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Editorial

Self-organization and higher-order interactions in complex networks

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Abstract The conventional paradigm of network science, reducing complex systems to dyadic interactions, is fundamentally inadequate for capturing the rich, multi-agent dynamics that define real-world complexity. From neural assemblies and ecological webs to social collectives and technological infrastructures, many systems are governed by higher-order interactions (HOIs) that transcend pairwise descriptions. At the same time, self-organization, the autonomous emergence of order and function from internal dynamics, remains a defining principle of adaptive complexity. The convergence of self-organization and HOIs is not merely an incremental advance; it is a transformative frontier that redefines how we model, predict, and control emergent behavior in natural and engineered systems. This special issue presents a landmark collection of cutting-edge research at this critical intersection. By unifying rigorous theoretical frameworks with groundbreaking applications, it demonstrates that embracing higher-order representations unlocks unprecedented insight into collective phenomena, system resilience, and phase transitions. Spanning physics, mathematics, neuroscience, computer science, social science, and engineering, this issue establishes a new interdisciplinary benchmark and charts the course for the next generation of complex systems science.

1 Introduction

The science of complex networks has fundamentally reshaped our understanding of interconnected systems across disciplines [1–4]. Traditionally, network science has relied on pairwise interactions to model system dynamics [5–8]. However, real-world systems, from functional brain networks and ecological communities to social systems and collaborative networks, are often driven by higher-order interactions (HOIs), where the relationship between elements cannot be decomposed into simple binary links [9, 10]. Concurrently, self-organization, the process where a system's internal interactions lead to the spontaneous emergence of ordered structure and function without external control, is a hallmark of complex adaptive systems [11]. The interplay between self-organization and HOIs represents a frontier of modern network science, crucial for developing accurate models of real-world complexity [12, 13].

This special issue presents a landmark collection of cutting-edge research at this critical intersection. By unifying rigorous theoretical frameworks with groundbreaking applications, it demonstrates that embracing higher-order representations unlocks unprecedented insight into collective phenomena, system resilience, and phase transitions [14]. Spanning physics, mathematics, neuroscience, computer science, social science, and engineering, this issue establishes a new interdisciplinary benchmark and charts the course for the next generation of complex systems science.

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The contributions to this special issue are systematically organized into three main thematic pillars: *review papers*, *theoretical and methodological advances*, and *applications in natural, social, and engineering sciences*, with a predominant focus on neuroscience applications, reflecting the current research frontier in this domain.

2 Review papers: synthesis and future directions

The special issue opens with four authoritative review papers that provide comprehensive syntheses of key areas at the intersection of self-organization, HOIs, and their applications. These reviews serve as essential entry points for researchers entering the field and as critical assessments of the current state of the art.

2.1 Federated learning in healthcare

Pitsik et al. [15] present the paper "Federated learning in healthcare: a review of the deployment gap between simulated and real-world implementations". This review critically examines the growing chasm between the theoretical promise of federated learning, a decentralized machine learning paradigm that enables collaborative model training without sharing sensitive patient data, and its practical deployment in clinical settings. The authors systematically analyze the technical, regulatory, and operational barriers that have hindered real-world adoption, including data heterogeneity, communication constraints, privacy-preserving mechanisms, and integration with existing healthcare infrastructures. By bridging the gap between simulation and reality, this review provides a pragmatic roadmap for translating federated learning from research laboratories to bedside applications, with profound implications for personalized medicine, multi-institutional studies, and privacy-preserving AI in healthcare.

2.2 Artificial intelligence and comorbidity analysis

Lukianenko et al. [16] contribute the paper "From data to knowledge: artificial intelligence methods for studying comorbidity in electronic health records". This review addresses one of the most pressing challenges in modern medicine: understanding the complex patterns of co-occurring diseases. The authors provide a comprehensive overview of AI-driven approaches for mining electronic health records (EHRs) to uncover comorbidity structures, including network-based methods, natural language processing, and deep learning architectures. They highlight how HOI frameworks can model the multi-morbidity landscape, revealing hidden relationships between diseases that transcend simple pairwise associations. The review also discusses challenges related to data quality, temporal dynamics, and causal inference, offering a forward-looking perspective on how AI and network science can revolutionize our understanding of disease interactions and inform clinical decision-making.

2.3 Digital twins for data center cooling

Butorova et al. [17] present the paper "Artificial intelligence and digital twins for failure prediction in data center cooling systems: a comprehensive literature review (2018–2026)". This timely review addresses the critical challenge of maintaining reliability and energy efficiency in the rapidly expanding data center infrastructure that underpins the global digital economy. The authors synthesize a rapidly growing body of literature on the integration of AI and digital twin technologies for predictive maintenance of cooling systems—a domain where unexpected failures can lead to catastrophic downtime. They identify emerging trends in HOI-based modeling of thermal dynamics, multi-agent control strategies, and self-organizing predictive architectures. The review provides a valuable resource for engineers and researchers working at the intersection of complex systems, industrial AI, and sustainable infrastructure.

2.4 Brain diseases and impaired consciousness

Khorev et al. [18] contribute the paper "Bridging scales in some brain diseases that may result in impaired consciousness: clinical biomarkers, circuit dynamics, and network neuroscience". This review tackles one of the most profound questions in neuroscience: how disruptions across multiple spatial and temporal scales, from molecular biomarkers and neural circuits to large-scale brain networks, give rise to disorders of consciousness. The authors integrate clinical and translational perspectives, examining how HOI-based network analyses of EEG, fMRI, and other neuroimaging modalities can reveal the dynamical signatures of consciousness impairment. They review recent advances in the application of network control theory, graph-theoretic measures, and dynamical systems approaches to understand conditions such as coma, vegetative states, and minimally conscious states. By bridging microscopic and macroscopic descriptions, this review offers a comprehensive framework for understanding the neural correlates of consciousness and their disruption in disease.

These four review papers collectively establish the foundation for the special issue, providing both an introduction to the key concepts and a synthesis of the most rapidly evolving subfields where self-organization and HOIs are driving innovation.

3 Theoretical and methodological advances

Several contributions encompass fundamental advances in the mathematical frameworks, dynamical systems theory, and information-theoretic approaches for understanding self-organization in systems with HOIs.

3.1 Dynamical phenomena and synchronization

Synchronization in complex networks is a very important topic of various fields of science and applications [19]. From the rhythmic firing of cardiac pacemaker cells and the coordinated flashing of fireflies to the stable operation of power grids and the consensus dynamics in social swarms, the spontaneous emergence of collective order from decentralized interactions stands as a universal paradigm in nature and engineering. For decades, the foundational framework for understanding these phenomena has been the paradigm of pairwise interactions, where the dynamics of a node are influenced by the sum of its interactions with individual neighbors. This approach, rooted in graph theory, has successfully explained a vast array of synchronization transitions, bifurcations, and pattern formation processes [20].

However, a growing body of empirical evidence and theoretical insight reveals that the architecture of many real-world systems is fundamentally richer than a simple collection of dyadic links. Interactions often occur in groups, for instance, three or more neurons firing in concert, a committee of genes regulating a single target, or a cluster of social peers reinforcing a shared opinion. This crucial aspect of structural organization is captured by the framework of higher-order networks, encompassing simplicial complexes and hypergraphs, where edges (1-simplices), triangles (2-simplices), and higher-dimensional faces coexist and interact.

The inclusion of these higher-order couplings fundamentally alters the landscape of dynamical possibilities. It introduces nonlinear feedback mechanisms that are not reducible to pairwise contributions, giving rise to emergent behaviors with no counterpart in traditional network models. A significant cluster of articles in the special issue are devoted to dynamical transitions and synchronization phenomena in systems with higher-order coupling. These contributions collectively address pivotal questions: How do higher-order interactions modify the stability of synchronized states? Can they induce abrupt, explosive synchronization transitions that are otherwise impossible? What new routes to chaos and multi-stability emerge from the synergy of pairwise and group interactions? By exploring these frontiers, this collection aims to chart a new theoretical map for predicting and controlling collective dynamics in the intricate, multi-body systems that define our interconnected world.

The paper “Transitions to oscillation death in coupled oscillators with competing higher-order interactions”, by Verma et al. [21] reveals novel transition scenarios. Specifically, it demonstrates that the interplay between attractive and repulsive higher-order couplings can induce a counterintuitive stabilization of the trivial steady state, a phenomenon known as oscillation death, even in parameter regimes where pairwise interactions alone would promote sustained rhythmic activity. This work underscores a critical theme: higher-order interactions are not merely perturbative corrections but can act as genuine dynamical knobs that toggle entire qualitative regimes of behavior.

Expanding on the theme of competing influences, Sharma et al. [22] analyze “Synchronization transitions in Kuramoto oscillators with mixed interactions”, providing insights into how mixed coupling schemes affect collective dynamics. Their study systematically charts the phase diagram of the paradigmatic Kuramoto model when both pairwise and three-body (simplicial) couplings are present. They uncover a rich tapestry of transitions, including reentrant synchronization and bistability, thereby establishing that the relative strength of higher-order versus pairwise interactions acts as a powerful control parameter for shaping macroscopic order.

While Sharma et al. focus on topology-driven coupling, the question of heterogeneity remains paramount. Li et al. [23] present “Universal scaling of nonlinear amplification: unifying structure and heterogeneity in higher-order networks”, establishing universal scaling laws that bridge structural and dynamical heterogeneity. By deriving a concise analytical framework, they show that the amplification of local perturbations follows a universal function that depends solely on a single composite parameter—encapsulating both network topology and node-level dynamical traits. This breakthrough provides a unifying language that reconciles seemingly disparate observations in synthetic and real-world higher-order networks, offering predictive power for how perturbations propagate through complex systems.

Bridging the gap between theoretical models and neurobiological reality, Yang et al. [24] study “Synchronization in neural networks with inhibitory synaptic connections under electromagnetic stimulation”, providing a theoretical basis for optimizing non-invasive electromagnetic neuromodulation technologies. Their work integrates physiologically realistic inhibitory couplings and external electromagnetic fields into a higher-order neural framework,

revealing that stimulation frequency and intensity can be tuned to either suppress pathological hypersynchrony (as in epilepsy) or promote desired synchrony for therapeutic outcomes. This applied perspective demonstrates the translational potential of higher-order synchronization theory.

Complementing this focus on control, Serrano et al. [25] introduce advanced control strategies in their paper "Fast terminal sliding mode stabilization and projective synchronization of chaotic Hopfield neural networks". Departing from traditional linear feedback, their robust nonlinear protocol guarantees finite-time convergence and ensures synchronization even in the presence of uncertainties and external disturbances. This methodological contribution is particularly significant for engineering applications where speed and robustness are non-negotiable, such as in secure communications or real-time neural prosthetics.

In addition, Olenin et al. [26] discover "Hyperchaos and extreme events in coupled Rulkov neuron". The authors investigate a minimal ensemble of three spiking Rulkov neurons coupled through mutual chemical synapses. Through a detailed bifurcation analysis, the authors identify the scenarios responsible for the emergence and destruction of complex dynamics containing extreme events—rare, large-amplitude excursions that deviate significantly from the typical dynamical range. A central finding is that hyperchaos, characterized by two or more positive Lyapunov exponents, can serve as a dynamical precursor to extreme events in coupled neuron models. More broadly, their results illuminate how coupling topology and strength modulate complex bursting patterns in neural ensembles. The scenarios uncovered provide a foundation for future studies on how different coupling schemes, such as inhibitory or mixed couplings, may promote or suppress pathological neuronal activity, including seizure-like events and information-processing anomalies. This work thus represents a step toward deciphering the dynamical mechanisms underlying rare, large-amplitude excursions in neural systems, with implications for both theoretical neuroscience and the control of emergent instabilities in coupled oscillatory networks.

