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Perspective

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Neuromimetic circuits enabled by dynamic regulation of the electrical double layer

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Iontronics presents a transformative paradigm for energy and information processing via ions as active charge carriers. Here, triboiontronics is introduced, a novel strategy leveraging contact electrification to achieve dynamic regulation of electrical double layers. Inspired by signaling mechanisms of biological neural systems, triboiontronics enables enhanced ionic-electronic coupling without external power input, offering a material-independent and self-powered pathway for programmable interfacial behavior, underscoring its promise for post-Moore, energy-autonomous information technologies.

In both the expansive infrastructure of the Internet of Things (IoT) and the intricately interconnected architecture of the human brain, the efficiency of energy utilization serves as a fundamental constraint on information flow and processing[1,2]. As billions of distributed sensors and cloud-edge collaborative devices are deployed, conventional computing paradigms, rooted in the von Neumann architecture, are facing escalating limitations in the post-Moore era, marked by exponential increases in data throughput and stringent energy demands[3]. These challenges have catalyzed a paradigm shift toward distributed, ultra-low-power computational frameworks[4,5]. The human brain, with its highly coordinated ion fluxes and glial-neuronal signaling networks, exemplifies a model of energy-efficient information processing and offers a compelling blueprint for next-generation computing[6–8]. In this context, iontronics has emerged as a promising frontier, forging a link between artificial electronics and biological intelligence[9–11]. By enabling neuromorphic platforms that emulate the brain's intrinsic synergy between energy and information, iontronics holds significant potential to redefine the principles of intelligent, energy-autonomous systems[12,13].

Iontronics, a discipline that utilizes ions as active charge carriers for both energy conversion and information transmission, was recognized by the International Union of Pure and Applied Chemistry (IUPAC) as one of the Top Ten Emerging Technologies in Chemistry in 2024. Distinct from conventional electronics that rely exclusively on electrons or holes, iontronics harnesses coupled ionic-electronic dynamics at solid-liquid interfaces to enable inherently energy-efficient, adaptive, and neuromorphic signal transduction[14]. A compelling exemplar is the human brain, a fully integrated, ion-based processor, that performs complex cognitive functions with a power consumption of only ~12 W, vastly outperforming artificial systems in energy efficiency[15]. Although significant progress has been achieved in the development of ion logic circuits[16,17] and chemical logic devices[18,19], these platforms typically address either ion transport or chemical reactivity in isolation, often lacking the feedback-regulated, temporally modulated, and plastic signal processing capabilities intrinsic to biological neural systems. Conventional ion circuits predominantly facilitate static or preprogrammed ion flows, while iono-chemical systems focus on redox- or pH-responsive operations. In contrast, neuromimetic circuits aim to emulate the adaptive, energy-efficient dynamics of neural networks, encompassing features such as history-dependent plasticity, unidirectional signal propagation, and multimodal responsiveness. By replicating the architectural and functional principles of synapses and ion channels, these circuits integrate dynamic ion modulation and memory into signal transduction. This bioinspired strategy enables rich spatiotemporal regulation, adaptive learning, and ultra-low power consumption, attributes essential for the realization of next-generation intelligent and autonomous systems.

At the heart of iontronics lies the electrical double layer (EDL), a functional interfacial structure that governs charge redistribution and modulation[20–22]. Although EDL formation at conductive interfaces has been extensively studied through electrochemical methods for nearly two centuries, these mechanisms are intrinsically confined to conductive substrates[23–26]. The introduction of a two-step EDL model for dielectric-liquid interfaces, where electron transfer precedes ion migration, marked a key conceptual advance[27–29]. However, dynamic, reversible, and controllable modulation of EDLs at dielectric surfaces remains a major challenge, limiting the development of reconfigurable, energy-efficient, and flexible iontronic systems.

