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Architectural Design and Implantation Strategies of Brain–Computer Interfaces: A Comparative Review of Neuralink, Synchron, Precision Neuroscience, and Paradromics

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Abstract

Brain–computer interfaces (BCIs) are rapidly advancing toward clinical viability, offering new ways to restore function and enable direct communication between the brain and external devices. This comparative review focuses primarily on the architectural design, engineering strategies, and implantation methods employed by four industry leaders: Neuralink, Synchron, Precision Neuroscience, and Paradromics. Drawing from peer-reviewed publications, technical preprints, and public disclosures from the past five years, the analysis compares each platform's approach to electrode fabrication, surgical access, signal acquisition, and system integration.

Neuralink and Paradromics emphasize high-density intracortical systems for fine-grained neural decoding, while Synchron and Precision Neuroscience prioritize minimally invasive, scalable solutions compatible with existing clinical workflows. Although the systems differ in invasiveness and spatial resolution, they share a common trajectory toward closed-loop, AI-enhanced applications in motor control, communication, and neuromodulation. The paper also briefly considers ethical and regulatory issues, including neurodata privacy, algorithmic transparency, and device safety, to contextualize the broader implications of these technologies. Overall, the review provides a technical foundation for understanding the engineering trade-offs shaping the next generation of neural interface platforms.

Keywords: migraine; pathophysiology; prodromal / premonitory phase; 'pre-prodromal' phase / 'pre-premonitory' phase; migraine with aura (MwA); migraine without aura (MwoA); chronic migraine (CM)

Introduction

Brain–computer interfaces (BCIs) represent a rapidly advancing area of neurotechnology, offering new ways to restore lost function, enhance human capabilities, and reshape the relationship between neural activity and digital systems. What was once confined to exploratory research is now entering the realm of clinical viability, supported by advances in materials engineering, artificial intelligence (AI), low-power electronics, and precision surgical techniques. This momentum drives BCIs from experimental research projects toward viable therapeutic tools with meaningful and viable clinical impact. Four companies—Neuralink, Synchron, Precision Neuroscience, and Paradromics—have taken leading roles in this transition, each pursuing distinct technological approaches and design philosophies that reflect different visions for the future of neural interfacing.

This review compares their approaches across several dimensions, including device architecture, surgical methods, signal acquisition, and intended therapeutic use. The analysis highlights how each company balances trade-offs among invasiveness, signal resolution, biocompatibility, and long-term usability. From Neuralink's high-channel-count intracortical platform to Synchron's minimally invasive endovascular design, these companies represent a range of strategies shaping neurotechnology's future. By situating these developments within broader clinical, ethical, and regulatory frameworks, this review provides a clear picture of where the field stands today and how it may continue to evolve.

Methods

This comparative review was guided by a structured literature search conducted through PubMed and Google Scholar, focusing on publications from 2019 to 2025. Keyword combinations included terms such as "brain–computer interface + [company name]," "intracortical neural implant," "speech decoding + BCI," and "minimally invasive neural interface." Medical Subject Headings (MeSH) were applied to refine search results where appropriate.

Priority was given to peer-reviewed articles, technical preprints, and clinical studies that described device architecture, neural decoding methodologies, biocompatibility data, and major translational milestones. In instances where companies provided limited technical documentation to safeguard intellectual property, additional context was drawn from publicly available sources, including press releases, investor briefings, and white papers. These were cited selectively to support discussion of development timelines, regulatory progress, and product deployment.

All references were cross-validated for consistency, and preference was given to those with persistent identifiers such as DOI links to enhance traceability and reliability.

Neuralink

Neuralink's N1 platform represents a paradigm shift in intracortical BCI design integrating subcellular-scale electrode fabrication, high-throughput signal acquisition, and robotic microsurgery into a compact, fully implantable wireless device. Developed under Elon Musk's vision of achieving high-bandwidth symbiosis between humans and AI, the N1 system merges neuroengineering, AI, and materials science for both therapeutic and augmentative applications [1].