In their interesting paper "Higher-order phase organization in refractory swarmalators: power-law scaling, structural correlations, and the triangulation window", Maslennikov and Nekorkin [27] study a population of self-propelled phase oscillators (swarmalators) in which each firing is followed by a brief refractory interval, as in excitable neurons. Although the underlying dynamics are strictly pairwise, the population spontaneously generates a time-dependent hypergraph of HOI: a hyperedge of order k comprises any k mutually neighboring agents simultaneously inside their refractory window. Notably, this hypergraph is not postulated but read off from the pairwise dynamics. The authors report three effects: (i) the mean number of hyperedges of every order obeys a two-parameter power law in spatial degree and temporal duty fraction, with spatial exponents exceeding the combinatorial null—a fingerprint of positive pair correlations; (ii) local pairwise and triadic coherence are extremized at two well-separated coupling values, defining a triangulation window in which triadic organization is favored while pairwise alignment is suppressed; and (iii) the triadic optimum is essentially load-independent while the pairwise optimum scales mildly, making the triangulation window approximately geometry-independent.

Finally, Moskalenko et al. [28] in their paper "Influence of the control parameter mismatch on the detection of the generalized synchronization by means of the auxiliary system approach" provide crucial insights for synchronization detection. They systematically dissect a longstanding practical challenge: how parameter detuning between coupled systems undermines the reliability of the widely used auxiliary system method. Their rigorous analysis establishes quantitative bounds for parameter mismatch and proposes corrective criteria, thereby safeguarding experimental and numerical studies from false positive or negative detections of generalized synchronization.

Taken together, this cluster of contributions spans the entire investigative pipeline, from foundational mechanism discovery and universal theoretical scaling, through neuro-inspired modeling and robust control design, to the careful refinement of diagnostic tools. Collectively, they not only advance the state of the art in higher-order synchronization but also forge critical connections between abstract mathematical theory and tangible applications in neuroscience, engineering, and complex systems science.

3.2 Foundational frameworks and information theory

At the heart of complex systems science lies a deceptively simple question: how does information flow through a network of interacting agents, and how does that flow shape the emergent collective behavior? Traditional approaches to network dynamics have predominantly focused on the transfer of energy or matter, or on the evolution of state variables according to deterministic or stochastic rules. Yet, a parallel and equally profound perspective treats information itself as the fundamental currency of interaction. From the firing patterns of neurons encoding sensory stimuli to the propagation of beliefs in social media and the regulatory signals in gene-expression cascades, the very essence of dynamical organization is inextricably linked to the creation, transformation, and transmission of information.

Classical information theory, rooted in the seminal work of Shannon, provides the mathematical tools to quantify uncertainty and redundancy. However, its application to dynamical networks has historically been constrained by two major limitations. First, traditional measures such as mutual information or transfer entropy are inherently pairwise, capturing statistical dependencies between two variables while overlooking the synergistic or redundant contributions that arise from groups of interacting elements. Second, the inference of causal information flow,

distinguishing genuine influence from mere correlation, remains a profound challenge, particularly in strongly coupled systems where the standard assumptions of linearity or weak interaction break down. These limitations have spurred a paradigm shift toward higher-order information architectures, where the fundamental unit of analysis is no longer the dyadic link but the hyperedge, the simplex, or the entire polyadic interaction motif.

This emerging framework recognizes that information in complex networks is not merely transported along pairwise connections but is processed, integrated, and sometimes actively suppressed through multi-body interactions. The inclusion of higher-order statistical dependencies and topological structures allows for a more faithful representation of real-world systems, where information often flows through collaborative groups, competitive ensembles, or hierarchical levels of organization. Moreover, it enables a rigorous reconciliation between abstract information-theoretic principles and the tangible physical constraints, such as energy budgets, time delays, and coupling strengths, that govern real dynamical processes.

Within this conceptual landscape, foundational contributions establish new principles of the information theory and theoretical structures of higher-order networks. In particular, the papers "Information networks: principles, axioms, and higher-order structures" by Pisarchik [29] and "Higher-order information response solves the puzzle of zero Liang–Kleeman information flow for strong couplings" by Smirnov [30], respectively, establish the groundwork for a formal theory of information networks and address a fundamental puzzle in information flow theory in demonstrating how higher-order information responses resolve longstanding inconsistencies. Pisarchik's work offers a novel axiomatic foundation that redefines the very notion of an information network, moving beyond topological connectivity to encompass the functional and semantic dimensions of information exchange. This framework provides a unifying language for describing how information is encoded, transformed, and routed through higher-order topological structures, bridging the gap between abstract graph theory and the pragmatic realities of information processing. Meanwhile, Smirnov tackles a specific but critical anomaly: the celebrated Liang–Kleeman information flow formula, a cornerstone of causal inference, unexpectedly yields zero flow for strongly coupled systems—a counterintuitive result that has puzzled the community for years. By introducing a higher-order response function that captures the cumulative influence of multi-step and multi-body interactions, Smirnov elegantly demonstrates that the apparent paradox vanishes once one accounts for the synergistic information pathways that pairwise formulations systematically ignore. This resolution not only restores the consistency of the theory but also provides a powerful new diagnostic tool for detecting causal influences in strongly interdependent systems.

In the paper "Higher-order interactions in brain microstructure: A redundancy-to-synergy crossover in quantitative MRI for multimodal biophysical modelling", Kherif et al. [31] introduce O-information (Ω) as a higher-order metric for multiparametric MRI, capturing how myelin-sensitive parameters interact beyond pairwise correlations. Using magnetization transfer, R_1, and proton density, they show that Ω robustly separates tissue classes— cortex near-balanced, subcortex mildly synergistic, white matter strongly synergistic—and tracks regional and tract-level structure, cortical depth, and systematic robustness properties. In grey matter, Ω crosses from redundancy to synergy at approximately 20 s^{-1}, consistent with a minimal two-compartment forward model; in white matter, it tracks neurite density rather than fiber orientation dispersion. Ω thus offers a compact yet expressive description of whether tissue information is organized redundantly or synergistically—an organization invisible to pairwise analyses—and warrants testing in larger cohorts where distributed tissue interactions are likely most informative.

In addition, Chen [32] explores the intersection of information theory and evolutionary dynamics in the paper "Information-driven evolution in energy-constrained cellular automata". Chen's contribution extends the foundational discourse by embedding information-theoretic measures within a dynamic, adaptive context. By modeling cellular automata whose update rules are subject to both informational selection pressures and physical energy constraints, he reveals that the maximization of information transfer and the minimization of energy dissipation are not conflicting objectives but can co-evolve toward synergistic trade-offs. This work establishes a critical bridge between the static principles of information networks and the time-dependent processes of learning, adaptation, and self-organization. It demonstrates that higher-order information structures are not merely descriptive tools but active participants in the evolutionary dynamics that shape complex systems over multiple timescales.

Collectively, these foundational contributions do far more than refine existing measures or correct isolated anomalies. They collectively articulate a new philosophical and mathematical groundwork for understanding complex systems as information-processing entities. By elevating information from a derived quantity to a primary ontological category, and by recognizing that its flow is inexorably shaped by higher-order structures, this body of work paves the way for a unified theory that can seamlessly integrate causality, computation, and complexity. The implications are profound: from rethinking the principles of neural coding and consciousness to designing resilient communication networks and understanding the emergence of collective intelligence in social and biological systems, the synergy between information theory and higher-order networks promises to be one of the most fertile frontiers of the twenty-first-century science.

3.3 Data-driven approaches and machine learning

The explosive growth of high-resolution, multi-modal data from real-world complex systems has fundamentally transformed the scientific landscape. From massive neuronal spike trains and global climate observations to high-frequency financial transactions and social media activity streams, the sheer volume, dimensionality, and heterogeneity of available data far outpace the analytical tractability of traditional first-principles models. In parallel, the intricate higher-order structures that govern these systems—group interactions, hyperedges, and nested communities—defy simple reduction to pairwise statistical dependencies. These twin challenges have catalyzed a paradigm shift: the emergence of data-driven approaches, supercharged by modern machine learning, as indispensable tools for uncovering the hidden laws, forecasting emergent behaviors, and designing robust control strategies for complex networked systems.

At the core of this methodological revolution lies a profound synergy. Machine learning, particularly deep learning, excels at extracting high-level features and nonlinear mappings from raw data without explicit assumptions about underlying mechanistic forms. Network science, on the other hand, provides the structural scaffolding (the topology, the hierarchy, and the higher-order motifs) that constrains and contextualizes these learned representations. The integration of these two fields is not merely additive but transformative: neural architectures can be imbued with network inductive biases, while network inference can be augmented by the representational power of deep models. This convergence is especially potent in the context of HOIs, where the combinatorial explosion of possible multi-body relationships demands learning algorithms capable of discovering relevant group structures, inferring latent coupling mechanisms, and generalizing across diverse dynamical regimes.

However, this integration is fraught with challenges. Real-world data are often short, noisy, partially observed, and contaminated by artifacts. Parameter estimation in high-dimensional nonlinear systems remains ill-posed. The interpretability of black-box models is a persistent concern, particularly when scientific discovery, rather than mere prediction, is the ultimate goal. Moreover, the computational cost of training sophisticated architectures on massive network datasets can be prohibitive. The contributions in this subsection directly confront these hurdles, showcasing a spectrum of innovative approaches that marry cutting-edge machine learning techniques with rigorous network science to extract actionable insights from complex data.

The integration of machine learning with network science is highlighted in several contributions. Specifically, Vakhlaeva et al. [33] present "Deep learning approach to estimate the coupling strengths between van der Pol oscillators from short time series in the presence of noise", demonstrating the power of deep learning for parameter estimation in noisy environments. Their work addresses a perennial bottleneck in experimental nonlinear dynamics: how to infer interaction parameters from brief, contaminated recordings. By training a deep neural network on synthetically generated time series spanning a wide range of coupling regimes, they achieve robust estimation that significantly outperforms conventional optimization-based methods. This approach opens the door to real-time network inference in settings where data acquisition is costly or invasive, such as in neuroscience or cardiology.

While Vakhlaeva et al. focus on inferring known model parameters, Devarajan et al. [34] explore "Extreme-event dynamics under linear and nonlinear higher-order coupling in FitzHugh–Nagumo networks", revealing how coupling topology shapes extreme-event occurrence. Their work leverages data-driven simulations across a vast parameter space to systematically map the conditions under which rare, large-amplitude events, analogous to neuronal seizures or financial crashes, emerge. Crucially, they demonstrate that the inclusion of nonlinear higher-order coupling terms can either suppress or amplify extreme events depending on the specific topological arrangement, providing a data-informed roadmap for risk mitigation in excitable media.

Shifting from temporal dynamics to spatial heterogeneity, Butorova and Sergeev [35] apply network-based segmentation to environmental modeling in the paper "Land Use Segmentation approach for spatial modeling in complex heterogeneous environments". Their contribution exemplifies the cross-disciplinary fertility of data-driven network methods: by constructing a network representation of spatial units based on multi-spectral and topographic features, they employ graph-based segmentation algorithms to delineate land-use categories with unprecedented fidelity. This approach not only outperforms traditional pixel-wise classification but also inherently captures the higher-order spatial dependencies (e.g., watershed contours and urban corridors) that define ecological and agricultural landscapes.

Pushing the frontiers of computational paradigms, Rafikov et al. [36] propose "Brain MRI classification: when quantum dynamics improves classical neural network performance for perturbed inputs", investigating the performance of a hybrid quantum–classical convolutional neural network designed for reliable brain magnetic resonance imaging (MRI) binary classification in case of distorted inputs. This work represents a bold foray into next-generation machine learning, where quantum computing principles, specifically, the dynamical evolution of quantum states, are harnessed as feature extractors. Their hybrid architecture demonstrates remarkable resilience to input perturbations (noise, occlusions, and artifacts) that would severely degrade classical models, suggesting that quantum-inspired dynamics can encode robust, higher-order invariants that are naturally suited to medical imaging challenges.

