ISSN 1029-3019
MEDISAN 2025;29: e5222

Review article

Self-organization and criticality for measuring altered states of consciousness

Autoorganización y criticidad para la medición de alteraciones del estado de conciencia

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ABSTRACT

The scientific measurement of consciousness remains is an ongoing challenge, with some even arguing that it lies beyond the reach of science. Although methods like electroencephalography (EEG) provide insights into brain activity, traditional linear analyses are insufficient to capture its immense complexity. This article applies the concept of self-organization and criticality from physics to the brain. This concept describes a state in which the brain oscillates between order and chaos, enabling optimal information processing. This approach allows us to view the brain as a complex dynamic system and to develop mathematical methods for quantifying consciousness.

This model offers a promising way to explain the neural foundations of consciousness and could significantly enhance our understanding in the field of consciousness research.

Keywords: Self-organization, criticality; interdisciplinary perspective; thermodynamic phase transition; chaos and order; optimal information processing.

RESUMEN

La medida científica de restos de conciencia es un desafío continuado, con incluso argumentación que miente más allá del alcance de la ciencia. Aunque los métodos como el electroencefalográfico proporcionen las visiones en la actividad del cerebro, los análisis lineales tradicionales son insuficientes para capturar su inmensa complejidad. Este artículo aplica los conceptos de autoorganización y criticidad de las físicas del cerebro. Este concepto describe un estado en que el cerebro oscila entre el orden y caos, mientras habilita el proceso de información óptimo. Este acercamiento nos permite ver el cerebro como un sistema dinámico complejo y desarrollar los métodos matemáticos para cuantificar la conciencia. Este modelo ofrece una manera prometedora de explicar las fundaciones neurales de la conciencia y podría mejorar nuestra comprensión significativamente en el campo de la investigación de la conciencia.

Palabras claves: autoorganización; criticidad; perspectiva interdisciplinaria; la transición de la fase termodinámica; caos y orden; proceso de información óptimo.

Recibido: 18/11/2024

Aprobado: 03/02/2025

Introduction

The intrigue surrounding consciousness has captivated humanity since ancient times. The relationship between the conscious perception of stimuli and the orchestration of billions of neurons in the brain remains a perplexing and engaging topic for researchers worldwide. Over the years, a plethora of conceptual models with diverse philosophical underpinnings have been proposed, making direct comparisons challenging. Notably, the nonlinear dynamical system framework in neuroscience has generated numerous approaches and hypotheses regarding the relationship between neural dynamics and conscious experience. Such notions are compelling, given that consciousness is an inherently dynamic phenomenon involving the propagation of information, a temporal process often described as the "stream of consciousness."(1)

Despite the myriad of models, no current theory of consciousness has gained universal acceptance, either theoretically or empirically, highlighting the need for a cohesive and unifying framework. One promising candidate for this unifying framework is self-organization criticality (SOC), which provides a robust and competitive model to describe the physical mechanisms underlying spontaneous brain activity and, by extension, cognition, behavior, and consciousness.(2) Advancements in neuroimaging techniques with high spatial and temporal resolution have allowed for more precise explorations of the neural foundations of consciousness, reinvigorating research in this field.

This narrative review aims to provide a conceptual perspective on the most influential theories of consciousness. Specifically, it seeks to (i) explore the agreements and divergences among the leading theories of consciousness, and (ii) assess the potential of self-organization criticality (SOC) as a unifying framework for understanding consciousness.

Neurophysiological Measurements of States of Consciousness

Over the years, some authors have claimed that consciousness lies entirely beyond the reach of science and that "a purely materialistic analysis of a living being, focusing solely on the structure and function of the physical brain, will neither reveal the content nor the origin of our consciousness."(3) Allegedly, even Galileo said that we must place consciousness outside the realm of physical science to capture everything else in the language of mathematics and quantities. In his foundational work on altered states of consciousness, William James also took the perspective that consciousness does not originate in this physical world. Instead, it exists in another transcendental sphere, and access to higher aspects of consciousness depends on an individual's "threshold of consciousness," which determines whether various features of heightened consciousness are experienced.(1)

In a special issue of the journal "Science" commemorating its 125th anniversary, scientific knowledge gaps were highlighted through 125 questions that remained unanswered. The most fundamental question was "What is the universe made of?" followed by "What is the biological basis of consciousness?". To identify general principles underlying the large-scale organization of biological complexity, concepts from statistical physics have been adapted to living organisms. Particularly in neuroscience, understanding how the interaction of billions of neurons across different scales gives rise to emergent phenomena such as cognition, behavior, and consciousness has inspired researchers to adopt interdisciplinary perspectives.(4)

