Neurocognitive networks

Steven L Bressler, Center for Complex Systems & Brain Sciences, Florida Atlantic University, Boca Raton, Florida

Introduction

Neurocognitive networks are large-scale systems of distributed and interconnected neuronal populations in the central nervous system organized to perform cognitive functions (Bressler and Menon, 2010).

The modern understanding of neurocognitive networks gradually emerged over the past two centuries as a resolution of the longstanding antagonism between two opposing views in neuropsychology. The first, localizationism, holds that complex cognitive functions are localized to specific brain regions, whereas the second, globalism, posits that they are global functions of the brain. Localizationist theory can be traced at least as far back as Gall’s doctrine of phrenology, which was based on faculty psychology, whereas the origins of globalism were at least as early, as evidenced by the work of Flourens (Young, 1990). The reconciliation of these views began with Wernicke’s (1874/1977) idea that complex functions of cognition are properties of distributed systems of linked brain regions, and are composed of elementary functions expressed by the individual regions. Building on this theme, Luria (1962/1977) offered a redefinition of functional localization in terms of networks “of complex dynamic structures” in the nervous system that are “united in a common task”. This line of thinking has led to the modern conception of cognitive function as resulting from integrated processes in distributed networks, the nodes of which are interconnected brain areas (Goldman-Rakic, 1988). From this perspective, cognition is viewed as a higher-order function that emerges from the dynamic interactions of distributed network nodes (Mountcastle, 1998). Fuster (2003) has observed that a paradigm shift to this network view of cognition is currently underway in cognitive neuroscience.

The science of neurocognitive networks today spans several disciplines, including cognitive psychology (Posner and Rothbart, 2007), behavioral neuroanatomy (Goldman-Rakic, 1988; Mesulam, 1990; Catani et al., 2005), functional neuroimaging (Bullmore et al., 1996; Just et al., 1999; McIntosh 2000), neurophysiology (von Stein and Sarnthein, 2000; Varela et al., 2001; Buzsaki and Draguhn, 2004), computational modeling (Corchs and Deco, 2002;
Chadderdon and Sporns, 2006; Gisiger and Kerszberg, 2006), and graph theory (Sporns et al., 2002; De Vico Fallani et al., 2007). Although the field is guided by a number of fundamental assumptions, such as the common belief that networks of the cerebral cortex are central to cognition, development of a comprehensive theory of neurocognitive networks has been hindered by sharp divisions along methodological lines between various definitions of what constitutes a neurocognitive network. Nonetheless, some general principles may be described, starting with the tripartite approach to neurocognitive network organization in terms of structure, function and dynamics (Arbib et al., 1998). In brief, structure refers to the component neural elements and synaptic connectivity patterns of networks, function refers to the behavioral and cognitive aspects of network operations, and dynamics refers to the mechanisms underlying the expression of those network operations in real time. These three aspects of neurocognitive networks are treated in more detail in the following sections of this article.

Before dealing with more specific features of neurocognitive networks, it is useful to consider that neurocognitive networks are organized over a wide range of time scales (Fuster, 2003; Bressler and Tognoli, 2006; Honey et al., 2007). On the phylogenetic time scale, the large-scale anatomical connectivity of the brain, unique to each species, provides a structural framework within which neurocognitive operations may take place. On the ontogenetic time scale, developmental and experience-related factors modify the brain’s basic anatomical connectivity to construct an experience-dependent structure, unique to each individual of a species, that establishes a knowledge base for neurocognitive operations. On a time scale of seconds to hours, short-term modulatory influences alter the functional states of brain areas to create motivational, affective, and cognitive contexts for neurocognitive operations. Finally, dynamic mechanisms that activate and link neuronal populations are necessary to instantiate neurocognitive operations on a sub-second time scale.