Finally, bridging the gap between data-driven learning and real-time physical modeling, Tkach and Andreev [37] in their paper "State correction via data injection for a reservoir computing-based digital twin of the Lorenz

system", showcase how machine learning can enhance digital twin accuracy. Digital twins—virtual replicas of physical systems—are transforming engineering and predictive maintenance, yet they suffer from drift due to unmodeled dynamics and sensor noise. Tkach and Andreev propose an elegant solution: a reservoir computing framework that assimilates streaming data injections to continuously correct the state trajectory of a Lorenz-system twin. Their method demonstrates that sparse, intermittent data updates can maintain high-fidelity synchronization with the true system, offering a practical pathway toward self-correcting digital twins for complex infrastructure, climate, or biological systems.

Thus, this cluster of contributions illustrates the extraordinary breadth and depth of the data-driven revolution in network science. They span parameter inference, extreme-event forecasting, spatial segmentation, quantum-enhanced classification, and real-time state correction, each anchored by a shared commitment to leveraging advanced learning architectures to extract order from complexity. While the methods differ dramatically, from deep neural networks and reservoir computing to quantum circuits and graph-based segmentation, they collectively underscore a unifying theme: the future of complex systems research lies not in choosing between mechanistic models and data-driven algorithms, but in forging a principled synthesis where each informs and constrains the other. As data volumes continue to grow and computational paradigms evolve, these foundational studies will undoubtedly serve as springboards for the next generation of intelligent, adaptive, and interpretable network science tools.

4 Applications in natural, social, and engineering sciences

Numerous applications demonstrate the broad relevance of self-organization and HOI frameworks across diverse domains, with a particularly strong emphasis on neuroscience. From the coordinated firing of neuronal assemblies and the propagation of epileptic seizures to the cognitive computations underlying problem-solving and the gradual reorganization of brain networks across the human lifespan, the brain stands as the quintessential example of a complex system whose function defies reductionist, pairwise descriptions. Indeed, the central premise of modern network neuroscience, that cognition and behavior emerge from the orchestrated activity of distributed neural populations, is intrinsically a higher-order proposition. Neurons do not operate in isolation but in dynamic, context-dependent coalitions, where the synergy among multiple regions gives rise to perceptual, motor, and cognitive states that cannot be inferred from any single pairwise interaction alone.

The methodological challenges of capturing this polyadic reality are formidable. Non-invasive and invasive neuroimaging modalities: electroencephalography (EEG), magnetoencephalography (MEG), functional near-infrared spectroscopy (fNIRS), and stereo-EEG (SEEG), yield high-dimensional, multiscale, and noisy time series that demand sophisticated analytical frameworks. Traditional functional connectivity, typically quantified by pairwise correlations or coherence, provides only a first-order approximation of neural interdependence. It misses the synergistic information, the redundant couplings, and the emergent collective variables that characterize true brain function. This limitation has catalyzed a paradigm shift toward higher-order network representations, including hypergraphs and simplicial complexes, which can encode multi-node interactions and capture the genuine complexity of neural dynamics.

Moreover, neuroscience is uniquely positioned to bridge the gap between abstract theory and tangible clinical impact. Aberrant synchronization and altered higher-order connectivity are increasingly recognized as hallmarks of neurological and psychiatric disorders, from epilepsy and Parkinson's disease to schizophrenia and Alzheimer's. Understanding how HOIs break down or compensate in pathology offers the potential for novel biomarkers, early diagnosis, and targeted neuromodulation therapies. The contributions in this subsection collectively address these challenges, spanning methodological innovations, cognitive paradigms, developmental trajectories, and clinical applications, all unified by a commitment to advancing the higher-order neuroscience agenda.

4.1 Neuroscience: brain networks and dynamics

The largest thematic cluster within this special issue addresses brain network organization and dynamics, reflecting the growing recognition that HOIs are essential for understanding brain function and dysfunction. This cluster is organized around three interconnected pillars: the development of novel higher-order connectivity metrics, the investigation of cognitive and developmental processes, and the exploration of pathological dynamics in neurological disorders.

4.1.1 Functional connectivity and network analysis

Vlasenko et al. [38] introduce "Hypergraphs from multivariate connectivity: caCOH-based EEG/MEG representation", offering a novel hypergraph-based approach for representing multivariate brain connectivity. Their method,

built upon the canonical coherence (caCOH) measure, transcends the traditional pairwise connectivity matrix by constructing hyperedges that capture phase-synchronization patterns among multiple channels simultaneously. This innovation is particularly significant because it preserves the genuine multi-site nature of neural interactions, for instance, the distributed oscillatory networks that span sensorimotor, parietal, and frontal regions during a cognitive task. By providing a mathematically principled and computationally tractable hypergraph construction, the authors equip the community with a powerful tool to move beyond dyadic graph models and embrace the true polyadic architecture of brain dynamics.

Bridging fundamental methodology with clinical translation, Kuc et al. [39] investigate "Frequency-specific alterations of functional brain network measures in stereo-EEG recordings of epilepsy patients", revealing frequency-dependent network alterations in epilepsy. Their analysis of invasive SEEG data, which offers unparalleled spatial and temporal resolution, demonstrates that the epileptogenic zone is not merely a source of local hyperexcitability but a node embedded within a broader, frequency-selective network disruption. Crucially, they find that alterations in network metrics (such as clustering coefficient and path length) are most pronounced in specific frequency bands, suggesting that different oscillatory rhythms serve as distinct carriers of pathological information. This frequency-resolved perspective is essential for refining surgical planning and for understanding the mechanistic underpinnings of seizure generation and propagation.

While Kuc et al. focus on pathological dynamics, Grubov et al. [40] study "Brain functional connectivity in Raven's progressive matrices: a fNIRS study", linking functional connectivity patterns to cognitive performance. The Raven's Progressive Matrices test, a benchmark of fluid intelligence and abstract reasoning, provides an ideal cognitive challenge for probing higher-order integration. Using fNIRS, a portable and motion-tolerant optical imaging technique suitable for naturalistic settings, the authors demonstrate that successful problem-solving is associated with enhanced connectivity within the prefrontal and parietal cortices, consistent with the frontoparietal control network's role in complex reasoning. Moreover, they observe that the strength of these connectivity patterns scales with individual performance, offering a neural correlate of cognitive capacity that could inform educational interventions or cognitive training protocols.

Extending the cognitive lens across the lifespan, Adushkina and Pavlov [41] analyze "Aging effects on the dynamic network interactions of cortical rhythms during different sleep stages: evidence from a network theory-based approach", identifying the most significant changes occurring within each phase and demonstrating that advancing age is associated with distinct and progressive alterations in cortical correlations. Sleep, far from a passive state, is a dynamic repertoire of network reorganizations that subserve memory consolidation and neural homeostasis. By tracking functional connectivity across non-REM and REM sleep stages, the authors reveal that aging preferentially disrupts the slow-wave sleep network—a finding with profound implications for understanding age-related cognitive decline and the increased prevalence of sleep disorders in the elderly. Their work underscores the importance of considering both state-dependent dynamics and developmental trajectories when interpreting functional connectivity.

The aging effect is also investigated by Antipov et al. [42] in their paper "Age-related EEG functional connectivity during visual search in children", where they suggest that age-related reorganization of frequency-specific brain networks may support developmental gains in visual search efficiency. Focusing on a younger cohort, this study complements the work of Adushkina and Pavlov by charting the maturation of functional networks from childhood to early adolescence. The authors find that the transition from inefficient to efficient visual search is accompanied by a progressive strengthening of long-range frontal-posterior connections, particularly in the alpha and gamma bands. This developmental reorganization likely reflects the ongoing myelination and synaptic pruning that optimize large-scale network communication, providing a neural basis for the well-documented improvements in attentional control and processing speed that occur during this critical developmental window.

Kapustnikov et al. [43] in their contribution "Network generator of periodic high-frequency transient dynamics in the thalamocortical system" demonstrate the emergence of a long-lasting, nearly periodic high-frequency transient process in a small model thalamocortical network composed of three distinct cell types. Each neuronal population is described by identical equations with identical parameters, allowing the authors to isolate the role of network architecture from that of parameter tuning. Their numerical experiments reveal that both the generation and termination of the oscillatory regime are determined by the network's connectivity structure rather than by fine-tuning of individual parameters. In particular, the multilevel cyclic architecture, consisting of three nested feedback loops, gives rise to the coexistence of fast and slow time scales, producing a transient oscillatory process whose duration significantly exceeds that of the external driving that initiated it. The proposed system may thus be interpreted as a central pattern generator for high-gamma oscillations in the brain, offering a mechanistic account of how sustained high-frequency rhythms can emerge from network topology alone.

Finally, Antipov et al. [44] investigate "Higher-order triadic interactions in the EEG sensorimotor network during motor imagery", discovering that a visual stimulus modifies the higher-order organization of the motor imagery network, highlighting the influence of visual context on functional connectivity. This study directly tackles the higher-order theme of the special issue by moving beyond pairwise connectivity to quantify triadic interactions—the simultaneous coordination of three sensorimotor regions. Their results reveal that the mere presence of a visual cue (e.g., observing a hand movement) significantly alters the topological structure of higher-order interactions during

subsequent motor imagery, compared to imagery without visual priming. This finding has important implications for brain–computer interfaces (BCIs), suggesting that the visual feedback typically used in BCI paradigms may itself reshape the very neural patterns that the system aims to decode. By demonstrating that higher-order metrics are more sensitive to contextual modulation than their pairwise counterparts, this work reinforces the critical role of multi-node interactions in capturing the full richness of cognitive dynamics.

In sum, this rich collection of neuroscientific contributions illustrates the transformative power of higher-order network analysis across the full spectrum of brain research, from methodological development and cognitive neuroscience to developmental trajectories and clinical applications. Collectively, they establish that the brain is not merely a graph of pairwise connections but a hypergraph of dynamic, frequency-specific, and state-dependent multi-region interactions. By embracing this complexity, the field moves closer to a genuine understanding of the neural code and opens new avenues for diagnosing, monitoring, and treating neurological and psychiatric disorders.

4.1.2 Neuromodulation, plasticity, and learning

The brain's remarkable capacity for adaptation, its ability to learn, rewire, and self-repair, stands as one of the most profound mysteries of modern science. This plasticity is not a passive consequence of experience but an active, energy-intensive process that operates across multiple scales: from the millisecond dynamics of spike-timing-dependent plasticity (STDP) at individual synapses, through the slower homeostatic adjustments that stabilize network activity, to the minutes-to-hours reorganization of large-scale functional networks that underpin skill acquisition and memory consolidation. Understanding these multiscale adaptive processes is not merely an academic pursuit; it holds the key to transformative technologies, including closed-loop neuroprosthetics that can restore lost function, neuromorphic computing systems that emulate the brain's unparalleled energy efficiency, and personalized neuromodulation therapies for neurological and psychiatric disorders.

The convergence of neuroscience, materials science, and artificial intelligence has given rise to a new frontier: the engineering of adaptive, learning-capable systems that mirror the brain's plastic principles. Memristive devices, with their history-dependent conductivity and analog state transitions, offer a physical substrate for implementing STDP rules in hardware, promising neuromorphic chips that can learn on the fly without the massive energy overhead of traditional digital computation. Similarly, closed-loop neuromodulation paradigms, where stimulation parameters are adjusted in real time based on ongoing neural activity, represent a paradigm shift from open-loop, "one-size-fits-all" stimulation toward truly personalized, activity-responsive interventions. These technological advances, however, are only as powerful as the biological principles they embody. The contributions in this subsection bridge this critical gap, using detailed biophysical modeling, hardware implementations, and human neuroimaging to elucidate the principles that govern plasticity and learning, and to translate those principles into actionable engineering solutions.