A prominent method for non-invasive electrophysiological recording of brain activity is electroencephalography (EEG). This technique records voltage fluctuations on the scalp associated with neuronal ionic currents, representing the summation of inhibitory and excitatory postsynaptic potentials. Due to its high temporal resolution in the millisecond range, EEG is well-suited for assessing dynamic neural function. Its historical origin dates back to 1875 when British physician Richard Caton first recorded electrical activity in rabbits and monkeys. About half a century later, in 1929, German psychiatrist Hans Berger used EEG on humans for the first time. Until the 1980s, EEG signals were recorded on paper, allowing interpretation of EEG wave frequency by counting pen movements per second. With the advent of computer technology enabling numerical recording of EEG signals, spectral analysis methods such as the fast Fourier transform (FFT) and wavelet transform were developed to analyze the signal in the frequency domain. These linear methods have long been considered the "gold standard" for analyzing electrophysiological data and characterizing the five main brain waves (Delta, Theta, Alpha, Beta and Gamma). Various correlations with cortical functions have also been observed. However, it has been shown that classification based solely on frequency range is too simplistic for understanding the functional role of these rhythms in cognitive functions such as attention and multimodal coordination.[5]

A large body of literature deals with changes in oscillatory brain activity related to altered states of consciousness (ASC). Several potential neurophysiological parameters have been investigated, including frequency-specific synchronization in different brain regions, local gamma responses, and event-related potentials such as the contingent negative variation or the P3b component. However, most of them have proven to be misleading. For example, it has been observed that gamma synchronization increases during non-REM sleep, under anesthesia, or during seizures, and it has been shown that the P3b component has low sensitivity in distinguishing between vegetative and minimally conscious states.[5]

Currently, the dynamic approach in neuroscience has gained wide recognition, and extensive research suggests that nonlinear methods are more suitable for analyzing EEG data. This means that there is a consensus in the scientific literature that consciousness is associated with dynamic neural complexity, which can be assessed using quantitative measures.[6] Therefore, new indices capturing the degree of differentiation (the diversity of different firing patterns) and integration (neuronal activity that behaves like a single unit) could be applied to approximate ASC as a result of quantitative changes in the degree of complexity. Exploring markers capable of capturing how neural signals are combined, dissolved, and reconfigured over time would be of particular interest in psychotherapy research. Psychological and psychosomatic interventions aim to change a patient's mindset, including their emotional and cognitive disposition as well as their bodily self-awareness. For this reason, numerous techniques enabling changes in the state of consciousness have found their way into therapeutic practice. It is assumed that changes in neural complexity patterns occur during therapeutic processes, and measures to assess effectiveness could be useful. Furthermore, such analytical tools could be clinically important for advancing diagnosis and paving the way for identifying generalizable fingerprints of changes in consciousness.

The Theory of self-organization Criticality

self-organization criticality (SOC) is a concept from physics and the study of complex systems. It describes a particular kind of behavior that occurs during a phase transition within a system. A phase transition means that the properties of a system, called "order parameters," change depending on a "control parameter." For example, the evaporation of water involves a transition from a liquid to a gaseous state. Here, the order parameter reflects the properties of each phase (such as water or steam), while the control parameter is the temperature. As the control parameter changes, the order parameter changes gradually until a sudden change occurs at a specific point.

Graphically, a phase transition appears either as a sudden jump in the phase diagram or as a sharp corner. This is known as a "continuous second-order phase transition," where the system is exactly between two states. In this "critical state," the system behaves between two different behaviors, like order and disorder. Sometimes, this state is referred to as the "edge of chaos." If the control parameter is below the critical value, the system is in a "subcritical state," and if it is above, it is in a "supercritical state." Systems in the critical state exhibit complex behavior with special properties such as scale invariance, meaning no specific time or spatial scale dominates the behavior. This property manifests in spatial and temporal similarities across many scales.

The idea of self-organization criticality was developed in the late 1980s by the Danish physicist Per Bak and his colleagues. They proposed that in certain open systems subjected to a constant influx of energy or matter, complex structures could spontaneously form, exhibiting critical states. In his book "How Nature Works," Per Bak uses the canonical example of a sandpile. Imagine continuously adding grains of sand to a pile. Initially, small heaps form, but over time, larger areas begin to collapse as the pile becomes unstable, leading to occasional large slides or avalanches. This behavior resembles what can be observed in complex systems.[7]

