI technology. Furthermore, an application-based taxonomy readily accommodates new technologies as they emerge.

An important caveat is that the top-level taxonomy that we outline here cannot cover every specific case, and we anticipate that each professional organization will further develop it to meet their specific needs[4–7]. Yet we are confident that the spirit of an application-based taxonomy will support the aims of all stakeholders.

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Author contributions

All authors contributed to the writing of the Comment. J.T.R. and S.L.N. organized the project and facilitated inclusive discussions among the authors.

Competing interests

J.T.R. is a shareholder, director and employee of Motif Neurotech, Inc. S.L.N. is a director and employee of Forest Neurotech. T.D. is founder and director of Amber Therapeutics, non-exec chairman of Mint Neurotechnologies Ltd. and advisor for Cortec Neuro. N.V. is a shareholder, director and employee of Neurosoft Bioelectronics S.A., a Swiss company building BCIs. M.M.S. is an inventor on patents or patent applications related to neural decoding and stimulation. R.M.F. is a shareholder, director and employee of Kernel. A.L.O. is a scientific advisor for Meta Reality Labs. S.A.S. is a shareholder of Motif Neurotech, and has consulting agreements with Neuropace, Boston Scientific, Zimmer Biomet and Koh Young. A.F. is a shareholder, director and employee of Cognixion Corporation. M.R.A. is a shareholder, director and employee of Paradromics, Inc. C.J.R. is an inventor on intellectual property

related to neurotechnology, and a shareholder and member of the scientific advisory board of Motif Neurotech, Inc. S.D.S. is an inventor on patents or patent applications related to BCIs and is an advisor to Sonera. T.G.C. is a shareholder and director of Mint Neurotechnologies, Ltd. M.S. is an inventor on patents or patent applications related to neural decoding and stimulation. C.X. is an inventor on intellectual property related to neurotechnology, and a shareholder of Neuralthread, Inc. J.P.D. is a shareholder and board member of Pathmaker Neurosystems, and an advisor to Neurable and to Beacon Biosignals. All other authors declare no competing interests.