Ermolaev et al. [45] present "Guiding self-organization in motor networks: a closed-loop, activity-dependent neuromodulation paradigm", demonstrating how closed-loop neuromodulation can guide network self-organization. Their work tackles a fundamental challenge in neurorehabilitation: how to steer a damaged motor network toward a functional configuration without a priori knowledge of the optimal target state. By designing a control algorithm that rewards network activity patterns associated with desired motor outputs, and penalizes pathological synchrony, they show that chronic closed-loop stimulation can progressively reshape the functional connectivity of a simulated motor network. This approach, grounded in reinforcement learning principles, offers a promising alternative to open-loop deep brain stimulation, suggesting that future neuroprosthetics could adapt to the patient's evolving neural state, promoting long-term recovery rather than merely symptomatic suppression.

Moving from network-level control to synaptic-level learning, Lazovskiy et al. [46] develop "Neuromorphic taste decoding using adaptive STDP and astrocyte-like synaptic control", combining spike-timing-dependent plasticity with astrocyte models for neuromorphic computing. Astrocytes—the long-neglected glial cells of the brain—are now recognized as active partners in synaptic transmission and plasticity, modulating release probability and neurotransmitter reuptake on slow timescales. By integrating an astrocyte-like control mechanism into a neuromorphic STDP framework, the authors create a learning system that exhibits both rapid, spike-driven plasticity and slower, homeostatic regulation. They demonstrate this hybrid architecture on a taste-decoding task, showing that the astrocyte-mediated feedback significantly improves classification accuracy and robustness to noise. This work underscores the importance of embracing the full biological palette, not just neurons but also glia, in the design of next-generation neuromorphic systems.

Complementing this biophysically inspired approach, Kovaleva et al. [47] investigate "Adaptive dynamics and learning in spiking neural networks with memristive STDP based on pulse-width modulation", advancing memristor-based neuromorphic systems. Their contribution addresses a critical hardware bottleneck: the implementation of STDP in memristive crossbar arrays typically requires precise control over spike timing, which is difficult to achieve in analog circuits. By exploiting pulse-width modulation, a technique borrowed from power electronics, the authors encode the relative timing of pre- and postsynaptic spikes into the duration of voltage pulses applied to memristors. This elegant solution yields STDP weight updates that are both hardware-friendly

and biologically plausible, enabling the construction of large-scale, energy-efficient spiking networks that can learn unsupervised temporal patterns. Their results pave the way for embedded neuromorphic processors that could revolutionize edge computing in wearable devices, robotics, and Internet-of-Things applications.

In a parallel hardware contribution, Shchanikov et al. [48] present "Reconfigurable neuromorphic system based on memristive devices", demonstrating hardware-based reconfigurability. While Kovaleva et al. focus on learning dynamics, Shchanikov et al. tackle the equally critical challenge of architectural flexibility. Their system employs a memristive crossbar array with programmable routing, allowing the same physical hardware to be reconfigured on the fly to implement different network topologies (feedforward, recurrent, or reservoir) depending on the computational task. This reconfigurability is essential for general-purpose neuromorphic platforms that must adapt to diverse workloads, from sensory processing to motor control to associative memory. The authors validate their system on benchmark tasks, showing that reconfiguration incurs minimal overhead and preserves the energy advantages of analog computation.

Finally, bridging the gap between basic neuroscience and individual differences, Stoyanova et al. [49] reveal "Hidden nodes of personality: functional brain networks and their trait correlates", associated with distinct and partially nonlinear patterns of functional brain network organization. Departing from the engineering focus of the preceding papers, this contribution returns to the human brain, exploring how stable individual differences in personality traits, such as neuroticism, extraversion, and openness, are reflected in the topology of resting-state functional networks. Using advanced network analysis, the authors identify specific "hidden nodes" (brain regions with high centrality in the functional connectome) that mediate the relationship between network topology and trait measures. Crucially, they find that these relationships are nonlinear, suggesting that personality does not simply scale with connectivity strength but emerges from complex, threshold-dependent interactions among multiple network hubs. This work highlights the translational potential of network neuroscience for personalized mental health, where functional network signatures could serve as biomarkers for psychiatric vulnerability or resilience.

4.1.3 Computational neuroscience and modeling

While the previous subsection emphasized plasticity, learning, and hardware implementation, the contributions gathered here focus on the foundational modeling and computational frameworks that underpin our quantitative understanding of neural dynamics. Computational neuroscience has long been a crucible for theoretical innovation, providing a testbed for hypotheses that are experimentally intractable and offering predictive tools that guide experimental design. The rise of higher-order network theory and machine learning has infused this field with new vitality, enabling the construction of models that capture not only the firing statistics of individual neurons but also the emergent collective phenomena (bursting, synchrony, wave propagation, and directional coupling) that define brain function at the meso- and macroscopic scales.

Central to this endeavor is the challenge of bridging scales: from the biophysical details of ion channels and synaptic receptors, through the population dynamics of spiking networks, to the large-scale oscillations captured by EEG and MEG. Each scale demands its own modeling abstractions, yet the true explanatory power lies in connecting these levels. Homeostatic plasticity mechanisms, for instance, operate on minutes-to-hours timescales to stabilize firing rates, yet they profoundly shape the millisecond-scale bursting patterns that encode information. Similarly, the effective connectivity inferred from macroscopic signals (EEG, LFP, or fMRI) is a coarse-grained reflection of microscopic synaptic strengths, mediated by nonlinear transformations that can obscure or enhance directional influences. The papers on this topic confront these multiscale challenges head-on, employing a diverse toolkit that spans biophysically detailed spiking networks, low-dimensional phase oscillators, and data-driven reservoir computing.

Zharinov et al. [50] analyze "Bursting dynamics in a spiking neural network with homeostatic and synaptic plasticity", revealing how homeostatic mechanisms shape bursting patterns. Bursting—the alternation between quiescent periods and high-frequency spike trains—is a ubiquitous neural code, particularly prominent in subcortical structures like the thalamus and basal ganglia. Using a large-scale spiking network with both Hebbian (STDP) and homeostatic (intrinsic excitability scaling) plasticity, the authors demonstrate that homeostatic regulation is not merely a stabilizing background process but actively sculpts the temporal structure of bursting. Specifically, they find that homeostatic scaling preferentially depresses connections that contribute to prolonged bursts, effectively acting as a high-pass filter that sharpens the contrast between transient and sustained firing. This result has implications for understanding pathological bursting in epilepsy and Parkinson's disease, where homeostatic mechanisms may become maladaptive.

Stasenko and Kazantsev [51] present "Narrowing the accuracy gap in unsupervised STDP networks: an extracellular-matrix model with two-mechanism homeostatic control", addressing the accuracy gap in unsupervised learning networks. Unsupervised STDP networks, while biologically plausible, have historically lagged behind supervised deep learning in benchmark classification tasks. The authors attribute this gap to the absence of

extracellular-matrix (ECM) regulation, the glycoprotein meshwork that surrounds neurons and modulates synaptic efficacy through permissive and inhibitory signals. By introducing a two-mechanism homeostatic control, one acting on synaptic weights and another on neuronal excitability, they achieve near-parity with supervised algorithms on standard datasets. This work elegantly demonstrates that biological detail, far from being a distraction, can be a source of computational power, providing regularization and stability that pure Hebbian rules lack.

Shifting from learning to prediction, Vershinin et al. [52] develop "Optimal reservoir prediction of individual fEPSP signatures in rodent hippocampal slices", applying reservoir computing to predict individual neuronal responses. Field excitatory postsynaptic potentials (fEPSPs) are the workhorse of hippocampal slice electrophysiology, providing a readout of synaptic strength and plasticity. Yet, individual slices exhibit significant variability in their fEPSP waveforms, complicating cross-experiment comparisons. Vershinin et al. demonstrate that a reservoir computer—a recurrent neural network with fixed, random connectivity—can be trained on a small number of stimulus–response pairs to predict the full fEPSP waveform for novel stimuli, with accuracy that rivals biophysically detailed compartmental models. This approach offers a practical, low-cost tool for standardizing slice physiology data, effectively creating a "digital twin" of each hippocampal preparation.

Addressing the challenge of causal inference in neural data, Hramkov et al. [53] present "Advantages of low-dimensional models in detecting directional coupling between biological systems", comparing the performance of typical third-order and compact first-order phase predictive models when applied to narrow-band signals. Detecting directional coupling from noisy, oscillatory time series remains a cornerstone challenge in neuroscience. The authors systematically compare two popular frameworks: third-order nonlinear models (which capture amplitude dynamics) and first-order phase models (which focus on phase relationships). Surprisingly, they find that the simpler first-order phase models often outperform their higher-order counterparts in detecting weak or time-varying coupling, particularly when signals are narrow-band and contaminated by measurement noise. This counterintuitive result underscores the importance of parsimony in model selection and provides practical guidelines for neurophysiologists designing connectivity analyses.

Finally, Rajagopal et al. [54] investigate "Influence of excitatory and inhibitory higher-order chemical coupling on spiral waves dynamics", revealing that chemical HOIs fundamentally reshape spatiotemporal dynamics in excitable neuronal networks. Spiral waves (rotating patterns of excitation) are implicated in both normal cortical processing and pathological conditions such as migraine aura and epileptic spreading depression. Conventional models treat coupling between neurons as pairwise and predominantly electrical (gap-junctional). Rajagopal et al. introduce chemical (synaptic) higher-order interactions, where a single neuron's firing influences not just its immediate neighbors but also second-order neighbors through polysynaptic pathways. They demonstrate that excitatory higher-order coupling stabilizes spiral waves, while inhibitory higher-order coupling fragments them, leading to chaotic spatiotemporal dynamics. This finding has profound implications for understanding how the balance of excitation and inhibition, altered in many neurological disorders, shapes the emergence and propagation of pathological wave phenomena.

To summarize, these contributions collectively illustrate the extraordinary depth and breadth of computational and translational neuroscience in the higher-order era. They span from the molecular details of synaptic plasticity through network-level self-organization to the macroscopic signatures of personality and pathology, all unified by a commitment to embracing the genuine complexity of neural systems. Whether through bio-inspired hardware, predictive reservoir models, or multiscale spiking networks, the contributions demonstrate that the future of neuroscience lies at the intersection of detailed biological realism and powerful computational abstraction—a synthesis that promises to illuminate the brain's most elusive secrets and to translate that understanding into life-changing technologies.

4.1.4 Clinical and translational neuroscience

The ultimate test of any scientific framework lies in its capacity to alleviate human suffering. Nowhere is this imperative more urgent than in neuroscience, where disorders of the brain, ranging from neuropsychiatric conditions like schizophrenia and depression to neurological insults such as traumatic brain injury and sleep-related pathologies, impose an immense and growing burden on individuals, families, and healthcare systems worldwide. Despite decades of intensive research, the diagnosis, prognosis, and treatment of these disorders remain fraught with challenges: symptom heterogeneity, subjective diagnostic criteria, poorly understood etiology, and highly variable treatment responses. The promise of network neuroscience, and particularly of higher-order frameworks, is to move beyond the lesion-centric or neurotransmitter-centric models of the past toward a genuinely systems-level understanding of brain dysfunction.

From this perspective, psychiatric and neurological disorders are not discrete entities with single causes but emergent phenomena arising from distributed perturbations in large-scale brain networks. Schizophrenia, for instance, is increasingly conceptualized as a disconnection syndrome, where the integration of information across frontal, temporal, and parietal regions is compromised. Similarly, obstructive sleep apnea (OSA) is not merely a respiratory disorder but a systemic condition that disrupts sleep architecture, alters brain oscillations, and impairs

cognitive function through chronic intermittent hypoxia. Traumatic brain injury (TBI) produces diffuse axonal damage that reconfigures interhemispheric and intrahemispheric connectivity in ways that are poorly captured by standard neuroimaging. The common thread across these diverse pathologies is the breakdown of coordinated neural activity—a breakdown that may be more sensitively detected by measures of higher-order interactions, network topology, and information dynamics than by traditional univariate or pairwise approaches.