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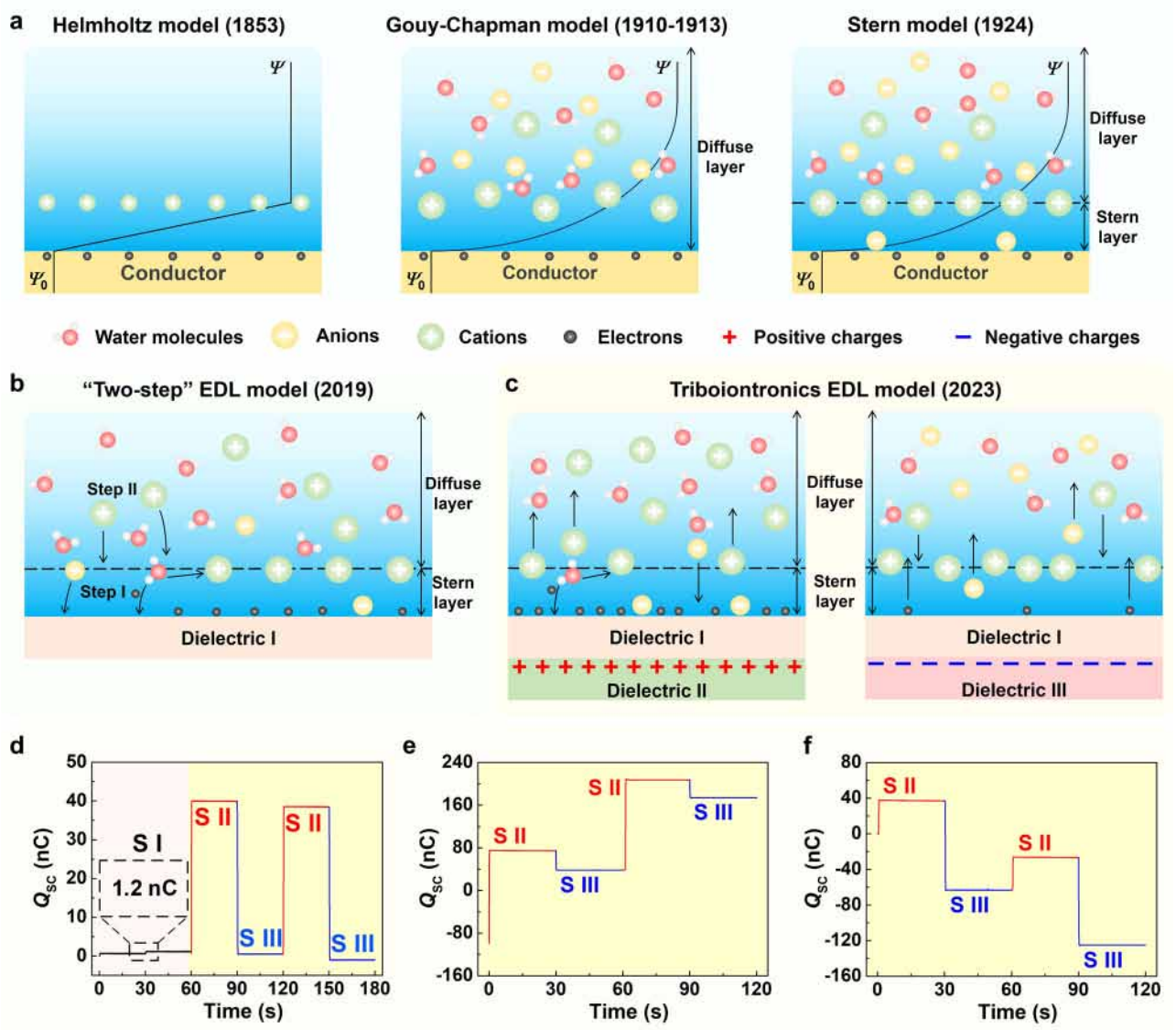

Fig. 1 | Evolution of the electrical double layer model. a Classical EDL models at conductor-liquid interfaces. **b** The "two-step" EDL model at dielectric-liquid interfaces. **c** Triboiontronics EDL model for dynamic regulation of interface charge. **d-f** Verification of the dynamic regulation mechanism of the triboiontronics EDL model. Reproduced with permission[30]. Copyright 2023, Matter published by Elsevier Inc.

In this Perspective, triboiontronics is proposed as a conceptual and experimental framework to overcome the long-standing challenge of dynamically regulating EDLs at dielectric solid-liquid interfaces. By harnessing contact electrification, triboiontronics enables robust, reversible ionic-electronic coupling without external bias, offering a material-independent, energy-efficient strategy for programmable interfacial control[30–32]. Its potential in information flow systems was demonstrated through self-powered neuromimetic applications, including bioinspired neuromorphic circuit regulation[12,30,32,33], underwater wireless transmission[34,35], and fluidic ion memory for synaptic emulation[8,36], the critical for the advancement of autonomous, distributed iontronics. Looking forward, triboiontronics presents a promising route toward post-Moore information technologies, enabling non-silicon, low-power, and adaptive architectures. Integration with emerging flexible electronic platforms may unlock transformative innovations in brain-inspired computing, brain-computer interfaces, human-machine interaction, and neurorestorative medicine.

