VIEWPOINT

Consciousness as Sequential Dynamics, Robustness, and Mental Disorders

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Consciousness as a Sequential Process Operating With Cognitive Patterns

Human behavior is a sequential process, and at least its mechanical side can be described by equations. A similar statement related to consciousness is not so evident. A common view is that consciousness is an intriguing but too complex phenomenon and thus a topic not ready for mathematical description. However, converging evidence from imaging and from perceptual and modeling experiments suggests that all components or modules of consciousness, such as autobiographic memory, attention, learning, and thought generation, are sequential processes. In such sequential processes, one pattern transiently prevails on the others. Mathematically, this can be described as a transition between the vicinity of different metastable states, ie, semiattractors formed within brain functional hierarchical networks through learning and development.[1]

The informational content of these metastable states depends on the function performed by the considered brain networks at a finite interval of time. It can be engrams of movie star faces in a person's episodic memory or strophes of a favorite poem that are loaded into semantic memory. If we aim to create a dynamic theory of such processes, we have to find answers to at least the following questions: how the brain hierarchically organizes the sequential switching between engrams to keep it robust and reproducible and how many engrams can participate in the switching. The last question is evidently related to the information capacity of the corresponding cognitive process. If the process is not robust, we may face a psychiatric disorder. A too-robust sequential dynamics, from which there is no escape, can also result in a pathological behavior.

Network Inhibition

Imaging experiments have revealed distinct consciousness basic processors whose informational content, engrams, is sequentially organized.[2] Such sequential organization can be based on a winnerless competitive process among interactive agents that can be only transient winners.[3] This process is realized in the nervous system by nonsymmetrical inhibitory connections in functional networks, which result in robust sequential switching dynamics. Competition in asymmetric inhibitory networks is a mechanism that maintains the highest level of variability and stability of global brain dynamics, especially during transients.[1] The mathematical image of robust transient cognitive dynamics based on this principle in global mental space is a stable heteroclinic channel, a sequence of metastable states and their vicinity connected by trajectories called separatrices that link them in a chain (**Figure**, A). The robustness of such a channel means that trajectories in the neighborhood of the sequence of the separatrices do not leave it until the end of the channel is reached.

Different consciousness modules interact with each other. Mathematically, this can be described if network inhibition is not too strong and metastable states have not one but several unstable separatrices that connect different cognitive modalities through the creation of interconnected heteroclinic channels in the phase space of this mental network. Analyses of such networks help to reveal the conditions for the robustness of cognitive functions such as memory recall, binding, chunking, memory switching, imagination, and creativity. This is a new perspective for the understanding of many psychiatric disorders and their corresponding nonlinear dynamical description.

Dynamic Image of Obsessive-Compulsive Disorder

Obsessive-compulsive disorder can be characterized by importunate thoughts or images pushing to sequential compulsive rituals.[4] An emerging new field of nonlinear dynamical psychiatry provides computational methods as well as phenomenological insights for a deeper understanding of obsessive-compulsive disorder processes.[5] The core of these nonlinear models has to be supported by experimental observations and the assumption that mental and emotional states are described by the sequential dynamics of metastable states. The dynamical interruption of the cognitive activity by the ritual can be represented in the phase space by the interaction between 2 heteroclinic channels (Figure, B). The joint cognitive-emotional dynamics governed by this interaction is often chaotic and recurrent. Such dynamics can arise because the functional connections in brains with obsessive-compulsive disorder become abnormal. In these modes, the cognitive information flow irregularly pulsates and is quantified by measuring the sequential Kolmogorov-Sinai entropy.[1] The discussed models could hint at how to keep the stability of the cognitive performance by breaking the dynamical robustness of the ritual. For example, it could be done by controlling the level of inhibition, eg, through an external stimulus delivered at the right time.