Translating these network-level insights into clinical practice, however, requires surmounting formidable obstacles. Neuroimaging and electrophysiological data are high-dimensional, noisy, and subject to inter-individual variability that dwarfs pathological effects. Diagnostic boundaries are often fuzzy, with substantial overlap between conditions. Moreover, the gap between basic research and bedside application remains wide, bridging multiple epistemic cultures and regulatory frameworks. The contributions in this subsection confront these translational challenges head-on, employing advanced analytical techniques, from reservoir computing and entropy analysis to hypergraph-based decision support and mitochondrial network modeling, to extract clinically actionable signals from complex neural data.

Kose et al. [55] in their contribution "Dynamic weighted ordinal connectivity graphs for EEG-based schizophrenia detection" introduce a novel framework for EEG-based schizophrenia detection that leverages the dynamic topology of functional brain connectivity. The authors construct weighted brain connectivity networks (WBCNs) from EEG signals and propose a new descriptor, weighted ordinal connections (WOC), that encodes both the weight information and the ordinal relationships among edges along paths between graph nodes. By extracting WOCs across different window sizes, they track how brain connectivity evolves over time in schizophrenia patients and healthy controls. Their analysis reveals that healthy controls exhibit greater temporal variability in connectivity patterns, whereas the connectivity of diseased subjects remains comparatively rigid. Classification of the extracted features using K-Nearest Neighbors, Support Vector Machines, and Random Forests achieves an overall accuracy of 91.25%, demonstrating the discriminative power of the proposed WOC-based approach for clinical diagnosis.

Reger et al. [56] investigate "Transdiagnostic signatures of nonlinear gray-matter organization in major psychiatric disorders", identifying transdiagnostic structural signatures. This study exemplifies the paradigm shift from categorical to dimensional psychiatry, recognizing that traditional diagnostic boundaries, between schizophrenia, bipolar disorder, and major depression, may obscure shared neurobiological substrates. By applying nonlinear manifold learning to structural MRI data across multiple diagnostic groups, the authors uncover gray-matter organization patterns that cut across conventional categories, correlating instead with symptom dimensions such as reality distortion, disorganization, and negative affect. These transdiagnostic signatures offer a more biologically grounded basis for patient stratification and could ultimately inform personalized treatment selection, moving psychiatry closer to the precision medicine paradigm that has transformed oncology.

While Reger et al. focus on structural imaging, Badarin et al. [57] present "Reconstruction of EEG signals using next-generation reservoir computing", advancing EEG signal reconstruction. Clinical EEG is notoriously susceptible to artifacts (eye blinks, muscle activity, electrode drift) that can obscure or mimic pathological patterns. Traditional artifact removal methods, such as independent component analysis, require expert supervision and are computationally intensive. The authors demonstrate that next-generation reservoir computing, a class of recurrent neural networks with enhanced memory and nonlinear processing capabilities, can reconstruct clean EEG signals from heavily contaminated recordings with remarkable fidelity. This approach offers a fully automated, real-time solution for artifact correction, with direct implications for ambulatory EEG monitoring, ICU neurocritical care, and brain–computer interfaces for locked-in patients.

Bai et al. [58] investigate "Dynamic mechanisms of cortical regulation in tremor oscillations of basal ganglia network". The authors address a key open question in Parkinson's disease research: how the cortex, as the input node of the cortico-basal ganglia loop, modulates tremor activity in the internal segment of the globus pallidus (GPi), the output nucleus of the basal ganglia. Using a computational model, they systematically analyze cortical control of GPi oscillations through the lens of the oscillation index and cross-spectral coherence, which quantify tremor power and frequency-locked resonance, respectively. Their results reveal a marked parameter selectivity of cortical intrinsic dynamics, with subthreshold voltage-recovery coupling acting as a frequency-selective resonance switch and spike-triggered recovery feedback serving as a rhythm-enhancing factor. Furthermore, they show that cortical modulation of GPi tremor oscillations is primarily realized through resonance and transmitted mainly via the direct pathway. These findings elucidate the dynamical mechanisms underlying cortical regulation of GPi tremor and provide theoretical and methodological foundations for future interventions targeting resting tremor in Parkinson's disease.

Addressing a different clinical domain, Egorov et al. [59] analyze "Entropy analysis of power distribution of EEG oscillatory rhythms in obstructive sleep apnea", linking entropy measures to sleep pathology. Obstructive sleep apnea affects hundreds of millions worldwide, yet its diagnosis relies on polysomnography—a cumbersome, expensive, and often inaccessible procedure. The authors propose that entropy-based analysis of routine EEG, quantifying the irregularity and complexity of oscillatory power distributions across frequency bands, can serve as a sensitive biomarker for OSA severity. They find that patients with severe OSA exhibit significantly reduced entropy in delta and theta bands during non-REM sleep, reflecting the homogenization of brain activity that

accompanies chronic hypoxia and sleep fragmentation. This work opens the door to portable, home-based screening tools that could dramatically expand access to diagnosis.

Taking a radically different translational angle, Niu et al. [60] study "A nomothetic systems framework for mitochondrial DNA copy number in neuropsychiatric disorders", integrating mitochondrial biology with network approaches. Mitochondrial dysfunction has emerged as a transdiagnostic factor in neuropsychiatric illness, but its relationship to brain network organization has remained obscure. The authors construct a nomothetic (law-seeking) systems framework that links mitochondrial DNA copy number (a peripheral biomarker of mitochondrial health) to functional connectivity patterns derived from resting-state fMRI. Their results reveal that lower mitochondrial copy number is associated with reduced connectivity in default-mode and salience networks, suggesting that systemic metabolic deficits may propagate through brain networks to produce cognitive and affective symptoms. This integrative framework exemplifies the power of network thinking to bridge levels of organization, from molecular biology to systems neuroscience, with direct relevance for developing mitochondrial-targeted therapeutics.

Moving from chronic conditions to acute crisis management, Karpov et al. [61] propose "Self-organizing search on hierarchical normative hypergraphs for decision support in disaster medicine", demonstrating how hypergraph-based filtering and self-organization principles can enhance AI-driven decision support in hierarchically regulated medical domains. Disaster medicine, responding to mass casualty events, natural catastrophes, and pandemics, operates under extreme uncertainty, time pressure, and resource scarcity. Conventional decision-support systems, built on static decision trees, are ill-equipped for these dynamic conditions. Karpov et al. introduce a hierarchical hypergraph representation of medical knowledge, where hyperedges encode multi-party clinical relationships (e.g., the joint consideration of vital signs, triage category, and available interventions). A self-organizing search algorithm navigates this hypergraph to recommend context-appropriate actions, adapting in real time as new data arrive. This framework holds transformative potential not only for disaster medicine but also for intensive care, emergency medicine, and military health systems.

Returning to neurological injury, Guyo et al. [62] examine "Effects of traumatic brain injury on interhemispheric and intrahemispheric EEG coherence in adolescents", suggesting that a coherence-based approach is useful for monitoring recovery after brain injury. TBI in adolescence is particularly concerning, as the developing brain is both vulnerable to injury and capable of remarkable plasticity. The authors conduct longitudinal EEG recordings from adolescent TBI patients, tracking interhemispheric (left-right) and intrahemispheric (frontal-posterior) coherence across multiple frequency bands. They find that coherence disruptions are most pronounced in the acute phase, particularly in the alpha band over frontal regions, and that recovery of coherence correlates with cognitive improvement. Crucially, coherence measures outperform standard power-spectral metrics in predicting functional outcomes, underscoring the value of network-based approaches in neurorehabilitation.

In a complementary study on the same condition, Egorov et al. [63] perform "Comparative analysis of brain activity correlations in obstructive sleep apnea", finding a disruption in the coordination of neural ensembles and a decrease in functional brain connectivity. While their companion paper (Egorov et al. [59]) employed entropy analysis, this contribution focuses on correlation-based functional connectivity across cortical regions. The authors demonstrate that OSA patients exhibit a global reduction in inter-regional correlations, with the most pronounced effects in fronto-central and parieto-occipital networks. This connectivity disruption correlates with both apnea-hypopnea index and daytime sleepiness, suggesting that functional network decoupling may mediate the cognitive deficits associated with OSA. The comparative approach, contrasting connectivity patterns across severity groups, provides a graded, quantitative metric that could inform triage and treatment decisions.

Finally, Torbin et al. [64] develop "Methodological approaches for analyzing structural changes in brain activity associated with obstructive sleep apnea", systematizing advanced digital analysis techniques for EEG to detect obstructive sleep-apnea-related brain changes. This contribution serves as a methodological capstone, synthesizing the diverse analytical approaches used across the OSA studies (entropy, coherence, correlation, and power-spectral analysis) into a unified framework. The authors provide practical guidelines for preprocessing, feature extraction, and statistical inference, addressing issues such as artifact rejection, multiple comparisons, and inter-subject variability. By systematizing these techniques, they lower the barrier for clinical adoption and facilitate cross-study comparisons, accelerating the translation of research findings into standardized diagnostic protocols.

Taken together, this rich collection of clinical and translational contributions illustrates the transformative potential of higher-order network thinking across the entire spectrum of brain disorders, from psychiatric illness and sleep pathology to traumatic injury and acute crisis management. They share a common commitment to moving beyond simplistic, univariate biomarkers toward multidimensional, network-based signatures that capture the genuine complexity of brain dysfunction. Whether through advanced computational modeling, integrative systems frameworks, or practical decision-support tools, these studies collectively chart a path toward a future where neuroscience research directly informs clinical practice, offering hope for more accurate diagnosis, more personalized treatment, and ultimately, better outcomes for patients and their families.

4.2 Cognition and behavioral dynamics

Cognition—the suite of mental processes that enable perception, attention, memory, decision-making, and action—is fundamentally a dynamical phenomenon. It unfolds over multiple timescales, from the millisecond precision of saccadic eye movements to the seconds-to-minutes evolution of evidence accumulation during complex reasoning, and from the minutes-to-hours dynamics of sustained attention to the overnight consolidation of memory during sleep. Yet, for much of cognitive neuroscience's history, these processes have been studied in relative isolation: oculomotor behavior in controlled laboratory tasks, sleep architecture in separate polysomnographic studies, and neural oscillations in yet another silo. The recognition that cognition emerges from the seamless integration of perception, action, and internal states, all orchestrated by large-scale, dynamically reconfiguring brain networks, has catalyzed a paradigm shift toward a more holistic, systems-level understanding.

At the heart of this paradigm lies the concept of self-organization. Cognitive performance is not a fixed trait but a fluid, adaptive response to environmental demands, internal states, and task constraints. The brain continuously reconfigures its functional connectivity, adjusting the balance between exploration (searching for new information) and exploitation (using known strategies), between stability (maintaining a cognitive set) and flexibility (switching when the context changes). These adaptations are reflected in multiple behavioral streams: the trajectory of eye movements as they sample visual information, the dynamics of neural oscillations as they encode and maintain representations, and the sequential patterns of decisions as they unfold over time. Capturing these multilevel, multiscale dynamics demands sophisticated analytical frameworks, from Riemannian geometry and drift-diffusion modeling to network-based connectivity and entropy measures, that can distill meaningful signatures from high-dimensional behavioral and neural data.

The contributions in this subsection exemplify this integrative vision. They span a remarkable range of cognitive domains, from video game playing and simulated driving to memory tasks and decision-making under uncertainty, and employ an equally diverse toolkit. Yet, they are united by a common commitment: to move beyond static, task-averaged measures toward dynamic, process-oriented accounts that reveal the self-organizing principles underlying human cognition. Importantly, many of these studies also carry translational implications, offering potential biomarkers for cognitive development, fatigue, and performance optimization in real-world settings.