Model evolution and dynamic regulation of the EDL

At solid-liquid interfaces, the interplay between charge transfer and adsorption processes gives rise to the EDL, a fundamental regulator of interfacial physicochemical behavior. Nearly two centuries of theoretical advancement have significantly enriched our understanding of the dynamic charge distribution governing these interfaces (Fig. 1a). The foundational concept of the EDL dates back to the 19th century, when Helmholtz introduced a parallel-plate capacitor model in which surface charges on a conductor are exactly balanced by a compact layer of counterions, forming a rigid electrostatic equilibrium[23]. While intuitive, this model overlooked the thermal motion and diffusion of ions in the liquid phase. In the early 20th century, Gouy and Chapman independently refined this view by introducing a diffuse ion layer governed by electrostatic forces and thermal fluctuations, culminating in the Gouy-Chapman model[24,25]. This framework described an exponential decay in ion concentration with distance from the surface but treated ions as point charges, neglecting their finite size, hydration shells, and specific adsorption effects, factors that become significant under high ion strength or in the presence of multivalent electrolytes. To address these shortcomings, Stern introduced the Gouy-Chapman-Stern (GCS) model in 1924[26], partitioning the EDL into a compact Stern layer and an outer diffuse layer. The Stern layer comprises the inner Helmholtz plane (IHP), formed by specifically adsorbed ions, and the outer Helmholtz plane (OHP), consisting of solvated ions attracted by long-range

electrostatics. Beyond the Stern layer, the diffuse layer extends into the bulk, with ion distributions governed by a balance of electrostatic and entropic forces. While classical models effectively describe interfacial charge behavior at conductive solid-liquid interfaces and are tunable via electrochemical means, they fall short of capturing the complex dynamics at dielectric interfaces. In 2019, Wang and colleagues proposed a "two-step" EDL model for dielectric-liquid interfaces[27–29,37], representing a significant conceptual breakthrough (Fig. 1b), offering a more nuanced perspective. In the first step, thermal fluctuations and pressure-driven collisions between water molecules and ions enhanced their interaction with the dielectric surface, promoting electron cloud overlap between solid atoms and liquid molecules, thereby facilitating electron transfer and potential surface ionization. This process led to the formation of a compact IHP. In the second step, oppositely charged ions in the liquid migrated toward the charged surface via electrostatic attraction, forming the OHP. Together, these layers comprise the Stern layer, with the diffuse layer extending beyond into the bulk solution. This model expanded the current understanding of charge behavior at dielectric solid-liquid interfaces and provided deeper insights into the structure of the EDL and its role in interfacial charge transfer. However, due to the insulating nature of dielectric materials, achieving real-time, reversible modulation of the EDL remains difficult, posing a major challenge to the realization of efficient energy conversion and information transmission in such systems.