Each N1 implant includes 64 ultra-flexible polymer threads, with 16 platinum–iridium electrodes on each, totaling 1,024 recording channels. These threads are manufactured using multilayer photolithography on polyimide substrates and measure approximately 4–6 µm thick and 20 µm wide. Their mechanical compliance (Young's modulus ≈ 2.5 GPa) is tailored to match the softness of cortical tissue, reducing strain-induced gliosis and improving long-term biocompatibility. Finite element modeling, a computational method for simulating material behavior under physical forces, has shown that this design reduces von Mises stress, a standard metric for tissue strain, at the electrode–glia interface compared to conventional silicon shanks [2][3].

The electrodes are electrochemically modified with platinum black or iridium oxide to increase surface area and charge injection capacity. This modification yields impedance values of approximately 250–300 kΩ at 1 kHz, balancing thermal noise suppression with bandwidth requirements. These electrical properties enable the simultaneous detection of single-unit action potentials (>300 Hz), local field potentials (1–300 Hz), and subthreshold synaptic activity. The array's spatial resolution allows for laminar profiling across cortical layers II through V. Stability across repeated use has been confirmed by in vitro electrochemical impedance spectroscopy and cyclic voltammetry, which showed minimal degradation over more than one million stimulation cycles [1].

Implantation is performed using Neuralink's R1 surgical robot, a six-degree-of-freedom system that incorporates optical coherence tomography (OCT), fluorescence angiography, and micro-CT imaging to reconstruct cortical surfaces in real time. These data are processed by convolutional neural networks trained to detect vasculature, sulcal boundaries, and anatomical landmarks. The robot inserts threads using a tungsten–rhenium alloy needle with a 40 µm tip radius, operating at a rate of six insertions per minute with submillimeter precision. A closed-loop motion compensation system synchronizes deployment with cardiac and respiratory rhythms, reducing cortical displacement and lowering the risk of hemorrhage or edema [1][4]. The procedure is guided stereotactically, with real-time depth feedback via impedance monitoring and OCT.

Neural signals are processed by custom application-specific integrated circuits (ASICs), built using a 65 nm CMOS process. Each ASIC handles 16 recording channels, providing low-noise amplification (<2.2 µV RMS), 20 kHz sampling, and on-chip data compression using a predictive coding algorithm. These data are transmitted wirelessly via 2.4 GHz frequency-shift keying, with forward error correction and AES-256 encryption. Power is delivered wirelessly via resonant inductive coupling at 6.78 MHz, with the receiver coil embedded in the cranial mount and the transmitter located in an external wearable device. The implant is hermetically sealed in a titanium–ceramic enclosure, with a total volume under 450 mm³ and mass of approximately 4.5 grams, allowing complete subdermal placement with no percutaneous connectors [5][6].

Preclinical studies in rodents and non-human primates have demonstrated stable neural recordings over periods exceeding 12 months. The system achieved spiking yields above 70 percent and signal-to-noise ratios greater than 6.5 to 1, with minimal channel dropout. Neural decoding utilizes a hybrid architecture consisting of Kalman filters, which estimate trajectories from noisy data, long short-term memory (LSTM) networks for learning temporal dynamics, and particle filters for probabilistic inference. These models have achieved classification accuracies over 90 percent and latencies below 100 milliseconds in standard tasks such as center-out and reach-to-grasp movements. Post-explantation histology has shown minimal astrocytic encapsulation and preserved neuronal density within 50 µm of electrode sites, supporting the implant's long-term biocompatibility [3].

In 2025, Neuralink launched the PRIME Study (NCT06429735), its first human trial of the N1 system. The trial targets individuals with cervical spinal cord injury or amyotrophic lateral sclerosis (ALS) and aims to evaluate safety, signal fidelity, and functional restoration. The first participant, a quadriplegic veteran, successfully used the system to control a computer cursor using volitional intent, representing a major clinical milestone in neuroprosthetics [4].

Neuralink's development roadmap includes a range of bidirectional stimulation applications. One program, titled "Blindsight," targets the primary visual cortex (V1) with patterned intracortical microstimulation (ICMS) to restore visual perception in individuals with optic nerve damage. According to Musk, the eventual goal is to surpass the capabilities of the human eye [7]. Preclinical studies have shown that spatially resolved phosphenes can encode alphanumeric characters. Additional areas under development include somatosensory feedback through primary sensory cortex (S1) stimulation, hippocampal theta entrainment for memory enhancement, and neuromodulation of limbic circuits for treating depression and obsessive-compulsive disorder [3][8].