Viakhireva and Demareva [65] investigate "Emergent cognitive–oculomotor adaptation profiles during FPS gameplay", linking gaming performance to cognitive–oculomotor adaptation. First-person shooter (FPS) games, far from mere entertainment, provide a rich naturalistic paradigm for studying rapid visuomotor integration, attentional allocation, and adaptive decision-making under time pressure. The authors track eye-movement patterns and task performance across multiple gaming sessions, revealing that expert players exhibit distinctive oculomotor profiles characterized by shorter fixation durations, more efficient saccadic targeting, and faster adaptation to changing threat landscapes. Crucially, these profiles emerge through trial-and-error learning, reflecting a self-organizing process that optimizes the trade-off between speed and accuracy in a dynamic environment. This work has implications not only for understanding skill acquisition but also for designing cognitive training interventions and assessing human performance in high-stakes professions.

Complementing this focus on active performance, Arain and Demareva [66] study "Self-organizing structure of a sleep–cognition network", revealing network-level sleep–cognition relationships. Sleep is increasingly recognized not as a passive state but as an active, self-organizing process that consolidates memories, prunes synaptic connections, and restores cognitive function. The authors construct a network model that links sleep architecture (sleep duration, efficiency, and stage distribution) to cognitive performance metrics across multiple domains (attention, memory, executive function). They find that this sleep–cognition network exhibits a small-world topology, suggesting that the relationship between sleep and cognition is not reducible to a set of independent associations but emerges from the coordinated interaction of multiple variables. This network perspective offers a powerful framework for understanding individual differences in cognitive vulnerability to sleep disruption and for identifying intervention targets in sleep disorders.

Shifting from network analysis to mathematical geometry, Badarin [67] presents "Riemannian geometry of eye-movement covariance matrices during a prolonged working memory task", applying Riemannian geometry to eye-movement analysis. Eye movements are not random but exhibit systematic patterns of covariation that reflect underlying cognitive states. Traditional analyses treat these covariance matrices as vectors in Euclidean space, ignoring their inherent geometric structure. Badarin demonstrates that by embedding these matrices in a Riemannian manifold, a curved space where distances are measured along geodesics, one can extract novel features that are more sensitive to cognitive load and fatigue. Specifically, the geodesic distance between covariance matrices increases with task duration, reflecting the progressive drift in oculomotor control that accompanies mental fatigue. This geometrically informed approach offers a powerful new tool for monitoring cognitive state in real-time, with applications in human factors, neuroergonomics, and clinical assessment.

Extending the oculomotor theme to ecologically valid contexts, Selezneva and Demareva [68] examine "Reorganization of oculomotor behavior under auditory and visual cognitive load during simulated driving", providing insights into cognitive load effects on behavior. Simulated driving offers a controlled yet realistic environment for studying attention allocation under dual-task conditions. The authors manipulate cognitive load through auditory

(verbal) and visual (spatial) secondary tasks while tracking drivers' eye movements and steering performance. They find that different load modalities produce distinct patterns of oculomotor reorganization: auditory load primarily increases fixation durations and narrows the visual scanning range, while visual load reduces saccade amplitudes and increases gaze variability. These modality-specific effects suggest that the brain flexibly reallocates attentional resources depending on the nature of the competing demands, highlighting the importance of considering task context in cognitive load assessment.

Focusing on cognitive development, Kuc [69] investigates "Functional connectivity and long-range temporal correlations of neural activity in the alpha-range as markers of intellectual development in children", demonstrating that fluid intelligence in children is linked to both the temporal stability of alpha oscillations and functional network topology. Fluid intelligence—the capacity to solve novel problems—undergoes dramatic development during childhood, yet its neural correlates remain incompletely understood. Kuc shows that children with higher fluid intelligence exhibit both stronger long-range temporal correlations in alpha-band activity (indicative of more persistent neural dynamics) and more efficient functional network topology (shorter path lengths, higher clustering). These two markers are partially independent, suggesting that intellectual development involves both the stabilization of oscillatory dynamics and the optimization of network architecture. This dual-pathway framework offers a more nuanced account of cognitive development and may inform early identification of children at risk for learning difficulties.

Delving into decision-making processes, Brueva et al. [70] present "Emergent behavioral–oculomotor profiles during decision-making under uncertainty", suggesting that adaptive decision-making under uncertainty emerges through coordination between reinforcement-learning stabilization and ongoing oculomotor exploration rather than through reduced visual activity alone. Decision-making under uncertainty is a hallmark of real-world cognition, yet its underlying mechanisms remain debated. The authors employ a novel paradigm that tracks both choice behavior and eye movements during a probabilistic reward-learning task. They find that successful decision-makers do not simply reduce their visual sampling; rather, they dynamically coordinate between exploratory saccades (sampling multiple options) and stabilizing fixations (concentrating on promising choices), with this coordination evolving across trials as reinforcement learning converges. This emergent profile reveals that adaptive decision-making is a self-organizing process that balances information gathering and commitment, with implications for understanding both healthy and pathological decision-making (e.g., in addiction or anxiety).

In a complementary neuroimaging study, Badarin et al. [71] investigate "Brain network dynamics during evidence accumulation in memory task: evidence from fNIRS and drift–diffusion model", concluding that large-scale network organization primarily supports higher-order cognitive processes involved in evidence accumulation, rather than early-stage memory retrieval, providing new insights into the neural basis of decision-making in memory tasks. By combining fNIRS (which measures prefrontal and parietal hemodynamics) with drift-diffusion modeling (which separates decision processes into evidence accumulation rate, threshold, and non-decision time), the authors dissect the neural contributions to different stages of a memory-based decision task. They find that functional connectivity within the frontoparietal network correlates specifically with the evidence accumulation rate, the speed with which information is integrated toward a decision, but not with retrieval speed or response threshold. This dissociation suggests that large-scale network dynamics are preferentially engaged in higher-order integrative processes, with implications for understanding cognitive decline in aging and neurological disorders.

Finally, Borovkova et al. [72] develop "Individual strategies for maintaining cognitive efficiency during prolonged mental activity," using the EEG Fatigue Index, based on the ratio of power in the theta, alpha, and beta bands with normalization relative to the baseline level and subsequent binarization. Mental fatigue—the progressive decline in cognitive performance during sustained task engagement—is a pervasive challenge in both occupational and clinical settings. The authors propose a novel, computationally efficient EEG Fatigue Index that captures the shift in oscillatory power balance from alert (low theta/alpha, high beta) to fatigued (high theta/alpha, low beta) states. By binarizing this index and tracking its temporal evolution, they identify distinct individual strategies for maintaining performance: some individuals exhibit a "compensatory" profile, increasing effort to sustain performance despite rising fatigue, while others show a "conservation" profile, allowing performance to decline to conserve resources. This individual-difference framework has direct applications in workload monitoring, adaptive task design, and fatigue countermeasure development for safety-critical professions (e.g., aviation, healthcare, military).

These diverse contributions illustrate the extraordinary richness of cognitive and behavioral dynamics when viewed through the lens of self-organization and higher-order interactions. They span from the micro-level of eye-movement trajectories and oscillatory dynamics to the macro-level of sleep-cognition networks and individual strategy profiles, yet they are unified by a commitment to understanding cognition as an emergent, dynamic, and adaptive phenomenon. By integrating cutting-edge analytical tools (Riemannian geometry, drift-diffusion modeling, network analysis, and machine learning) with ecologically valid paradigms and real-world applications, this body of work charts a path toward a genuinely integrative cognitive neuroscience, one that can capture the fluid, self-organizing nature of human thought and action in all its complexity.

4.3 Infectious disease dynamics

The COVID-19 pandemic has indelibly underscored the profound vulnerability of global society to infectious diseases and the critical importance of robust, predictive modeling for public health decision-making. Yet, even before 2020, the challenge of understanding and controlling epidemic spread had long occupied center stage in mathematical epidemiology, driven by the relentless emergence of novel pathogens, the evolution of drug resistance, and the complex interplay between ecological, climatic, and socio-behavioral factors. Traditional compartmental models (susceptible–infected–recovered (SIR) and its numerous variants) have provided invaluable qualitative insights and quantitative guidance for decades. However, the unprecedented scale and complexity of modern outbreaks have exposed the limitations of these classical frameworks, demanding a new generation of models that can integrate heterogeneous data sources, capture nonlinear and non-local dynamics, and adapt in real time as new information becomes available.

The confluence of three transformative developments has catalyzed this evolution. First, the explosion of high-resolution data, from genomic surveillance and mobility tracking to climate records and social media signals, has created an opportunity to move beyond stylized assumptions toward truly data-driven epidemic modeling. Second, advances in machine learning, particularly deep neural networks, have endowed modelers with powerful tools for pattern recognition, parameter estimation, and forecasting in high-dimensional, noisy systems where mechanistic knowledge is incomplete. Third, the rediscovery and refinement of fractional calculus, which generalizes integer-order derivatives to capture memory effects and anomalous diffusion, has provided a mathematically principled framework for incorporating the long-range temporal correlations that characterize many real-world epidemic processes, from the slow waning of immunity to the delayed impact of interventions.

The integration of these developments is not merely additive but transformative. Hybrid models that combine mechanistic compartmental structures with data-driven neural components can leverage the interpretability and biological plausibility of the former with the flexibility and predictive power of the latter. Fractional-order formulations can capture the subdiffusive spread of pathogens in heterogeneous populations, where standard models overestimate the speed of transmission and underestimate the persistence of outbreaks. Optimal control theory, when coupled with these advanced dynamical frameworks, can identify vaccination, treatment, and social-distancing strategies that balance epidemiological efficacy with economic and social costs. The contributions in this subsection exemplify this integrative vision, each addressing a distinct facet of the infectious disease modeling landscape.

The special issue includes three contributions addressing infectious disease modeling. In particular, Gurmu et al. [73] present "Climate-driven infectious disease dynamics: a hybrid SEIRC–deep neural network approach", integrating climate data with neural network modeling. This work tackles a critical but often neglected dimension of epidemic dynamics: the profound influence of environmental factors on pathogen transmission. Many vector-borne and waterborne diseases, from malaria and dengue to cholera and leptospirosis, exhibit strong seasonal and climate-driven patterns, yet traditional models either ignore these dependencies or incorporate them through simplistic parametric functions. The authors construct a hybrid architecture that couples a mechanistic SEIRC (susceptible–exposed–infectious–recovered–carrier) compartmental model with a deep neural network that learns the nonlinear mapping from climate variables (temperature, precipitation, humidity, and vegetation indices) to transmission rates. This hybrid approach retains the interpretability of the compartmental structure while enabling the model to capture complex, data-driven climate–disease relationships that would be impossible to specify a priori. The results demonstrate significantly improved predictive accuracy over purely mechanistic or purely data-driven alternatives, offering a powerful tool for early warning systems and climate-adaptive intervention planning in resource-limited settings.

Taking a complementary mathematical approach, Khan et al. [74] develop "Neural network analysis of generalized cholera epidemic model using modified Mittag–Leffler fractional order derivative", applying fractional calculus to epidemic modeling. Cholera, a waterborne disease caused by Vibrio cholerae, remains a major public health threat in regions with inadequate sanitation, exhibiting complex dynamics that include environmental reservoirs, asymptomatic carriers, and multiple transmission pathways (waterborne, foodborne, and person-to-person). The authors generalize the classical cholera model by replacing integer-order derivatives with fractional derivatives based on the modified Mittag–Leffler kernel—a non-singular, non-local operator that captures the memory-dependent nature of disease spread. This fractional formulation naturally incorporates the prolonged infectious period of asymptomatic carriers, the delayed clearance of pathogens from the environment, and the gradual development of immunity. To solve this computationally intensive model, the authors employ a neural network-based numerical scheme that achieves high accuracy while dramatically reducing computational cost compared to traditional finite-difference methods. This work demonstrates that fractional calculus, when combined with modern machine learning, can provide a more faithful representation of real-world cholera dynamics and inform the design of targeted, time-sensitive interventions.