The triboiontronic EDL model[20,30], which leverages triboelectric fields to regulate ion distributions, offers a promising solution to this longstanding challenge. By harnessing triboelectric-induced polarization via contact electrification, this approach enables dynamic modulation of the EDL at dielectric solid-liquid interfaces without the need for external bias (Fig. 1c). In one scenario, positive charges accumulated on dielectric material II via solid-solid contact electrification generate a strong electrostatic field that induces forward triboelectric-induced polarization. This enhances electron transfer from water molecules to the surface of dielectric I and promotes the preferential adsorption of anions with lower free energy from the solution, leading to the formation of a more compact IHP. Simultaneously, the electrostatic field repels some cations from the solid-liquid interface, increasing the net negative charge within the Stern layer while enriching cations in the diffuse layer, thereby reinforcing its ion polarity. Conversely, when dielectric material III acquires a higher density of negative charges through contact electrification, it produces a strong electrostatic field in the opposite direction, inducing reverse triboelectric-induced polarization. This repels anions and attracts cations toward the interface. However, due to their high hydration energy, cations typically do not adsorb directly onto the dielectric surface and instead accumulate near the OHP. As a result, the IHP is primarily composed of polarized water molecules, producing a net positive charge in the Stern layer and driving anion enrichment in the diffuse layer. Compared to forward triboelectric-induced polarization, the EDL exhibits an inverted charge configuration. Triboiontronics EDL model demonstrates that the triboiontronic EDL model enables active, reversible regulation of both Stern layer charge distribution and diffuse layer ion polarity, offering a versatile, self-powered, and material-independent strategy for precise interfacial charge control. To verify the dynamic regulation mechanism of the triboiontronics EDL model, A precisely orchestrated three-stage experiment employing a polyethylene terephthalate (PET)-based humidity generator (spray volume ~1 mL) was devised to emulate triboiontronic modulation of interfacial ion distributions[30], as illustrated in Fig. 1d. In Stage I, the water mist was generated solely through contact electrification between the PET shell and water. The transferred charge (Q_{SC}) measured at the collector was merely 1.2 nC, reflecting limited solid-liquid interfacial charging. In Stage II (forward triboelectric-induced polarization), a positively charged rabbit fur (pre-charged by contact electrification with the PTFE film) was brought into contact with the PET-based humidity generator. The electrostatic field from the fur induced forward triboelectric polarization in the PET shell surface, thereby enhancing the adsorption of anions onto the PET surface and enriching cations in the water mist. The measured Q_{SC} sharply increases to 40.0 nC, indicating significantly enhanced cation-dominated ion transport. In Stage III (reverse triboelectric-induced polarization), upon removal of the fur, electrons were transferred from the fur to the PET shell surface, generating a negatively charged surface. This reversed the polarization direction, promoting the adsorption of cations at the interface and facilitating the enrichment of anions in the water mist. The Q_{SC} now shifted to about -40.0 nC, demonstrating polarity inversion of the ion flux. Moreover, the study further showed that modulating the degree of contact electrification could allow effective tuning of the interfacial electrostatic field strength, thereby regulating the ion transport behavior. In Fig. 1e, increasing the positive charge density on the fur could enhance the forward triboelectric-induced polarization, leading to a Q_{SC} of 180 nC, suggesting an order-of-magnitude increase in cation flux. In Fig. 1f, intensifying negative surface charge on PET under reverse triboelectric-induced polarization could drive a stronger anion flux, with Q_{SC} reaching -100 nC. These results directly support the concept that contact electrification-induced surface charge distributions dynamically modulate EDL structure, affecting the ion species, polarity, and intensity of ion transport. This mirrors the biological processes of membrane depolarization/repolarization and ion-selective gating that underlie action potentials and neural signal propagation. Importantly, this triboiontronic EDL modulation enables real-time, reversible, and bidirectional control over ion flux, without external bias. This property is foundational for implementing neuron-like behaviors, such as unidirectional signal transmission (analogous to axonal propagation), charge polarity inversion (akin to hyperpolarization/depolarization cycles), and stimulus-dependent signal strength modulation (paralleling neural coding plasticity).

Neuromimetic circuits through dynamic regulation of the EDL

By dynamically regulating the EDL to modulate interfacial charge behavior, a robust framework can be established for emulating biological neural signal transmission, thereby enabling the construction of neuromimetic circuits for efficient information flow. In particular, triboiontronics-based dynamic EDL modulation offers a bioinspired ionic-electronic coupling strategy to simulate rhythmic and multi-degree motor control, exemplified by human locomotion. In the human body, gait generation and coordination are governed by the integrated activity of the brain, spinal cord, and peripheral neurons, wherein central pattern generators (CPGs) in the spinal cord autonomously orchestrate rhythmic activation of flexor and extensor muscles (Fig. 2a). This process is governed by ion-based signaling circuits modulated through intricate feedforward and feedback mechanisms. Analogously, the triboiontronics-inspired neuromorphic circuit utilizes a self-powered, triboelectric-induced polarization strategy to dynamically regulate EDL charge migration in real time, enabling adaptive and efficient control of ionic-electronic signal transduction (Fig. 2b). By dynamically modulating interfacial charge distribution to reverse the ion polarity within the diffuse layer, the system emulates neuronal depolarization and repolarization cycles[30,32,33]. In proof-of-concept demonstrations, a droplet-actuated triboiontronic neuromorphic circuit responded to external mechanical cues, such as the contact and separation of positively charged fur with polyethylene terephthalate, by autonomously generating bidirectional ion migration and corresponding electron current pulses. This behavior is reminiscent of CPGs and neuronal excitability in that triboelectric-induced polarization produces time-resolved, programmable ion signals. While not replicating biological spiking in a strict sense, this system provides a bioinspired framework for encoding temporal stimuli through self-powered ion gating. The most significant advancement lies in the circuit's self-powered, adaptive, and ultra-low-energy operation. Unlike conventional neuromorphic systems that rely on complex power and control architectures, the triboiontronic circuit leverages solid-liquid contact and electrostatic induction to locally govern ion transport and globally transduce signals. This approach not only reduces energy consumption and system complexity but also enhances the flexibility, integrability, and environmental robustness of next-generation human-machine interfaces, critical attributes for applications in soft robotics, neuroprosthetics, and