Memory Capacity, Binding, and Chunking

While we are thinking about a sequence of episodes or complex objects, our mind, using attention, unifies several representing operations with different features, modalities, of the episodes to achieve a stable holistic representation. This is a binding process. From the dynamic point of view, this process can be represented in the mental space by a network of heteroclinic channels. Each channel corresponds to a different modality and is connected to others by unstable separatrices. For a successful performance, the bind-

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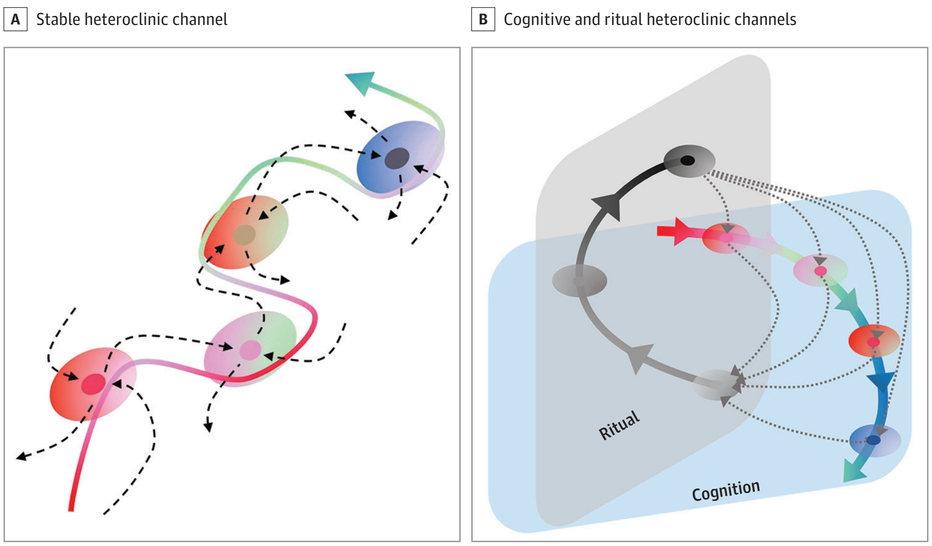
Figure. Image of Hierarchical Sequential Dynamics



A, Representation of a stable heteroclinic channel: a set of metastable states sequentially connected by unstable separatrices.[1] The robustness of such a channel means that trajectories in the neighborhood of the sequence of the separatrices do not leave it until the end of the channel is reached. B, Illustration of cognitive and ritual heteroclinic channels representing the recurrent cognitive-ritual interaction. The pointed trajectories illustrate the fact that the interruption of the cognitive performance can happen at any stage. The system can start the ritual sequence from any cognitive mode and, after completing the ritual, return to the cognitive process.

ing dynamics have to be robust against perturbations. As we know from everyday experience and rigorous mathematical analyses of these dynamic models,[1] working memory information capacity, ie, the number of patterns that we can recall without order mistakes, is finite and usually not too high. However, we can successfully recall more informative sequences if we create groups of elementary items (engrams), ie, chunks. We can continue increasing such hierarchy and build superchunks, and so on. A clear example of this is written text: a chunk of words is a sentence whereas a superchunk is a paragraph.

Creativity: Universality of the Dynamic Model

It is generally accepted that a creative idea or action has to be original, unexpected, and, at the same time, useful or pleasant. Creativity arises by the dynamic interaction between global brain networks rather than by specific brain areas. From the dynamic point of view, the critical stage in creative processes can be considered as a random walk among many different information patterns, which can be quantitatively characterized by the value of Kolmogorov-Sinai entropy.[1] Once this stage is concluded at so-called a-ha moments, the system jumps from an irregular search regimen to a new metastable state that is the result of feedback between all stages involving working memory.

Human creativity processes of different nature, such as poetry composition, musical improvisation, and painting, are supported by the same brain networks that cooperate during any conscious creative activity.[6] Such universality strongly supports the idea that the mathematical structure of creativity in a dynamic model has to be invariant across different classes of creativity. The content of the information patterns (engrams) specifies the kind of artistic process. It is reasonable to assume that this invariant principle is also applicable to address mental disorders with the same theoretical formalism based on metastable dynamics.

A dynamic view on psychiatric diseases results in novel perspectives to understand the origin and evolution of such disorders.[7] In this Viewpoint, we have hinted how a mathematical theory that describes the information flow phenomena of robust sequential dynamics provides mathematical images of key cognitive processes and their associated pathologies. Models built under this theory can be qualitatively compared with functional magnetic resonance imaging, electroencephalograms, and behavioral data for a better interpretation of existing experimental/clinical results and to unveil dynamic signatures of disorders that are hidden under traditional analyses. Theoretical efforts in this direction will also result in the development of highly effective experimental paradigms in psychiatric basic research, possibly including a more successful correlation between genetic, morphological, physiological, and behavioral data. Finally, we can envision that future model-driven interactive protocols will provide novel mitigation and rehabilitation procedures, including disorder-free cognitive interactions between artificial intelligence and human participants.

ARTICLE INFORMATION

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