Dynamical bridge between brain and mind

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The bridge between brain structures as computational devices and the content of mental processes hinges on the solution of several problems: (i) inference of the cognitive brain networks from neurophysiological and imaging data; (ii) inference of cognitive mind networks – interactions between mental processes such as attention and working memory – based on cognitive and behavioral experiments; and (iii) the discovery of general dynamical principles for cognition based on dynamical models. In this opinion article, we focus on the third problem and discuss how it provides the bridge between the solutions to the first two problems. We consider the possibility of creating low-dimensional dynamical models from multidimensional spatiotemporal data and its application to robust sequential cognitive processes in the context of finite processing capacity of the mind.

Nonlinear dynamics in cognition

Experimental neuroscience and cognitive science are currently based on the premise that neural mechanisms underlying human perception, emotion, and cognition are well approximated by activity measurements of specific neuronal groups or brain centers. However, recent brain imaging and neurophysiological data indicate that cognition is neither a property of a single brain center nor of the entire brain [1–3]. Modern experiments have shown that cognitive functions arise from integrated processes in distributed circuits of interconnected brain areas [4,5], that is, the cooperative activity of many elements that form temporal associations for specific cognitive tasks.

Brain dynamics generates spatiotemporal patterns with a high level of coherency; we can refer to these as cognitive modes. These modes interact with each other during cognitive processing. The number of interacting modes that represent the activity of large-scale functional brain networks at a given time is usually not very high. Thus, the number of corresponding variables to model these cooperative cognitive modes and describe the performance of task-dependent cognitive functions is much smaller than the number of basic network elements. This means that the dynamics of these variables can be investigated in the framework of low-dimensional models, whose logic is illustrated in Figure 1. As suggested by existing work, breaking out low-dimensional network dynamics in conjunction with a flexible dynamical model that includes environmental and intrinsic variables is needed to effectively predict behavior.

Diverse and complex dynamics can emerge from excitatory and inhibitory connections between these cognitive modes (see Glossary). The level of mode excitation is usually stabilized by inhibition. In general, excitation is responsible for bringing information to active modes, and inhibition is responsible for their competitive interaction [6]. Because of such interaction, the thinking brain demonstrates very rich temporal activity. The robust performance of task-dependent cognitive functions can be viewed as a dynamical process that happens through a sequence of transient states. Such states are important elements of cognitive processes and are associated with the temporal clusterization of brain centers that execute a specific cognitive task. In cognitive science, these temporal clusters can be named as dynamical modes and the corresponding transient states are named as metastable states [7,8]. Sequential transient states have two main features: they are resistant to noise and, at the same time, they are input-specific and convey information about what caused them. Thus, such dynamical processes are stable and reproducible, that is, robust.

The intuitive understanding that human cognition is a transient dynamical process was articulated more than a century ago in 1890 by William James: 'Thought is in constant change ... no state once gone can recur and be identical with what it was before' [9]. In other words, we move continuously from one relatively stable thought to another. Following James, many scientists have emphasized the crucial role of itinerant brain activity in human cognition [10]. Recently, the traditional perspective of temporal patterns of thought that are based on the characterization of reproducible rhythmic activity is giving way to one that tries to understand observable neural phenomena as robust transient mind dynamics [11–15] (Figure 2).

fMRI data and sequential mental processes

fMRI brain imaging data are collected in 3D pixels (voxels) over a time dimension. The time series for these voxels are