These advanced capabilities introduce complex ethical and regulatory challenges. The bidirectional nature of the system raises concerns about neurodata privacy, algorithmic bias, and unauthorized stimulation. Musk has repeatedly emphasized that Neuralink is not solely a therapeutic company but also a vehicle for cognitive enhancement and eventual human–AI integration [1]. In response, scholars have called for dynamic consent models, long-term neuroethics monitoring, and transparent algorithmic oversight to protect user autonomy. As the distinction between therapy and enhancement continues to erode—a direction Musk endorses as necessary to address the risks of advanced AI—ongoing collaboration among neuroscientists, ethicists, regulators, and patient advocates will be essential to guide the responsible deployment of high-resolution neural interfaces [1][8].

Synchron

In contrast to Neuralink's intracortical system, Synchron takes a minimally invasive endovascular approach to brain–computer interfacing with its Stentrode™ device. This self-expanding electrode array is implanted within the superior sagittal sinus, adjacent to the motor cortex, using techniques familiar to interventional neurologists. By accessing the brain through the internal jugular vein and avoiding open-brain surgery,

Synchron's approach reduces procedural risks and expands eligibility for patients with comorbidities or contraindications to craniotomy [9][10].

The Stentrode is delivered via a 9 French catheter under fluoroscopic guidance and deployed within the venous sinus, where it conforms to the curvature of the vessel wall without requiring direct fixation to brain tissue. Once anchored, it passively integrates with the endothelium, providing stable long-term positioning for neural signal acquisition [9][10]. Structurally, the Stentrode is a laser-cut nitinol scaffold measuring about 40 mm in length and 8 mm in diameter, embedded with 16 platinum–iridium electrodes. These electrodes are coated with iridium oxide to improve charge transfer and long-term electrochemical stability.

Although the device does not penetrate brain tissue, it can record high-frequency electrocorticographic (ECoG) signals through the vessel wall. These signals include gamma-band activity (70–150 Hz) and lower-frequency beta rhythms associated with motor planning and execution. Signal data are transmitted via tunneled leads to a subcutaneous telemetry unit implanted in the chest, which digitizes the signals and relays them wirelessly using Bluetooth Low Energy (BLE) to external processing hardware [11].

Despite its lower spatial resolution compared to intracortical arrays, the Stentrode can reliably decode motor intentions for digital communication tasks. Clinical validation has come from two major studies: the SWITCH trial in Australia and the COMMAND trial in the United States. In the SWITCH study, four participants with severe upper-limb paralysis used the system to control digital interfaces with no serious device-related adverse events over 12 months [11]. Participants achieved typing speeds of up to 14 characters per minute using motor imagery alone, with accuracy rates above 90 percent. The decoding pipeline involved extracting features from mu (8–12 Hz), beta (13–30 Hz), and gamma (30–150 Hz) bands, followed by classification using support vector machines (SVMs) tailored to individual neural signatures.

In the U.S.-based COMMAND trial, six participants underwent successful implantation. No migration, thrombosis, or need for explantation was observed, and all users achieved functional digital control within 60 days post-implant. Signal quality remained stable over the full 12-month follow-up, with no decline in decoding performance [12].

The endovascular route presents unique biological and engineering challenges. Signals must pass through the endothelial lining and dura mater, which can introduce impedance variability and signal attenuation. Additional risks include endothelial remodeling, fibrin sheath formation, or thrombus development. Synchron addresses these concerns using antithrombogenic coatings, perioperative systemic heparinization, and computational modeling to optimize electrode placement based on hemodynamic shear stress [13]. In ovine preclinical models, stable recordings have been maintained for over 190 days. Histological evaluations confirmed minimal vascular remodeling, preserved endothelial integrity, and no thromboembolic events [14].

Synchron's broader design philosophy emphasizes safety, scalability, and compatibility with everyday technologies. The system is intended for outpatient deployment without requiring neurosurgical infrastructure. It is already interoperable with platforms such as Apple Vision Pro, Amazon Alexa, and NVIDIA Holoscan. The latter allows edge-based AI processing of neural data, reducing latency and enhancing privacy by limiting dependence on cloud-based systems [15].

