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NEUROCHIPS AND BRAIN-COMPUTER INTERFACES: CURRENT STATE AND OPPORTUNITIES

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Annotation. This paper examines current status and future prospects of neurochips and brain-computer interfaces, designed to create direct communication channels between the human nervous system and external computing devices. These technologies are increasingly moving from the research arena into the clinical arena, greatly impacting the treatment of neurological conditions and the possibility of cognitive enhancement. The research is also aimed at providing valuable information for clinicians, engineers, and policymakers on the future prospects of neurochips and brain-computer interfaces.

Keywords: brain-computer interface, neurochip, neural implant, EEG, deep brain stimulation, neural signal decoding, neuroethics, neurostimulation, biocompatibility.

Introduction. The concept of direct, real-time communication between the human brain and digital machines has progressed from theories to the clinical fact in the course of a single generation. Brain-computer interfaces, defined by the ability to acquire, interpret, and act upon brain signals, now permit paralyzed individuals to control robotic limbs, restore partial vision to the blind, and even decode intended speech from brain signals alone. Underlying many of the most sophisticated implementations of such technologies is the presence of neurochips, small silicon-based integrated circuits capable of simultaneously recording signals from thousands of individual neurons, interpreting these signals, and wirelessly transmitting the results to external devices.

It has been driven by a series of advancements in microelectronics, materials science, machine learning, and neuroscience. While the history of BCI research itself dates back to Hans Berger's 1924 recording of the first human electroencephalogram, as well as to Jacques Vidal's 1973 formalization of the «BCI challenge» it is perhaps in the last decade that BCIs have moved from laboratory curiosity to the widespread clinical application following a series of important milestones in the development of high-density neural recording arrays and deep learning decoders [1].

In this paper, an overview of the current status of neurochip and BCI technology will be given, with emphasis on recent hardware breakthroughs, signal processing strategies, clinical applications, and the challenges that must be addressed before neurochip and BCI technology reaches its full potential. Such an overview is designed to be useful to those entering the field of neurochip and BCI technology or clinicians interested in emerging therapeutic options.

Main part. Brain-computer interfaces differ in their invasive properties. Non-invasive brain-computer interfaces utilize electroencephalography, which records aggregate electrical activity on a subject's scalp. These interfaces are safe to use and inexpensive but lack high spatial resolution.

Partially invasive electrocorticography arrays are placed on top of the cortical surface, which results in high signal quality. Fully invasive intracortical electrodes, as represented by the Neuralink N1 chip [Fig. 1], which was implanted in a human subject for the first time in January 2024, record single-unit activity with the highest fidelity but pose a high risk of chronic tissue response and infection.

The neurochip combines amplification, digitization, multiplexing, and signal processing in an implantable device. The Neuralink N1 neurochip has 1,024 recording channels that are spread over 64 flexible polymer threads and use Bluetooth for wireless transmission.

The 2025 BISC neurochip developed by Columbia University takes this concept further with 65,536 electrodes combined in a single chip with minimally invasive form factor [2].

Neuromorphic processors are neurochips that use an architecture similar to that of biological neurons and provide order-of-magnitude improvements in power efficiency for spike-sorting and decoding operations that are crucial to BCI function, which is an important consideration for implants that must be thermally efficient.

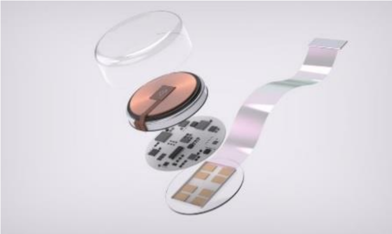

Figure 1–The Neuralink N1 neurochip

Deep learning has emerged as the primary approach to translating neural signals into meaningful outputs. Convolutional and recurrent neural networks extract complex features from EEG and intracortical signals, which are then used to continuously decode motor intention, imagined speech, and cognitive states [3].

Shared autonomy models use AI agents to infer and complete user intention from noisy neural signals, while closed-loop decoder adaptation adjusts model parameters to combat neural non-stationarity without requiring user recalibration.

The most advanced clinical applications are motor BCIs that restore limb functions in tetraplegia, speech BCIs that can synthesize intended words from motor cortex activity at rates approaching natural conversation, and DBS for Parkinson's disease. The latest generation of closed-loop DBS devices that adapt stimulation based on real-time biomarkers has now demonstrated improved symptom control.

Neural interfaces produce real-time data that represents cognitive states and intentions, which creates new types of privacy risks. There are issues of agency when AI systems control volitional action and equity problems will arise if brain-computer interface technologies are only available to well-resourced. Chile's decision to enshrine the rights of people with neurological disorders in its constitution in 2021 marks the beginning of a needed dialogue on global governance [4].

Outside of these concerns, the informed consent process, as it is developed for traditional clinical trials, is not well suited to the intensely personal nature of neural implantation, where the line between therapeutic intervention and identity alteration is not easily drawn. Neural data, unlike other forms of biometric data, has the potential to reveal intentions and cognitive processes that were not even consciously expressed, opening the door to exploitation by employers without the individual's knowledge. As enhancement technologies near the point of commercial viability, the potential for forced pressure on individuals to undergo neural modification in competitive professional environments is a tangible social concern that must be addressed, not only through new legal instruments but through an ongoing dialogue between engineers, ethicists, and the populations.

Conclusion. Neurochips and brain-computer interfaces have emerged from the research tools to clinically validated technology that can significantly enhance the quality of life of those suffering from severe neurological disorders. The integration of high-density recording, artificial intelligence-based decoding, and flexible bioelectronics is breaking traditional boundaries at an accelerating rate. Unlocking the full potential of this technology, from both a clinical and safety perspective, will require continued collaboration among neuroscience, engineering, medicine, law, and the social sciences, along with meaningful engagement with those most impacted by the technology.

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