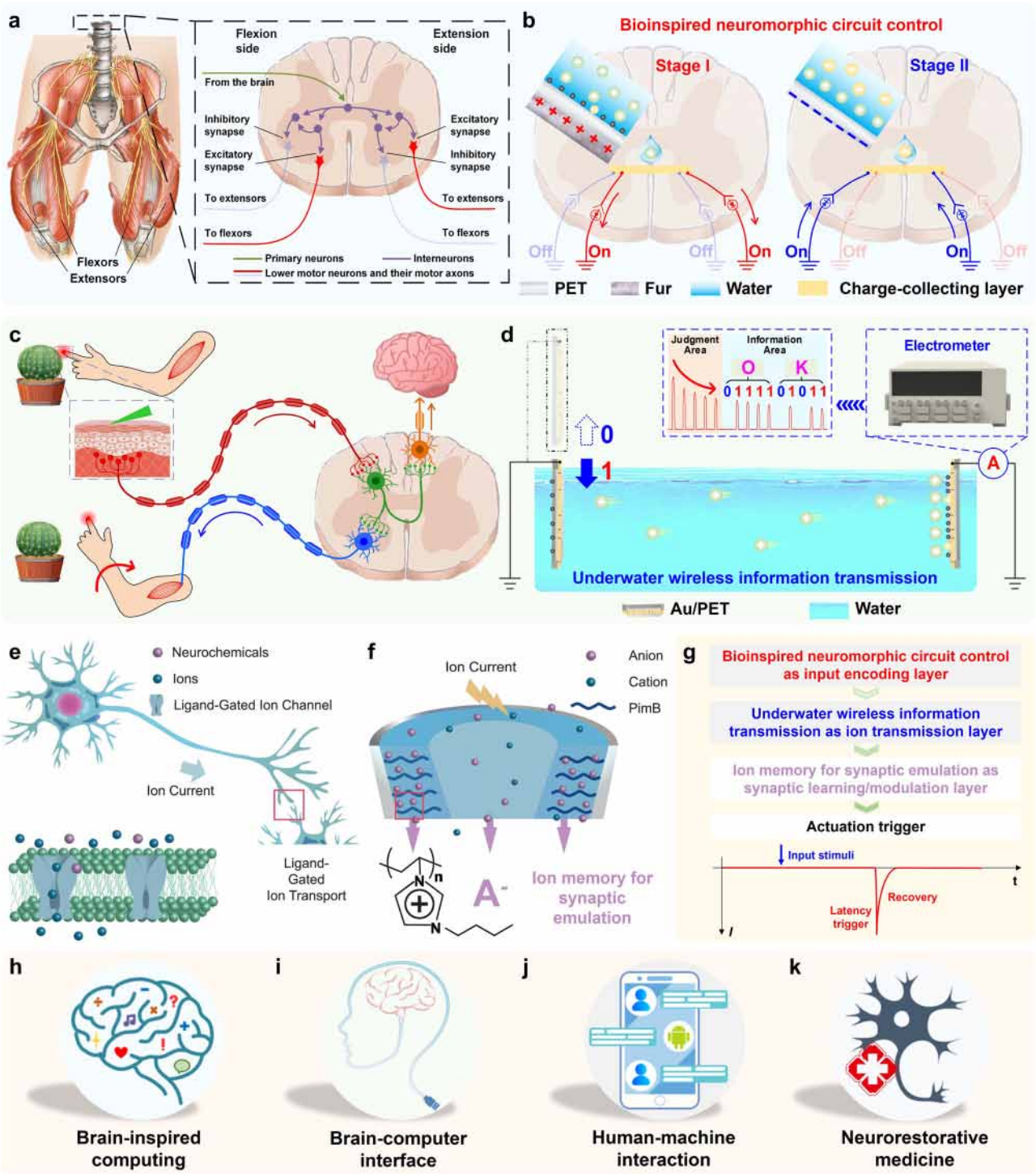

Fig. 2 | Neuromimetic circuits via dynamically regulating EDL for efficient information flow. a, **b** Triboiontronics bioinspired neuromorphic circuit based on dynamically regulating the EDL. Reproduced with permission[30]. Copyright 2023, Matter published by Elsevier Inc. **c**, **d** Bioinspired underwater wireless information transmissions via dynamically regulating the EDL. Reproduced with permission[35]. Copyright 2025, Joule published by Elsevier Inc. **e**, **d f** Inspired by the structure and function of ion channels, a polyelectrolyte-confined fluidic memristor was developed to mimic synaptic behavior via dynamic regulation of the EDL. Reproduced with permission[8]. Copyright 2023, Science published by the American Association for the Advancement of Science. **g** The full operational logic of the neuromimetic system. **h**–**k** Potential applications in the field of efficient information flow based on dynamically regulating the EDL.