Beyond its current focus on motor decoding, Synchron is exploring endovascular stimulation to enable bidirectional communication. Preclinical studies are underway in treatment-resistant depression, epilepsy, and autonomic regulation, including baroreflex modulation for managing hypertension. These efforts support the development of endovascular deep brain stimulation (eDBS) and expand the potential applications of the Stentrode platform beyond digital communication into neuromodulatory therapy [16].

Precision Neuroscience

Precision Neuroscience's Layer 7 Cortical Interface is a high-density, subdural neural array designed to provide research-grade signal resolution with a minimally invasive surgical footprint. Unlike intracortical systems that penetrate brain tissue, Layer 7 is placed just beneath the dura, resting directly on the pia mater. This design allows for close contact with the cortical surface while preserving the brain's structural integrity and minimizing the risk of tissue damage. The array conforms naturally to the folded surface of the cortex, maintaining stable coverage across both sulci and gyri without causing indentation or displacing cerebrospinal fluid [17].

The array is built on a flexible polyimide substrate and contains 4,096 microelectrodes spread across an 8 cm^2 area. Electrode diameters range from 50 to 380 μm, with submillimeter spacing that enables mesoscale mapping of cortical field potentials. The electrodes are manufactured using MEMS lithography and thin-film metallization, and coated with gold and iridium oxide. These coatings help achieve impedance values between 10 and 50 kΩ at 1 kHz, balancing signal quality and charge injection capacity. With a total thickness of less than 20 μm, the array closely conforms to the brain's surface and minimizes movement artifacts. Compared to standard ECoG grids, Layer 7 offers over 600 times higher electrode density, making it capable of capturing laminar and columnar activity within the cortex [17][18].

Implantation is performed through a cranial micro-slit technique that requires a craniotomy smaller than 1 mm in diameter. A proprietary delivery tool guides the flexible array through the slit and unfolds it across the cortical surface, eliminating the need for dural retraction or direct cortical manipulation. In preclinical studies involving Göttingen minipigs, the array was implanted bilaterally over motor and visual cortices at an insertion rate of more than 40 milliseconds per channel. No evidence of cortical damage, impaired blood flow, or inflammatory encapsulation was observed [17]. The procedure is designed to be scalable, reversible, and compatible with standard neurosurgical workflows.

Clinical use of Layer 7 began in 2024, when it received FDA 510(k) clearance for temporary implantation lasting up to 30 days. Its primary applications included intraoperative mapping during epilepsy surgery and tumor resection [19]. As of 2025, the system has been tested in over 40 patients at centers such as Mount Sinai, Penn Medicine, and the Rockefeller Neuroscience Institute. No serious neurological complications have been reported. The company is pursuing approval for chronic use, supported by long-term biostability data showing minimal gliosis and consistent signal performance [17][20].

Signal processing is handled through an integrated conditioning pipeline. Each channel undergoes low-noise amplification and 16-bit analog-to-digital conversion, followed by real-time digital filtering to suppress motion artifacts and electrical interference. Filtering methods include finite impulse response (FIR) and notch filters. Although the current system uses a percutaneous lead, a fully wireless version is under development. The sampling rate exceeds 20 kHz per channel, and decoding latency in real-time tasks—such as cursor control or speech synthesis—has been measured at under 100 milliseconds, supporting closed-loop feedback with low perceptual delay [17][21].

Functionally, the Layer 7 system has demonstrated strong performance in decoding imagined speech, achieving classification accuracies over 85 percent across multiple phonemic categories. These results were obtained using deep recurrent neural networks (RNNs) and convolutional architectures. Potential applications include communication aids for patients with locked-in syndrome, brainstem stroke, or anarthria [1][5]. In addition to recording, the array supports electrical stimulation. Early

studies have shown that it can be used for adaptive neuromodulation in conditions such as focal epilepsy and treatment-resistant depression, and possibly for cognitive enhancement. Stimulation parameters are guided by finite element modeling and in vivo impedance spectroscopy, with charge densities maintained below 30 μC/cm² per phase, which is within safety limits for subdural interfaces [18][21].