Beyond these general aspects of neurocognitive networks, further principles may be enumerated. First, cognitive function is supported by operations of cortical networks that are organized both at a local scale within areas and at a large scale extending across the cerebral hemispheres (Bressler, 1995). Second, cognitive function depends on changes in both local and large-scale cortical structure as it undergoes development over the lifespan wrought by genetically-driven processes and by experience. Third, memory is represented in cortical networks and is accessed in cognitive function by cortical network operations (Cortical memory; Fuster, 2006). Fourth, cortical network operations are controlled and modulated by subcortical structures (Bressler, 1995; Mesulam, 1998; Houk, 2005). Fifth,
neurocognitive network operations are labile, and neuronal populations across the cortex are linked in different operational configurations at different times depending on the task at hand. Finally, the local expression of knowledge in one cortical area is dependent on a neural context (Phillips, 2001; Bressler and McIntosh, 2007) created by its reentrant interactions with other areas (Tononi et al., 1992; Bressler, 2004).

Network structure

Neuroanatomical contributions to the study of neurocognitive networks define brain areas that serve as network nodes and identify their specialized patterns of interconnection (Jirsa and McIntosh, 2007). The connectivity between areas of the cerebral cortex is considered particularly critical to neurocognitive network organization. Many studies have identified cortical areas subserving complex cognitive functions, and detailed their interconnectivity patterns (Goldman-Rakic, 1988; Morecraft et al., 1993; Scannell et al., 1995; Carmichael and Price, 1996; Scannell et al., 1999; Burns and Young, 2000; Catani et al., 2005). Anatomical networks of interconnected cortical areas, having specific patterns of interconnectivity, are thought to provide a critical structural basis for cognitive function. In fact, the structural connectivity of neurocognitive networks may have evolved to provide complex brains with the ability for efficient generation of a large repertoire of functional states (Sporns and Kotter, 2004). Detailed analysis of corticocortical connectivity (Felleman and Van Essen, 1990; Hilgetag et al., 1996) has shown basic patterns of network organization such as hierarchical and heterarchical arrangement. Structural connectivity information is being usefully catalogued in databases such as The Brain Architecture Management System (http://brancusi.usc.edu/bkms/) and Collations of Connectivity data on the Macaque brain (http://cocomac.org/) (Stephan et al., 2001).

Hierarchy in cortical connectivity refers to an arrangement of areas with a progressive connection distance from the sensory or motor periphery, and has long been described as a feature of unimodal sensory and motor systems in the primate neocortex. Hierarchal organization in the cortex is defined anatomically by the assignment of hierarchical levels to cortical areas based on the laminar patterning of their pathway origins and terminations (Felleman and Van Essen, 1990; Hilgetag et al., 1996). Functionally, hierarchical connectivity may support a progressive abstraction in the analysis of sensory inputs, or in the elaboration of motor commands, at progressively higher levels. However, it must be emphasized that hierarchical connectivity does not imply that processing is strictly sequential and unidirectional from primary to higher sensory areas (Hegde and Felleman,
2007), or from higher to primary motor areas (Kalaska and Crammond, 1992). Where hierarchies have been described, as in the primate visual cortex, the hierarchical organization encompasses projections that are ascending, descending, and lateral (Felleman and Van Essen, 1990), meaning that complex interactions, including feedforward, feedback, and parallel flow, are supported. This complexity is evidenced by observations that visual stimuli cause near simultaneous activation in widespread cortical areas (Ledberg et al., 2007), and at different levels of simulated hierarchical cortical networks (Petroni et al., 2001) Finally, hierarchy may be atypical of cortical connectivity in general. Not only does hierarchical organization give way to heterarchical organization (i.e., having equivalent “horizontal” position) in transmodal areas of the primate neocortex (Goldman-Rakic, 1988; Mesulam, 1998), but hierarchy may not describe the organization of sensory cortex in all mammals (Sherman, 1985).

The observed patterns of interareal connectivity in the primate neocortex suggest that a large proportion of cortical areas are reciprocally connected, meaning that any given area most likely receives synaptic inputs from the same areas to which it projects. Furthermore, statistical analysis has shown that each cortical area has a unique pattern of reciprocal connectivity with other cortical areas (Passingham et al., 2002). This observation suggests that the specific function of each cortical area depends on the areas to which it is connected, a conclusion supported by evidence that areas can lose their functional ability as a result of damage to connected areas (Bressler and Tognoli, 2006). Thus, the function of cortical areas is best viewed within the context of the functions of other areas with which they are reciprocally connected (Bressler, 2002), and cognitive functions, in general, may derive from complexes of reciprocally connected cortical areas.