ISSN 1029-3019
MEDISAN 2025;29: e5222

Alan Turing was probably the first to speculate that the brain might be in a critical state in his pioneering article on artificial intelligence from 1950. A decade later, advances in explaining the principles of self-organization and non-equilibrium phase transitions, such as Herman Haken's groundbreaking work on synergetics and Stuart Kauffman's investigations, paved the way for understanding the brain as a complex system.In 2003, Beggs and Plenz demonstrated that the spread of activity in networks of cortical neurons could be described by equations governing cascades indicative of self-organization Criticality. The authors termed this new form of network activity "neuronal avalanches."(8) A decade later, Shriki and colleagues analyzed the resting-state activity of the brain in 124 participants using magnetoencephalography (MEG). They identified large fluctuations at individual MEG sensors and analyzed them as cascades, indicating critical dynamics.(9) Subsequent studies also described spatial critical dynamics in whole-brain functional imaging data (fMRI).(10)

The hypothesis that neural networks might operate near a state of self-organization criticality has profound implications for our understanding of information processing in the brain. Interestingly, studies on criticality in physical systems suggest that systems in the critical state can exhibit optimal computational properties.(11) It has also been shown that critical dynamics in the brain could be associated with functional advantages.(12) The idea of self-organization criticality implies balanced signal transmission, significantly impacting the dynamics of neural networks. This balance is based on the likelihood that an impulse will cause each other neuron to become active. This balance can be captured by the branching parameter σ, which defines the ratio between the number of events in a time interval t (descendants) and the number of events in the subsequent interval t+1 (ancestors).

Experimental evidence suggests that critical dynamics occur when excitation and inhibition are balanced. This balance is fundamental for the transmission and processing of information. The advantages of criticality have been confirmed in both neural network models and empirical recordings. For example, it has been shown that the dynamic range of a neural network is maximized in the critical state. Additionally, neural models in the critical state have been reported to exhibit optimal information transfer, storage, and capacity.[12] Remarkably, scale-free patterns observed near the critical point of a phase transition display the greatest variability, creating the maximum number of configurations and thus a diverse range of possible brain states.[13]

This raises the question of whether mind-body interventions can shift neural dynamics towards the critical point of a phase transition associated with optimized information processing. This question was investigated in a doctoral thesis, which showed that criticality parameters could distinguish between different meditative states such as focused attention and presence in a group of experienced meditators (d= -0,32, p=.02).[14] Neural dynamics shifted closer to the critical point during pure states of presence and thoughtless emptiness. Similar results were observed in a study with non-meditating participants during a guided "body scan" meditation, where parameters were significantly closer to the critical transition state. Additionally, studies by Robin L. Carhart-Harris and colleagues suggested that "qualia" or the subjective quality of a conscious state, especially the "richness" of its content, could be captured using quantitative measures of entropy in an information-theoretical sense. Initially, entropic states were associated with a supercritical regime, while states with low entropy were linked to a subcritical regime. They hypothesized that psychedelic substances might bring the brain closer to the critical point compared to the normal waking state.[15]

Thus, self-organization criticality emerges as a promising model for describing the physical mechanisms underlying spontaneous brain activity and, consequently, consciousness.[11] Moreover, the neurodynamic concept can synthesize the most influential theories in the field of consciousness research.[15]

Self-organization Criticality in the Context of the Global Workspace Theory

When Bernard Baars first formulated the Global Workspace Theory (GWT) in 1988, he used the metaphor of the "theater of the mind" to describe a cognitive structure. The stage represents working memory, illuminated by a spotlight to highlight consciously experienced events. This spotlight is controlled by limited selective attention. Unlike

ISSN 1029-3019
MEDISAN 2025;29: e5222

the Cartesian theater, which implicitly includes an observer, the audience and director remain hidden backstage and are thus unconscious in Baars' model. The central idea of GWT is that conscious contents are globally available for various cognitive (unconscious) processes like memory and attention. Consciousness could serve as a gateway, enabling access between otherwise segregated neural functions. Thus, the theory suggests that the function of conscious awareness is to broadcast information within the brain.[16,17]

Later, StanislasDehaene and his team built on this foundation and developed the "neuronal global workspace." Initially, researchers emphasized distinguishing between conscious access and selective attention, referring to William James' definition of attention: "the possession of the mind, in clear and vivid form, of one of what seem several simultaneously possible objects or trains of thought". They focused on the aspect of conscious "grasping of the mind." The question of conscious access, such as "How does external or internal information gain access to conscious processing, defined as reportable subjective experience?" led to a series of empirical studies using experimental paradigms like masking, binocular rivalry, and inattentional blindness to investigate the minimal contrast between conscious and unconscious stimuli.[18]

Dehaene et al. further postulated that information becomes conscious by activating a network of "workspace neurons," making the information accessible to other modular brain networks that process it unconsciously. In this view, "this global availability of information is what we subjectively experience as a conscious state". Interestingly, this perspective resembles the "dynamic core" idea proposed by Edelman and Tononi: "When we become aware of something... it is as if suddenly many different parts of our brain have access to information that was previously confined to a specialized sub-system."[19] While Edelman and Tononi considered thalamocortical and corticocortical feedback as the fundamental mechanism facilitating interaction between distant brain regions, GWT posits that a nonlinear network cascade, coupled with recurrent processing, strengthens and maintains a neural representation, allowing global access by local processors.