Precision Neuroscience emphasizes surgical reversibility, hardware modularity, and integration with existing clinical infrastructure. The system supports deployment of multiple arrays across different brain regions without increasing procedural complexity. This strategic focus on scalability, regulatory compliance, and clinical utility positions the Layer 7 platform as a viable candidate for both short-term and chronic neurotechnology applications in real-world healthcare environments.

Paradromics

Paradromics is developing the Connexus® Direct Data Interface (DDI), an intracortical BCI designed for high-throughput, bidirectional communication with the brain at single-neuron resolution. Targeting patients with severe motor impairments caused by conditions such as ALS, brainstem stroke, or spinal cord injury, Connexus has received FDA Breakthrough Device Designation for its assistive communication potential [22][23][24].

At the core of the system is a monolithic silicon array containing more than 1,600 penetrating microelectrodes. These are fabricated using deep reactive-ion etching (DRIE) to form Utah-style shanks ranging from 1.0 to 1.5 mm in length. Each shank is coated with platinum–iridium to improve charge transfer and reduce polarization impedance, typically reaching 100–300 kΩ at 1 kHz. The tips are sharpened to sub-10 μm radii to facilitate minimally traumatic insertion into cortical layers II through V. These dimensions support simultaneous recording of action potentials and local field potentials across both superficial and deep cortical laminae [22][25].

The array interfaces with custom CMOS electronics for on-chip signal conditioning. Each shank is connected to multiplexing and amplification circuitry that performs analog-to-digital conversion, spike detection, and data compression directly at the cortical surface. Sampling is supported at 30 kHz per channel, enabling sub-millisecond temporal resolution of neural signals [22][25].

To address long-term biocompatibility concerns associated with rigid silicon substrates, Paradromics employs a combination of surface microtexturing, perforated geometries, and biomimetic coatings. These design strategies help reduce glial scarring, promote vascular integration, and minimize inflammation due to micromotion. Preclinical studies in ovine models have shown stable single-unit recordings maintained over 2.5 years, with no evidence of chronic neuroinflammation and minimal signal degradation [23][26].

The system is encased in a titanium alloy housing that sits flush with the skull, minimizing mechanical stress and cosmetic impact. Data and power are transmitted through a hybrid telemetry system composed of a cranial cortical module, an internal chest-mounted transceiver, and an external wearable unit. Neural data is sent via a high-speed near-infrared photonic link (>100 Mbps), while power is delivered using inductive coupling at 6.78 MHz [22][26]. This infrastructure enables continuous, real-time streaming of neural data to an external processor.

Connexus supports advanced decoding pipelines built on multiple algorithmic architectures. These include linear discriminant analysis (LDA), convolutional neural networks (CNNs), and transformer-based models that extract motor intent and reconstruct speech from large-scale neural recordings. The system has demonstrated decoding latencies under 100 milliseconds, allowing for real-time closed-loop control of digital devices. In 2025, a first-in-human pilot study at the University of Michigan implanted the Connexus array during an epilepsy resection surgery. The device was explanted after 20 minutes with no adverse effects and successfully recorded high-resolution temporal cortex activity, validating its acute safety and signal fidelity in humans [27][28].

Bidirectional stimulation capabilities are also in development. Paradromics is prototyping current-controlled stimulation modules designed for somatosensory feedback, auditory pattern encoding, and modulation of limbic circuits. Stimulation parameters are optimized using finite element modeling and in vivo impedance spectroscopy, with charge densities maintained below 30 μC/cm² per phase to ensure safety and specificity [25][29].

Paradromics envisions Connexus as a scalable platform for restoring lost function and enabling new forms of communication and cognition. In partnership with DARPA, NIH, and other stakeholders in clinical research and defense, the company continues to invest in miniaturization, algorithm development, and regulatory strategy. Long-term goals include deploying high-bandwidth, modular neural interfaces capable of supporting cognitive prosthetics, adaptive neuromodulation, and fully integrated human–machine interaction at scale [23][24].

Comparative Analysis at a Glance

To highlight key differences and commonalities among Neuralink, Synchron, Precision Neuroscience, and Paradromics, Table 1 summarizes each platform's core attributes across surgical, technical, and clinical domains.