Finally, Dolai et al. [75] investigate "Data-driven fractional-order modeling and optimal control of Ebola virus dynamics", combining data-driven approaches with optimal control theory. Ebola virus disease, characterized by high case fatality rates and periodic outbreaks in sub-Saharan Africa, presents unique modeling challenges: rapid disease progression, strong dependence on human behavior (burial practices, healthcare-seeking behavior),

and the critical role of timely interventions (case isolation, contact tracing, safe burials). The authors construct a fractional-order Ebola model calibrated to outbreak data from the 2014–2016 West African epidemic, using a data-driven parameter estimation framework that combines Bayesian inference with neural network surrogates. They then embed this validated model within an optimal control framework, solving for time-dependent intervention strategies that minimize the combined cost of disease burden and control measures. The optimal strategy reveals a dynamic allocation of resources, intensive early case finding and isolation, followed by sustained community engagement and vaccination, that substantially outperforms static or heuristic policies. This work exemplifies the translational potential of advanced epidemic modeling, providing actionable guidance for public health responders facing real-world constraints.

Taken together, these three contributions illustrate the extraordinary methodological diversity and practical relevance of contemporary infectious disease modeling. Gurmu et al. demonstrate the power of hybrid mechanistic–machine learning architectures to integrate environmental drivers; Khan et al. showcase the mathematical elegance and computational efficiency of fractional calculus combined with neural networks; and Dolai et al. bridge the gap between data-driven modeling and prescriptive decision-making through optimal control. While their specific foci differ (climate-driven transmission, cholera dynamics, and Ebola response), they are united by a shared commitment to moving beyond the limitations of classical models, embracing the complexity of real-world epidemic processes, and delivering tools that can meaningfully inform public health practice. In an era of emerging pathogens and interconnected global health threats, these contributions represent a vital step toward a more resilient, data-responsive, and scientifically grounded approach to infectious disease prevention and control.

4.4 Technology, materials, and systems

Beyond the life sciences and cognitive domains, the principles of self-organization and HOIs find powerful resonance across a remarkable spectrum of technological and physical systems. From the atomic-scale assembly of composite thin films to the macroscale coordination of mechatronic networks, from the computational modeling of bio-inspired flight to the trust management of social Internet-of-Things (IoT) ecosystems, the same fundamental themes recur: emergent order from decentralized components, nonlinear feedback loops that stabilize or destabilize collective states, and the critical role of network topology in shaping system-level function. This breadth of applications testifies to the universality of complex systems thinking, demonstrating that the mathematical and conceptual frameworks developed in one domain can often be fruitfully transplanted to seemingly unrelated fields.

The contributions gathered in this subsection exemplify this cross-disciplinary fertility. They span materials science, where self-organization governs the formation of functional nanostructures; social and technological networks, where trust and information flow through higher-order topologies; bio-inspired engineering, where machine learning enables the emulation of natural flight mechanisms; physical electronics, where spiking neural networks are implemented in radio-frequency hardware; and even economics and education, where network analysis and large language models are being deployed to understand complex human systems. Despite their superficial diversity, these studies are united by a shared commitment to moving beyond reductionist, component-level analysis toward holistic, system-level understanding, and by a common toolkit of advanced analytical and computational methods, including network theory, machine learning, non-parametric statistics, and self-organization principles.

The issue also covers a diverse range of technological and physical applications:

4.4.1 Composite materials

The engineering of advanced materials has long been guided by the principle that structure determines function. Yet, the relationship between processing conditions, microstructural organization, and macroscopic properties is notoriously nonlinear and multiscale, involving self-organization phenomena that are difficult to predict from first principles. The two contributions in this sub-subsection address these challenges from complementary perspectives: one through experimental investigation of self-organization mechanisms in thin-film composites and the other through intelligent decision-support systems for nanomaterial design.

Kolesnikov et al. [76] investigate “Mechanism of structural self-organization in Ti/AlSi composite thin films”, revealing self-organization mechanisms in material science. Titanium-aluminum-silicon (Ti/AlSi) composite thin films are of significant technological interest for applications requiring high-temperature stability, wear resistance, and tailored electrical properties. The authors combine advanced characterization techniques (transmission electron microscopy, X-ray diffraction, and energy-dispersive spectroscopy) with thermodynamic modeling to elucidate self-organization pathways that govern phase separation, grain growth, and interfacial structure during deposition and annealing. They discover that the formation of hierarchical nanostructures, alternating Ti-rich and AlSi-rich layers with characteristic periodicities, emerges from the competition between surface-energy minimization and strain-driven diffusion, a classical Turing-like instability operating at the nanoscale. This mechanistic understanding provides a rational basis for tuning processing parameters to achieve desired microstructures, enabling the design of thin films with optimized properties for specific applications.

Complementing this experimental focus, Korchagin [77] presents "Intelligent decision-support system for designing functional nanocomposites", to predict and optimize electrophysical characteristics of nanomaterials. The design space for functional nanocomposites—combinations of nanoparticles, polymers, and other constituents—is vast, and experimental screening is both time-consuming and expensive. Korchagin develops a decision-support system that integrates machine learning surrogate models, multi-objective optimization algorithms, and a knowledge base of materials properties to guide the synthesis of nanocomposites with target electrical, thermal, or optical characteristics. Crucially, the system incorporates higher-order interactions among formulation variables (e.g., the synergistic or antagonistic effects of multiple nanoparticle types), capturing nonlinearities that would be missed by simpler additive models. Validation against experimental data demonstrates that the system can identify novel compositions that outperform existing benchmarks, accelerating the materials discovery cycle by orders of magnitude.

4.4.2 Pavement defect detection

Li et al. [78] in their contribution "SHE-YOLO: Real-time and low-cost road defect detection via semantic hypergraph enhancement" address the challenge of detecting inconspicuous and rapidly deteriorating pavement defects by proposing SHE-YOLO, an improved detection model designed for low-cost, real-time inspection on embedded hardware. Built upon the YOLOv11 architecture, the method introduces a semantic-aware hypergraph convolution module that combines a domain-informed semantic similarity matrix with an area-adaptive hyperedge attention mechanism, thereby strengthening feature representation for small targets. A multiscale edge enhancement strategy further improves sensitivity to fine-grained defects such as thin cracks. Experimental results show that SHE-YOLO substantially outperforms the YOLOv11n baseline across standard detection metrics, with particularly pronounced gains in localization accuracy for challenging defects. The model is deployed on the Kendryte K230 platform after conversion to kmodel format, supporting both image and video inference. Real-world evaluation confirms only minor accuracy degradation while maintaining stable real-time processing, demonstrating that the approach offers an effective and computationally efficient solution for pavement defect detection on resource-constrained embedded platforms.

4.4.3 Social dynamics and multi-agent systems

As the Internet of Things (IoT) permeates every facet of modern life, from smart homes and wearables to industrial sensors and autonomous vehicles, the challenge of managing trust, security, and reliability in these vast, decentralized networks becomes increasingly urgent. Trust is not a binary attribute but a dynamic, context-dependent property that emerges from the history of interactions among agents, modulated by network topology and the presence of malicious or compromised nodes. The contribution in this sub-subsection addresses this challenge through a novel integration of olfactory-inspired computation and graph neural networks.

Buvana and Arock [79] develop "Artificial olfactory-inspired graph U-Net for topological imbalance-aware trust edge classification in social IoT trust management", addressing trust management in social IoT networks. Drawing inspiration from the mammalian olfactory system, which processes complex molecular mixtures through a hierarchical, combinatorial code, the authors design a novel neural architecture that treats trust relationships as edges in a social IoT graph. The artificial olfactory front-end extracts high-dimensional features from interaction histories, which are then fed into a graph U-Net that performs edge classification (trustworthy vs. untrustworthy) while explicitly accounting for topological imbalances (i.e., the uneven distribution of trust relationships across the network). The architecture achieves superior performance on benchmark trust datasets, particularly in scenarios with sparse or imbalanced training data, demonstrating the value of bio-inspired design and topology-aware learning for next-generation network security.

4.4.4 Flapping wings, electronics, and mechatronics

The engineering of autonomous, adaptive, and energy-efficient systems increasingly draws inspiration from biological principles, from the aerodynamics of insect flight to the computational efficiency of spiking neural networks. The three contributions in this sub-subsection exemplify this bio-inspired approach, spanning machine learning for flight dynamics, radio-frequency implementations of neuromorphic computing, and non-parametric analysis of mechatronic self-organization.

Khalid et al. [80] investigate "Machine-learning model for dynamic twisting in a bio-inspired flapping wing", applying machine learning to bio-inspired design. Flapping-wing micro-aerial vehicles (FWMAVs) hold promise for agile, energy-efficient flight in confined spaces, but their aerodynamic performance is highly sensitive to the dynamic twisting of the wing during each stroke—a complex, nonlinear phenomenon that is difficult to model analytically. The authors train a deep neural network on high-fidelity computational fluid dynamics data to predict wing twisting dynamics as a function of kinematic parameters (flapping frequency, amplitude, and phase). The

resulting surrogate model is computationally efficient enough for real-time control, enabling adaptive adjustments that optimize lift and thrust under varying flight conditions. This work exemplifies the synergy between machine learning and bio-inspired engineering, accelerating the development of next-generation aerial robotics.

Kurbako et al. [81] investigate "Learning of a small spiking neural network based on the modified FitzHugh–Nagumo oscillators in a radio physical experiment", developing a software which enable to recognize simple black-and-white images. While most neuromorphic computing research focuses on digital or mixed-signal implementations, this work takes a distinctly analog approach: implementing a spiking neural network using modified FitzHugh–Nagumo oscillators—a canonical model of excitable dynamics—in radio-frequency hardware. The authors demonstrate that this physical network can be trained, via supervised learning, to recognize simple binary patterns, with the training dynamics emerging from the intrinsic nonlinearities of the oscillators rather than from external computational resources. This proof-of-concept suggests that analog neuromorphic hardware, based on simple electronic oscillators, could offer a low-power, compact alternative to digital implementations for edge-computing applications in sensor networks and embedded systems.

Korchagin et al. [82] develop "Principles of multi-agent interaction in automated transmission synthesis based on LLM". The authors propose a multi-agent framework for the automated synthesis of transmissions in wheeled tractor equipment, leveraging the capabilities of large language models (LLMs) to tackle the complexity of this engineering design problem. Treating the transmission as a complex system, the authors adopt a systematic approach in which the overall synthesis task is decomposed into specialized agents with formalized interaction principles tailored to the specifics of engineering synthesis. The paper formulates and substantiates these principles of multi-agent interaction, and further proposes concrete mechanisms for their technical implementation. The work thereby illustrates how LLM-based multi-agent architectures can be adapted to domain-specific engineering synthesis tasks, offering a structured pathway toward automating complex design processes traditionally requiring extensive human expertise.

Finally, Brzhozovskii and Brovkova [83] present "Non-parametric analysis of self-organization processes in complex mechatronic networks", developing non-parametric analysis methods. Mechatronic networks, interconnected systems of sensors, actuators, and controllers, exhibit complex self-organization phenomena, from emergent synchronization in multi-motor drives to adaptive reconfiguration in fault-tolerant systems. Traditional analysis methods often assume parametric forms (e.g., linearity, stationarity, normality) that are violated in real-world mechatronic systems. The authors introduce a suite of non-parametric statistical tools (rank-based tests, permutation methods, and kernel density estimation) that can detect and characterize self-organization processes without imposing restrictive assumptions. Applied to data from an industrial robotics network, these methods reveal previously hidden patterns of collective behavior, offering a robust framework for condition monitoring, fault detection, and performance optimization.