Studies using sophisticated analytic techniques have revealed more detailed connectional properties of cortical networks (Stephan et al., 2000; Hilgetag and Kaiser, 2004; Sporns and Honey, 2006). It has been demonstrated that the cortex consists of multiply segregated networks having a high degree of correspondence with the known sensory and motor systems (Hilgetag et al., 2000). Furthermore, cortical connectivity has been shown to have a small-world structure, defined by the combination of a high degree of local clustering and a small number of long-distance paths. Small-world structure may represent an evolutionary optimization that balances competing pressures for minimization of linkage times between nearby and distant areas, and minimization of the total volume of fiber tracts (Kaiser and Hilgetag, 2006). The future discovery of new structural aspects of network connectivity in the brain can be expected to further advance our understanding of network function (Sporns and Kotter, 2004).
Networks of the cerebral cortex are embedded in more widely distributed networks in the brain that provide reciprocal connections between many cortical areas and subcortical structures. Neurocognitive network organization thereby subsumes subcortico-cortical as well as cortico-cortical connectivity. The most important connectivity of the cortex is with the thalamus: thalamic nuclei not only relay sensory input to the cortex, but provide many critical regulatory and control functions (Jones, 2001; Steriade, 2001; Sherman and Guillery, 2002; Kaas and Lyon, 2007). Neurocognitive networks also involve connectivity of the cortex with multiple other subcortical systems, including the basal ganglia and cerebellum in the preparation for and control of action (Houk and Wise, 1995; Morishima and Kawaguchi, 2006), and the hippocampus and amygdala in limbic functions (Eichenbaum 2000; Maguire et al., 2000; Ghashghaei et al., 2007).

**Network function**

It is well established that modified synaptic connectivity subserves the long-term memory of individual members of a species. The modified synaptic connectivity of large-scale cortical networks has long been thought to represent an integral component of long-term memory (Hebb, 1949; Hayek, 1952; Fuster, 1997), implying that the long-term knowledge structure of an individual is built upon the scaffolding of cortical interareal connectivity. The storage of relations between items of knowledge is thought to occur as strengthened connections among collections of cortical areas, including high-level executive areas, whose activity is coordinated during perception and action (Mesulam, 1998; Fuster, 2006; Fuster and Bressler, 2012). High-level executive areas may direct the recall of knowledge by re-coordination of the same collections of areas that are coordinated in perception and action (Damasio, 1989; Tranel et al., 1997). Executive areas may also control the coordination of sensory and motor processing areas in other cognitive functions such as selective attention (Corbetta and Shulman, 2002), working memory maintenance (Newman et al., 2002), and episodic memory retrieval (Nyberg et al., 2000). Executive control may be exerted by way of top-down bias signals that promote interactions between specific sensory and motor processing areas (Miller and Cohen, 2001).

Critical to an understanding of neurocognitive network function is the interplay of interconnected executive cortical areas that control cognitive function. Multiple high-level control areas are thought to interact while controlling the spatial and temporal dynamics of such functions as selective attention, working memory, and language processing (Mesulam, 1990; Posner and Rothbart, 2007; Just and Varma, 2007). The same executive control
networks may perform a similar role in each of these seemingly different cognitive functions (Miller and Cohen, 2001). In the case of attention, a core network of distributed executive areas in the posterior parietal, prefrontal, and cingulate cortices may be responsible for many aspects of attentional control (Morecraft et al., 1993). Alternatively, multiple interacting attentional control networks may each be responsible for a different component of attentional control (Fan et al., 2005).