autonomous biohybrid systems. Beyond neuromorphic circuit control, dynamic EDL regulation also enables efficient bioinspired signal transmission. In biological systems, particularly within the central and peripheral nervous systems (Fig. 2c), the rapid, directional migration of ions such as Na^+ along concentration gradients underpins the generation and propagation of action potentials. This ion flux is precisely modulated by localized changes in membrane potential and gated ion channels, supporting highly efficient, adaptive neural communication across spatial scales from millimeters to over a meter. Drawing inspiration from neural signaling, triboiontronics leverages dynamic EDL regulation to modulate ion polarity and concentration gradients in real time via triboelectric-induced polarization[34,35]. By tuning interfacial charge distribution at dielectric–liquid interfaces, this

approach enables precise control of ion migration with high spatial and temporal resolution, mirroring the role of Na^+ flux in biological action potential propagation. In a bioinspired underwater communication system (Fig. 2d), triboelectric-induced polarization enhanced the ion concentration gradient by asymmetrically regulating the EDLs, thereby driving directional ion transport. The resulting time-resolved ion flux was converted into electronic pulse signals, enabling self-powered, low-energy, and high-fidelity wireless information transmission. This mechanism closely parallels long-range neural communication and highlights triboiontronics as a compelling platform for building adaptive, low-power iontronic systems.

In organisms, biological synapses are central to neural computation, enabling adaptive signal transmission, learning, and memory through dynamic ion-based mechanisms (Fig. 2e). Key features such as short-term plasticity (STP), frequency filtering, and chemical modulation arise from localized ion flux across membrane-bound EDLs, tightly regulated by voltage-gated ion channels and neurotransmitter signaling. Replicating these functions in artificial systems requires materials that can support dynamic, history-dependent ion behavior under biocompatible conditions. Inspired by the structure and function of ion channels, a polyelectrolyte-confined fluidic memristor (PFM) has been developed to mimic synaptic behavior via dynamic regulation of the EDL[8,36] (Fig. 2f). The device integrates a polyimidazolium brush (PimB) within a conical micropipette, creating a confined, positively charged channel. Upon electrical stimulation, anions such as Cl^- selectively accumulate or dissipate in the PimB layer, driven by electrostatic interactions and limited diffusion kinetics. This leads to hysteretic, time-dependent changes in conductivity, and characteristics of memristive behavior. Similarly, the ion memory device exhibits synapse-inspired modulation via dynamic EDL restructuring, capturing key qualitative features of short-term plasticity such as paired-pulse facilitation and frequency filtering. These results suggest a functional analogy to synaptic behavior, albeit without the full biochemical and structural complexity of biological synapses. Moreover, its response can be tuned chemically, as demonstrated by the modulation of ion dynamics using adenosine-triphosphate (ATP), and further extended to chemical-electric transduction, where neurotransmitter-mimicking ions induce electrical spikes without external power. Operating at low voltages (~±100 mV) and ultra-low energy (~pJ level), the PFM offers a bioinspired platform for soft, self-regulated neuromorphic circuits. Unlike solid-state systems, this approach leverages chemically gated EDL dynamics to exert precise control over ion memory and signal flow, closely mirroring biological synapses. Such capabilities highlight the potential of EDL-based fluidic memristors for bio-hybrid neuromorphic applications, including soft robotics, neural prosthetics, and brain-machine interfaces.