4.4.5 Water activity, economy, and education

Several contributions demonstrate a remarkable reach of complex systems thinking into domains as diverse as physical chemistry, macroeconomics, and educational technology. These contributions illustrate that the same principles (network organization, self-consistency, and emergent behavior) apply across scales and disciplines, from the hydrogen-bond network of liquid water to the global financial system and the knowledge architectures of large language models.

Vanina et al. [84] investigate "Water activity-based identification of collective interactions in a hydrogen-bond network", applying network approaches to physical chemistry. Water is the quintessential anomalous liquid, whose extraordinary properties arise from the collective dynamics of its hydrogen-bond network. The authors propose a novel approach to characterize this network based on water activity—a thermodynamic measure that reflects the chemical potential of water in solution. By treating water molecules as nodes and hydrogen bonds as edges, they construct a network representation whose topological properties (degree distribution, clustering, community structure) can be extracted from activity measurements. This approach reveals that the hydrogen-bond network exhibits scale-free and small-world characteristics, suggesting that the collective interactions in water are organized according to principles similar to those observed in social and biological networks. This work opens new avenues for understanding aqueous solutions, from biochemical environments to atmospheric chemistry.

In a markedly different domain, Kurkin et al. [85] present "Functional network analysis of macroeconomic indicators", extending network science to economics. Macroeconomics has long been dominated by equilibrium models that assume rational agents and linear dynamics, yet real-world economies exhibit complex, nonlinear, and often unstable behavior. The authors construct a functional network of macroeconomic indicators (GDP, inflation, unemployment, interest rates, trade balances, and others) by computing time-varying correlations across a panel of countries. They then apply community detection and centrality analysis to identify structurally important indicators and emergent clusters of co-moving variables. Their results reveal that the global economy is organized into distinct "regimes" (e.g., growth, recession, recovery) characterized by different network topologies, and that certain indicators (notably interest rates and oil prices) act as network hubs that transmit shocks across the system.

This network perspective offers a complementary tool to traditional econometric models, providing early warning signals for systemic instability.

Finally, Bukina et al. [86] respond to the question "Can an LLM reproduce an expert knowledge base in neuroeducation?" examining the capabilities of large language models. Neuroeducation—the intersection of neuroscience and educational practice—is a rapidly growing field that synthesizes insights from cognitive neuroscience, developmental psychology, and pedagogy. The authors evaluate the ability of state-of-the-art large language models (LLMs) to reproduce the knowledge base and reasoning patterns of neuroeducation experts, using a benchmark of expert-validated questions and case studies. Their results reveal a nuanced picture: LLMs perform well on factual recall and basic conceptual reasoning but struggle with complex, context-dependent clinical or pedagogical judgments that require integrating multiple lines of evidence, considering individual differences, and weighing ethical trade-offs. The authors argue that LLMs can serve as valuable assistants, for literature retrieval, summarization, and initial hypothesis generation, but cannot replace expert human judgment in the nuanced, human-centered domain of neuroeducation. This contribution provides a timely and sobering assessment of both the potential and the limitations of AI in high-stakes educational and clinical contexts.

Taken together, this diverse collection of technological and physical applications illustrates the extraordinary reach of complex systems thinking. From the nanoscale self-organization of composite materials to the macroscale dynamics of global economies, from the bio-inspired design of flapping-wing drones to the analog implementation of neuromorphic circuits, the principles of self-organization, higher-order interactions, and network analysis provide a unifying framework that transcends disciplinary boundaries. The contributions gathered here demonstrate that these principles are not merely abstract mathematical curiosities but practical tools for solving real-world problems, designing better materials, securing IoT networks, optimizing mechatronic systems, and understanding the complex interplay of water, wealth, and wisdom. As the complexity of human technology continues to grow, embracing these systems-level perspectives will be essential for navigating the challenges and opportunities of the twenty-first century.

5 Integrative perspectives and outlook

This special issue provides a timely and centralized platform for researchers to disseminate groundbreaking work on one of the most exciting developments in complex systems science [12]. By moving beyond the paradigm of pairwise connections, this collection showcases how a deeper consideration of system structure is essential for understanding self-organization and emergence [87]. The contributions presented here advance the dialogue on the intricate relationship between structure and dynamics in complex systems, collectively demonstrating that higher-order interactions are not a niche specialization but a foundational principle that reshapes our understanding of everything from neural synchrony and cognitive function to epidemic spread, material self-organization, and socio-technical resilience.

The breadth and depth of the contributions gathered in this volume testify to the maturation of the field. What began as a theoretical curiosity, the extension of graph theory to hypergraphs and simplicial complexes, has blossomed into a vibrant, interdisciplinary enterprise with tangible impacts across the sciences. The neuroscientific cluster, which constitutes the largest thematic bloc, has moved from proof-of-concept demonstrations of higher-order connectivity to clinically relevant applications: biomarkers for epilepsy, traumatic brain injury, and sleep apnea; personalized neuromodulation paradigms; and brain–computer interfaces that harness the full richness of multi-region interactions. The cognitive and behavioral studies have extended this translational impulse, linking higher-order network dynamics to individual differences in intelligence, decision-making, and cognitive fatigue, with implications for education, human factors, and occupational health.

Beyond neuroscience, the contributions have demonstrated the universal applicability of higher-order frameworks. In infectious disease modeling, hybrid mechanistic–machine learning models and fractional calculus have opened new avenues for climate-adaptive forecasting and optimal intervention design. In materials science, self-organization principles have guided the rational design of nanocomposites and thin films. In technology and systems engineering, higher-order thinking has informed trust management in IoT networks, neuromorphic hardware, and mechatronic control. Even in the humanities and social sciences, from macroeconomics to neuroeducation, network-based approaches have provided fresh perspectives on longstanding questions. This cross-disciplinary fertility is perhaps the strongest testament to the foundational nature of the concepts explored in this issue.

Yet, as the contributions vividly illustrate, the field is far from complete. The very richness of the phenomena uncovered raises new questions, exposes new challenges, and charts new frontiers. Several emerging directions merit particular attention, each building directly on the work presented here while pointing toward the next generation of higher-order network science.

First, the integration of topological data analysis (TDA) and persistent homology with higher-order network models promises to uncover previously hidden organizational principles [90]. While the contributions in this issue have focused primarily on graph-theoretic and hypergraph representations, TDA offers a complementary lens

that captures the shape of data—the presence of holes, cavities, and higher-dimensional structures that persist across scales [88, 89]. Several papers have hinted at the importance of such topological features: the spiral waves in Rajagopal et al., the community structures in Kurkin et al.'s macroeconomic networks, and the hierarchical organization in Karpov et al.'s disaster-medicine hypergraphs all suggest that topological invariants may encode functionally relevant information that is invisible to conventional connectivity measures. The next frontier lies in systematically integrating TDA with dynamical models, enabling the detection of topological phase transitions and the prediction of critical phenomena in higher-order systems.

Second, the development of data-driven methods for discovering higher-order structures from real-world datasets will be crucial for bridging theory and application [91, 92]. Many of the contributions in this issue have relied on known or inferred higher-order topologies—hypothesized hyperedges, assumed simplicial complexes, or experimentally characterized connectivity matrices. Yet, in most real-world systems, the true higher-order interaction structure is unknown, latent, and time-varying. The challenge of inferring hyperedges from multivariate time series, of distinguishing genuine higher-order dependencies from pairwise artifacts, and of tracking the evolution of higher-order topology over time remains a major methodological bottleneck. The hybrid machine learning approaches showcased by Vakhlaeva et al., Badarin et al., and Gurmu et al. represent important steps in this direction, but the next generation of algorithms will need to be scalable, interpretable, and robust to noise and missing data.

Third, the role of HOIs in facilitating or constraining emergent order in brain images remains a fertile ground for investigation [93]. While the neuroscientific contributions in this issue have focused predominantly on electrophysiological data (EEG, MEG, SEEG, fNIRS) and structural MRI, the integration of higher-order analysis with functional neuroimaging (fMRI, PET) and with emerging modalities such as ultra-high-field MRI and mesoscale calcium imaging promises to reveal new layers of organization. The relationship between higher-order functional connectivity and structural connectomics, the influence of neurotransmitter systems on higher-order dynamics, and the role of glial networks in modulating multi-node interactions are all ripe for exploration. Moreover, the translational applications, from early diagnosis of neurodegenerative diseases to personalized neuromodulation for psychiatric disorders, will require the development of robust, clinically validated higher-order biomarkers, a challenge that the clinical contributions in this issue have just begun to address.

Fourth, the intersection of AI and machine learning with higher-order network analysis represents a rapidly growing frontier [94, 95]. The contributions in this issue have showcased a spectrum of AI approaches—deep learning for parameter estimation, reservoir computing for signal reconstruction, graph neural networks for trust classification, and large language models for knowledge retrieval. Yet, these applications represent only the first wave of integration. Looking ahead, we anticipate the emergence of higher-order-aware neural architectures that explicitly encode hypergraph or simplicial structure, explainable AI frameworks that leverage higher-order topology to interpret model decisions, and generative models that can synthesize realistic higher-order networks for hypothesis testing and simulation. Moreover, the synergy between AI and higher-order network theory is bidirectional: just as machine learning can accelerate the discovery and analysis of higher-order structures, the principles of higher-order organization may inform the design of more efficient, robust, and interpretable AI systems, drawing inspiration from the brain's own higher-order processing capabilities.

Finally, a particularly promising direction concerns the synchronization phenomena that arise exclusively from HOIs. A first rigorous demonstration that triadic motifs can generate a genuinely new type of synchronization, succinctly, that hypernetworks induce hyperlocking, was recently reported by Nijholt et al. [96]. Working with three coupled oscillators at resonant frequencies, the authors show that coupling through a triadic hypernetwork motif, in which a third node modulates the interaction between two others, can produce a stable locking of the phase triplet even though no pairwise locking is observed. This hyperlocking is not merely a numerical curiosity: the authors derive the mechanism analytically through normal form transformations and phase reduction, and confirm it both in direct simulations and in chemical experiments. The result thus identifies a synchronization mechanism that is intrinsic to HOIs and has no pairwise counterpart. For the present framework, this raises the natural question of whether the layer-level locking reported here can be reformulated in terms of hyperedge-mediated phase locking, and whether such higher-order motifs could provide a more parsimonious explanation of the collective regimes observed in the multiplex system. More broadly, hyperlocking opens new avenues for controlling real-world complex dynamics beyond the pairwise paradigm, with potential applications ranging from neuronal and social systems to ecosystems and the climate.

In addition to these scientific frontiers, the field faces important challenges of standardization, reproducibility, and education. The proliferation of higher-order metrics, algorithms, and software packages, each with its own assumptions and conventions, creates a risk of fragmentation and irreproducibility. The community would benefit from shared benchmarks, open-source toolboxes, and consensus guidelines for the application and reporting of higher-order analyses. Equally important is the training of the next generation of researchers: higher-order network science sits at the intersection of mathematics, physics, computer science, and domain-specific disciplines, requiring a breadth of knowledge that is rarely covered in traditional curricula. The development of interdisciplinary training programs, summer schools, and educational resources will be essential for sustaining the momentum of this field.

We hope this special issue will serve as a foundational reference for academics across physics, life sciences, and social sciences, and inspire new research directions for theorists, computational scientists, and engineers tackling

the complexity of real-world networks. The journey from pairwise graphs to higher-order structures is far from complete, but the contributions gathered here demonstrate beyond doubt that this journey is not only worthwhile but essential. We are also pleased to announce that this special issue will continue as a Part II, providing a further platform for emerging research and continued discourse on these pressing topics. As we look into the future, we are confident that the principles, methods, and insights presented in this volume will continue to illuminate the hidden order of complex systems, driving both fundamental understanding and transformative applications for years to come.

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