GWT further describes the cascade as a sudden activation triggered by an external stimulus or occurring spontaneously and stochastically during the resting state. It has even been suggested that the timing of this cascade, when local modular processing generalizes through the formation of a global workspace, marks a phase transition, driving cortical systems toward the critical point. Kitzbichler and colleagues generally proposed that "it might be possible that the self-organization criticality of spontaneous cortical dynamics favors rapid transitions between different system states, supporting the adaptive emergence and disappearance of global workspaces in response to changing demands, without the need for an external driver like ascending neuromodulatory input."[20] Thus, the sudden activation facilitating conscious access can be attributed to self-organization criticality.

Self-organization Criticality in the Context of the Integrated Information Theory

The Integrated Information Theory (IIT), historically the first theory to make precise quantitative predictions about the content and extent of consciousness, has its origins in the early work on complexity and consciousness by Gerald Edelman, GiulioTononi, and Olaf Sporns.[21] Due to its theoretical framework, particularly its ability to "determine through calculation whether a physical system is conscious," IIT has sparked diverse reactions, debates, and criticisms. Over the years, it has been continuously refined. While Edelman and Tononi subtitled their book on the theory of consciousness "how matter becomes imagination" two decades ago,[19]Tononi and his colleagues emphasized in later publications that "IIT does not start from the brain and ask how it could lead to experience; instead, it starts from the essential phenomenal properties of experience, or axioms, and derives postulates about the properties required of its physical substrate."[22]

For Tononi, "every experience is holistic, and the entire set of concepts that constitute a particular experience - what the experience is and what it is not - are maximally integrated," and a "local maximum of integrated information is actually synonymous with consciousness."[23] Accordingly, consciousness arises from the integration of neural networks; the more interactions between neurons, the more conscious one is, even without sensory input. Mathematically, the theory predicts a function whose outputs encompass the contents of consciousness as elements of an experience space and the extent of consciousness, represented by the scalar value.Φ[22] Tononi adopts a structural perspective in his formulation, defining three regimes based on the degree of regularity in interactions. The middle regime, where segregation and integration are simultaneously maximized, corresponds to the conscious state. Dynamically, the three regimes are generated by changes in correlations. Accordingly, the structure of brain connectivity may remain the same while vastly different correlations can occur. As a result, the conscious state would correspond to the critical state, while a loss of consciousness would align with subcritical dynamics.[22]

Conclusions

To use the words of Dante Chialvo: "Understanding the brain is among the most challenging problems that a physicist can feel attracted to. As a system with an astronomical number of elements, each known to exhibit many nonlinearities, the brain shows collective dynamics that in many ways resemble some of the classical problems well studied in statistical physics."[24] In recent years, the assumption has emerged that self-organization criticality is a fundamental property of neural systems and that "all human behaviors, including thoughts, goal-directed or aimless actions, or simply any state of consciousness, are the result of a dynamic system - the brain - being in or near the critical state."[25] Such a theoretical framework is particularly intriguing because principles like self-organization criticality, which describe collective phenomena in any complex dynamic system, provide a theory to integrate the phenomenon of consciousness into the universal laws of the physical world. This opens up the possibility of empirically verifying mathematical measures as neurophysiological indicators of consciousness and altered states of consciousness.[2] Consequently, the concept of self-organization criticality proves to be a promising neurodynamic model of consciousness that can significantly advance understanding in the field of consciousness research.

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ISSN 1029-3019
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Conflict of interests

Los autores no declaran conflictos de intereses.

Authors contributions

Nike Walter: conceptualización de la investigación, curación de datos y análisis formal, investigación, metodología, administración del proyecto, recursos, supervisión, validación, redacción del borrador original (50 %)

Adolfo Rafael Lambert Delgado: metodología, validación, redacción, revisión y edición (20 %)

Alberto Erconvaldo Cobián Mena: metodología, validación, redacción, revisión y edición (20 %)

Thomas Loew: metodología, validación, redacción, revisión y edición (10 %)