Company	Surgical Access	Electrode Type	Channel Count	Signal Resolution	Telemetry	Clinical Status	Bidirectional
Neuralink	Intracortical (robot-assisted microsurgery)	1,024 flexible polyimide threads (16 electrodes/thread)	1,024 per implant	Single-unit + local field potentials	Wireless (2.4 GHz FSK, AES-256 encryption)	PRIME Study (NCT06429735); spinal cord injury & ALS	In early development
Paradromics	Intracortical (manual insertion)	1,600+ rigid silicon shanks (platinum–iridium)	6,400+ (scalable)	Single-unit resolution @ 30 kHz	Optical/electrical hybrid (100+ Mbps)	First-in-human pilot completed (epilepsy resection)	Prototyping
Precision Neuroscience	Subdural (micro-slit craniotomy)	4,096 thin-film electrodes (gold/iridium oxide)	4,096	High gamma, beta-band potentials	Percutaneous lead (wireless in development)	FDA-cleared for 30-day use; 40+ patients evaluated	Demonstrating
Synchron	Endovascular (jugular vein access)	16 stent-mounted ECoG electrodes (platinum–iridium)	16	Gamma & beta-band ECoG	Subcutaneous BLE telemetry	SWITCH & COMMAND trials; chronic digital control (12+ months)	In exploration

Table 1: Comparative Overview of Four Leading BCI Platforms

The comparative analysis reveals a trade-off continuum between spatial resolution and surgical invasiveness: Neuralink and Paradromics maximize precision at the cost of procedural complexity, while Synchron and Precision Neuroscience emphasize accessibility and safety. Paradromics currently offers the highest potential channel scalability and sampling frequency, whereas Precision's Layer 7 excels in rapid deployment and high-density subdural recording. Synchron is the only platform with long-term human implantation (>12 months) without craniotomy, supporting its translational maturity. All four are pursuing bidirectional functionality, though only Neuralink and Paradromics have outlined detailed microstimulation pipelines.

Conclusion

The brain–computer interface (BCI) industry is rapidly evolving from experimental systems to clinically actionable technologies. As reviewed here, Neuralink, Synchron, Precision Neuroscience, and Paradromics represent four distinct yet complementary approaches to neural interfacing, each shaped by different trade-offs in design philosophy, surgical complexity, and translational readiness. Neuralink and Paradromics are advancing high-resolution intracortical systems that prioritize single-neuron precision, real-time decoding, and bidirectional capabilities. These platforms offer the greatest potential for fine-grained control and cognitive applications but require more invasive surgical procedures and complex technical infrastructure.

In contrast, Synchron and Precision Neuroscience focus on safety, surgical accessibility, and seamless integration with existing clinical workflows. Their minimally invasive or non-penetrative platforms allow for broader patient eligibility and more immediate translation into real-world settings. While these approaches trade off some spatial resolution, they demonstrate robust performance for communication, motor restoration, and adaptive stimulation. Synchron's endovascular design, in particular, represents a novel category of interface with long-term implantation in humans already underway.

All four companies are actively pursuing some type of bidirectional communication, a frontier that promises to move BCIs beyond decoding into therapeutic neuromodulation and sensory restoration. However, the emergence of such powerful systems also raises critical questions around privacy, algorithmic oversight, and the ethical boundary between treatment and enhancement. The direction of this field will depend not only on technological milestones but also on how these systems are governed, regulated, and ethically integrated into society.

Ultimately, the value of these platforms will be measured by their ability to restore agency, extend communication, and support human dignity in patients facing profound neurological challenges. Achieving that goal will require continued innovation, rigorous clinical validation, and a sustained commitment to ethical design. Taken together, the four platforms reviewed here represent the leading edge of a rapidly maturing field—one that holds transformative potential for neuroscience, medicine, and the future of human–machine interaction.

Declarations

All journal policies and submission guidelines were carefully reviewed to ensure full compliance, and the manuscript has not been previously published or submitted elsewhere. The author declares no conflicts of interest. No human, animal, or plant subjects were involved in this literature review, so ethics approval, participant consent, and studies involving plants are not applicable. Additionally, no personal details, images, or videos of individuals are included, which makes publication consent unnecessary. The research did not receive external funding, and no data or supplementary materials are associated with the manuscript. Grammarly AI was used solely to refine grammar, syntax, and paragraph structure. It did not generate ideas or content, thereby preserving the originality of the work.

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