The above three demonstrations are fundamentally driven by reversible, triboelectrically induced modulation of EDLs at dielectric solid-liquid interfaces. This dynamic EDL regulation serves as a universal transduction mechanism linking mechanical, chemical, and electrical domains, analogous to how biological membranes use voltage-gated ion channels to couple physical stimuli with bioelectrical signaling. Importantly, these modules do not represent isolated functions; rather, they correspond to distinct yet interconnected roles within an artificial neuromorphic system, mirroring sensory encoding, axonal transmission, and synaptic plasticity in the biological nervous system. Firstly, neuromorphic circuit control operates as the sensory input and rhythmic generator. Triboelectric-induced EDL polarization converts mechanical stimuli (e.g., contact and separation with fur) into time-resolved ionic or electronic pulses, mimicking CPGs and stimulus-encoded spiking. This represents the input encoding layer. Secondly, underwater wireless information transmission serves as the signal conduction pathway, wherein asymmetric EDL polarization at two distant interfaces sustains an ion concentration gradient that drives the directional ion flow. This functionally resembles axon-mediated long-range signal propagation, constituting the transmission layer. Thirdly, the ion memory for synaptic emulation provides the modulatory and adaptive layer, where chemically confined EDL dynamics within polyelectrolyte-modified micropores emulate short-term plasticity, frequency filtering, and analog memory behaviors, thereby replicating core features of biological synaptic learning. As shown in Fig. 2g, to better articulate the full operational logic of the neuromimetic system, the signal flow is defined as: input encoding → ion transmission → synaptic learning/modulation → actuation trigger. This sequence parallels the biological process of perception → conduction → integration → response, and it establishes a closed-loop model for adaptive, low-power signal processing. To support the validity of this biomimetic architecture, a physiological analogy is drawn to the action potential propagation and synaptic transmission process in neurons[10]. In the nervous system, external stimuli trigger localized depolarization via voltage-gated Na^+ channels (input encoding), which propagates along the axon through Na^+ influx and K^+ efflux (ion transmission). Upon reaching the synaptic terminal, voltage-gated Ca^{2+} channels open, inducing neurotransmitter release (synaptic modulation). The neurotransmitters then activate downstream receptors, leading to Cl^- or Na^+-mediated ionic responses that elicit biological effects such as muscle contraction or sensory feedback (actuation trigger). This sequence demonstrates how ionic species simultaneously serve as energy carriers and information encoders in biological signal processing, a principle that is emulated via the dynamic regulation of the EDLs. To further reinforce this logic, a time-domain response diagram is introduced that illustrates the dynamic behavior of the system from input stimulus to latency trigger to recovery. Where applicable, frequency-domain data and time-resolved ion current measurements are also incorporated (e.g., in synaptic modules exhibiting paired-pulse facilitation and filtering) to demonstrate the programmable and dynamic characteristics of the system in a format that mirrors biological neural signaling.

Outlooks and challenges

These findings highlight the transformative potential of dynamic EDL regulation as a foundational mechanism for constructing bioinspired neuromimetic circuits. By emulating biological signal transmission, triboiontronics-enabled dynamic EDL modulation facilitates efficient, self-powered neuromorphic control and underwater wireless communication. These demonstrations not only validate the feasibility of EDL-based dynamic ion transport for high-fidelity information flow but also establish a novel framework for bridging biological and artificial intelligence. Looking ahead, integrating this mechanism into broader technological domains opens promising avenues for brain-inspired computing, intelligent neurointerfaces, and restorative bioelectronics. Firstly, the dynamic regulation of the EDL presents a promising strategy for realizing brain-inspired computing architectures that emulate biological neural signal transmission with enhanced energy efficiency and adaptability (Fig. 2h). In contrast to traditional von Neumann architectures, brain-inspired systems emphasize parallelism, distributed computation, and plasticity. Triboiontronics-based dynamic EDL modulation enables the construction of self-powered ionic-electronic hybrid devices capable of emulating synaptic behaviors, including potentiation, depression, and both short- and long-term plasticity. These functionalities lay the groundwork for energy-efficient neuromorphic processors with integrated memory and logic, advancing decentralized learning networks and adaptive intelligent systems. Secondly, integrating ionic-electronic circuits based on dynamically regulated EDLs into brain-computer interfaces offers a novel route toward more intuitive and biocompatible communication between biological and artificial systems (Fig. 2i). Unlike conventional brain-computer interfaces that depend on rigid electrodes and external power supplies, triboiontronics platforms can harvest energy from motion or biofluids while enabling real-time ion signal transduction. This capability opens up new possibilities for developing soft, wearable, or implantable brain-computer interfaces that employ triboelectric-induced polarization to modulate EDLs for neural information detection, encoding, and transmission, with reduced invasiveness and improved signal fidelity. Such systems may eventually support closed-loop neuroprosthetics and high-resolution cognitive enhancement. Thirdly, the capability to modulate ion charge transport through triboiontronics dynamic EDL regulation introduces a new paradigm in human-machine interaction (Fig. 2j). By directly mimicking the sensory transduction and

actuation mechanisms of biological tissues, EDL-based triboiontronic interfaces enable machines to perceive and respond to stimuli, such as touch, pressure, and temperature, in a manner analogous to human sensory logic. These systems can underpin next-generation intelligent prosthetics, soft robotics, and interactive wearables, providing enhanced sensory feedback, adaptive learning, and context-aware actuation. Their seamless integration into deformable platforms allows for real-time, autonomous operation in complex, dynamic environments. Finally, in the context of neurorestorative medicine, the convergence of triboiontronics and dynamic EDL regulation offers transformative therapeutic potential (Fig. 2k). EDL-mediated ion transport provides a biomimetic mechanism for restoring disrupted neural pathways via artificial synapses or ion signal regeneration. For patients with spinal cord injury, neurodegenerative disorders, or peripheral nerve damage, triboiontronic circuits could deliver localized, activity-dependent stimulation to promote neural plasticity and noninvasive neuromodulation. Critically, the self-powered nature of these platforms enables long-term in vivo operation, opening new avenues for implantable and flexible therapeutic devices that adaptively interface with damaged neural circuits and assist functional recovery.