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Glossary

Attractor: attractors are the regions of the phase space of a dynamical system (see below) towards which trajectories tend to evolve as time passes. As long as parameters are unchanged, if the system passes close enough to the attractor, that is, in the basin of attraction, it will never leave that region. Two examples of attractors are: (i) a stable fixed point and (ii) a stable periodic orbit (limit cycle) that, in particular, represents oscillatory activity of neurons in tonic spiking regime.
Binding: the process of combining informational items from different sources into one unified block or chunk.
Brain hubs: brain networks that transiently shift their functional connectivity patterns to implement control across a variety of cognitive tasks.
Chunking: the reduction of hierarchical complexity through the subgrouping of similar proximal pieces of information into singular units to allow further processing.
Cognitive mode: temporary stable activity pattern of correlated elements in a cognitive network. Because of the high level of intrinsic coherency, the dynamics of complex cognitive modes can be described with a small number of variables in a model. This number depends on the hierarchical structure of the cognitive process.
Cognitive network: task-dependent distributed brain network that participates in the performance of a specific cognitive function.
Dissipative dynamical system: if a system is closed, it does not exchange flows of energy, mass, information, etc. with the environment, and the intrinsic volume of the flow is preserved in the phase space. A system with internal friction, inhibition, or radiation is called a dissipative system. In such open systems, the volume of the flow contracts in the phase space. When time goes to infinity, the activity of this system can be represented by attractor dynamics. Dynamical models of cognition are exclusively dissipative systems.
Dynamical system (model): a mathematical description of how a point in a representative space (e.g., phase space) depends on time. The evolution of this system in time corresponds to a unique trajectory that is determined by initial conditions.
Fixed point in phase space: represents an equilibrium state of the modeled system. Such equilibrium can be stable, for example, a gymnast hanging head-up from a gymnastics horizontal bar, unstable, for example, a gymnast head-down griping over the bar, and metastable, for example, the ball in the saddle landscape of Figure 4A.
Generalized Lotka–Volterra (GLV) model: a mathematical framework for a dissipative dynamical system that can describe species' competition in ecology, chemical reactions, and economic and neural processes.
Hidden Markov model: a model that describes the temporal evolution of a system with a finite set of states with random variables. Transitions among these states are governed by a set of probabilities. In these types of models, the state is only partially observable (hidden) and, in particular, can be used to characterize the sequential activity of fMRI spatiotemporal patterns.
Metastability: in a metastable state, dynamical system variables reach and temporarily hold stationary values. It is characterized by slowing down the system motion in the vicinity of the stationary state. On the time series, this phenomenon is represented by a plateau or pause. The image of a metastable state in the phase space is a saddle point and its neighborhood (Figure 4A–C).
Phase space of a dynamical system: a space in which all possible states of the system are represented. Each possible state of the system corresponds to one point in the phase space and close points in the phase space represent close system states. The system evolving over time forms a phase space trajectory. As a whole, the phase portrait represents all behaviors that the system can demonstrate.
Robust transients: trajectories in a phase space of a dynamical model that are disposed in the vicinity of each other when initial conditions are varied. These trajectories are robust against noise. Examples of such transients are the trajectories inside the stable heteroclinic channel.
Saddle point: a stationary fixed point characterized by the coexistence of two types of trajectories in its neighborhood – one set of trajectories is going in, and the other set corresponds to trajectories going out. Those trajectories that intersect with fixed points are named stable and unstable separatrices (Figure 4A–C).
Stable heteroclinic channel (SHC): a transient attractor formed by a sequence of saddle states and their vicinity. If the compressing of the phase volume around the SHC is stronger than the stretching of the volume along the SHC, the trajectories that are attracted by the SHC cannot leave it. SHC denotes the image of robust transient behavior in a dynamical system.
Winnerless competition (WLC): a general dynamical phenomenon that denotes sequential switching of prevalence among participants. For example, if in a head-to-head competition, boxer A beats boxer B, boxer B beats boxer C, and finally boxer C beats boxer A, all participants are 'winners' for a finite time, but there is no overall winner such as in 'winner takes all'.

associated with either an external stimulus (using a correlation approach) [16–18] or an internal stimulus [19,20]. These approaches attempt to determine meaningful data-derived signals. Until recently, much of the analysis on these matrixes has treated the voxel in isolation and time has only had limited utility. Recent developments have attempted to infer more information from spatial [21,22] and temporal [23–25] patterns.

The role of time during information processing in the brain is fundamental for all aspects of mental activity – perception, motor programming, cognition, and emotion [26]. In fact, brain dynamics can be considered as task-dependent sequential activations of metastable states, that is, states where system variables reach and temporarily hold stationary values [27–31]. Learning and generating ordered sequences of metastable states can be considered a core component of cognition. This view is supported by novel results in brain imaging, multielectrode recordings, and modeling experiments [15,22,32,33] (Figure 3). The sequential low-frequency competition between different modes in default-mode brain networks was initially identified based on fMRI analyses [32] (Figure 2A). The application of the concepts related to robust transient dynamics to the analyses of perception, working memory, learning, behavior, speech production, and other types of mind activities has demonstrated its effectiveness and broad scope [8]. Two key events have advanced the application of dynamical systems approach to neuroscience: (i) experiments suggesting that macroscopic phenomena in the brain are sequential and represent transient interactions of mental modes (i.e., patterns of activity) [8,25,34,35]; and (ii) research in genetics, ecology, brain, and other sciences have led to the discovery of reproducible and robust transients that are at the same time sensitive to informational signals [15,36,37].

The performance of most cognitive and behavioral tasks needs the sequential participation of several specialized brain networks (e.g., Figure 2B). The switching from one network activity to the next is controlled by intrinsic goals, or external information [38,39]. A well-known example of such switching is the competition between the default-mode network – which is thought to support internally oriented processing – and external attention or salience networks that mediate attention to exogenous stimuli [40]. These networks show anticorrelated activity across a range of experimental paradigms. Based on fMRI experiments, control networks such as the frontoparietal brain network (FPN) would involve variable connectivity across networks and across tasks [38], acting as a 'flexible hub mechanism'. The sequential interaction between the FPN and specialized brain networks is a basis for the performance of complex task-dependent cognitive processes. The next step for the interpretation of these dynamics is to infer the meaning behind the sequential switching among networks. It is through meaningful shifts between these metastabilities that brain networks can organize to represent a multitude of cognitive functions.

To understand and predict the temporal characteristics of sequential cognitive processes, such as temporal overlapping of different functional networks activity, coordination, and stability against noise, it is necessary to build a general model that also incorporates the description of