While these outlooks highlight the unique potential of the neuromimetic circuits enabled by dynamic regulation of the EDL, several important challenges remain to be addressed before practical deployment and large-scale integration can be realized. Firstly, the stability of triboelectric charge under continuous operation is a key concern, as the surface charge on dielectric materials decay or redistribution may affect long-term reproducibility. Approaches such as dielectric surface functionalization, polymer blending, and charge storage layers may improve charge retention. Secondly, environmental sensitivity, especially to humidity, ion concentration, and temperature, can strongly influence EDL behavior and signal consistency. Robust encapsulation strategies and hydrophobic surface coatings may mitigate these effects and extend device durability in complex environments. Thirdly, device-to-device variability due to material inconsistency, fabrication tolerances, or interfacial defects can hinder the reproducibility and scalability of triboiontronic systems. Addressing this will require standardized fabrication protocols, surface engineering, and statistical modeling for parameter tuning. Fourthly, the operational speed of triboiontronic systems is inherently limited by ion mobility and the dynamic nature of the EDL formation, introducing time delays in signal generation and propagation. While this constrains temporal resolution in high-speed neuromorphic tasks, it can be mitigated by optimizing device geometry, ion transport pathways, concentration gradients, and adopting multi-mode triboelectric activation. Importantly, this delay can also be harnessed as a functional advantage. Triboiontronic devices can serve as delay-responsive sensors, where time-lagged ionic responses encode information on stimulus timing or frequency. This temporal coding mechanism complements conventional amplitude sensing, enabling applications in rhythmic signal decoding, sequential tactile sensing, and time-gated logic—key functions in bioinspired, spatiotemporal signal processing. Fifthly, system-level integration and programmability remain open challenges. Future directions include the development of modular triboiontronic circuits with multi-terminal control, hybrid integration with complementary metal oxide semiconductor (CMOS) electronics, and the implementation of learning rules at the hardware level for in-situ adaptive behavior. Sixthly, compared with established neuromorphic platforms such as memristor crossbars, gated synaptic transistors, or electrolyte-gated oxide devices, the triboiontronic system presented here offers distinct advantages in self-powered operation, energy-efficient brain-like computing, mechanically triggered ionic control, and interface adaptability. However, it currently remains limited in terms of temporal resolution, long-term plasticity, and multi-terminal integration, which are necessary for scaling toward more comprehensive neuromorphic functions. Addressing these challenges will not only improve the functional robustness of triboiontronic systems but also accelerate their translation into adaptive brain-machine interfaces, intelligent wearables, and soft robotic control systems.

In summary, this Perspective highlights the emerging potential of dynamically regulated EDLs as a foundational mechanism for constructing energy-efficient, bioinspired triboiontronic systems. By emulating the ion dynamics intrinsic to biological neural processes, triboiontronic dynamic EDL regulation enables precise, reversible control over ion migration. This capability facilitates three representative applications: (i) triboelectric-induced polarization dynamically modulates the EDL to drive self-powered neuromorphic circuits that simulate the rhythmic, feedback-regulated control of locomotion; (ii) asymmetric EDL regulation via concentration gradient engineering enables directional ion transport for wireless underwater communication, mirroring the efficient propagation of action potentials; and (iii) chemically confined ion memory through polyelectrolyte-EDL coupling allows for synaptic-like hysteretic behavior and chemically tunable signal processing in fluidic memristors. These findings not only offer novel insights into ionic-electronic integration at the solid-liquid interface, but also establish a versatile physical framework for interfacing bioelectrical phenomena with artificial intelligence systems. By coupling dynamic EDL modulation with triboelectric-induced polarization, this work introduces a new class of ionic-electronic hybrid systems that are low-power, self-sustaining, and responsive to environmental stimuli. As outlined in the Outlook, future research directions include extending these principles to brain-inspired computing architectures, next-generation brain-computer interfaces, human-machine symbiotic platforms, and neurorestorative technologies. Collectively, this work charts a promising roadmap for the development of intelligent, adaptive, flexible, and energetically autonomous systems, poised to fundamentally reshape the interface between biological intelligence and electronic systems.

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

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Competing interests

The authors declare no competing interests.

Additional information

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