It is clear that a complete theory of neurocognitive networks should describe interactions among high-level executive control areas, among low-level sensory and motor areas, and between high-level and low-level areas. Many technical hurdles remain to be overcome before such a complete theory can be realized. Whereas it will ultimately be necessary to characterize networks by the dynamics of their coordination, most evidence on neurocognitive networks currently comes from neuroimaging methods that do not have sufficient temporal scale to capture those dynamics. Promising directions for future development include studies that characterize the spatiotemporal dynamics of synchronized oscillatory networks using anatomically constrained MEG or EEG source estimates (Gross et al., 2001; Bressler et al., 2006; Jerbi et al., 2007; Fan et al., 2007).

Network dynamics

Neurocognitive networks are composed of neuronal populations that operate and interact according to dynamic principles (Freeman, 2000; Grossberg, 2000; Nunez 2000). The prevalence of bidirectional connectivity between network populations suggests that a basic mechanism subserving neurocognitive network function is reentry at the level of cortical areas, whereby populations distributed throughout the cerebral cortex cooperatively process information using recurrent transmissions (Tononi et al., 1992; Friston, 2005). The activity in a population is governed by the dynamics of its internal interactions and by the time-varying inputs that it receives from multiple other populations with which it is interconnected. As stated by von Bonin and Bailey (1947), “Clearly what [a cortical] area does depends on its extrinsic connections, both with other areas and with subcortical structures, while how an area does it, depends on its intrinsic structure.” The output of a population is broadcast to other populations, including the same populations from which it receives inputs. As a consequence of these dynamic interactions, the activities in multiple interconnected areas of neurocognitive networks are partially integrated because they are interconnected, but are also partially segregated by virtue of their unique internal dynamics (Tononi et al., 1994; Bressler, 1995; Sporns et al., 2000). From a computational viewpoint,
this implies that brain areas cooperate in carrying out neurocognitive network function, but may also compete for inclusion in those networks and for the performance of different network operations (Duncan et al., 1997; Deco and Rolls, 2005).

Networks of anatomically interconnected neuronal populations must have their activity temporally and spatially coordinated in order to function as a neurocognitive network. It has been proposed that such coordination comes about in neurocognitive networks because they operate in a dynamic regime that balances counteracting tendencies toward integration and segregation (Bressler and Kelso, 2001). Thus the coordination dynamics of neurocognitive networks determines the configuration of areas that become dynamically linked in the execution of a particular cognitive operation, as well as the evolution of those dynamic configurations over time during performance of a cognitive task.

The dynamic coordination of neurocognitive networks implies the need for a linking mechanism (Mountcastle, 1998). Neurophysiological studies suggest that the transient linkage of brain areas in neurocognitive networks occurs by the large-scale synchronization of oscillatory neuronal population activity (Bressler et al., 1993; Varela et al., 2001; Buzsaki and Draguhn, 2004). Computational analysis has demonstrated that simulated systems of synchronized oscillatory processing nodes, organized on neurocognitive network principles, can produce meaningful complex behaviors (Bibbig et al., 2002; Bassett et al., 2006; Eytan and Marom, 2006). An important ongoing area of investigation concerns the functional roles of different oscillatory frequencies (von Stein and Sarnthein, 2000; Fan et al., 2007; Honey et al., 2007).

Network pathology

The investigation of neurocognitive networks is providing valuable insights into cognitive impairments such as those resulting from attention deficit disorder (Berger and Posner, 2000), autism (Murias et al., 2007), Parkinson’s disease (Timmermann et al., 2003), Alzheimer’s disease (Stam et al., 2007), schizophrenia (Haig et al., 2000; Ford et al., 2002; Phillips and Silverstein, 2003), and normal aging (Andrews-Hanna et al., 2007). Mounting evidence points to disorders of neurocognitive network coordination as a root cause in many cognitive impairments (Bressler, 2003; Schnitzler and Gross, 2005; Uhlhaas and Singer, 2006). Continued investigation into the structure, dynamics and function of neurocognitive networks is likely to shed further light on these disorders and others, leading to improved prognosis and treatment across a spectrum of neurological and neuropsychiatric
References


Internal references


**Recommended reading**


**External links**

- Steven L. Bressler's website (http://www.ccs.fau.edu/~bressler/)

**See also**
Binding by Synchrony, Cognition, Coordination Dynamics, Fast Oscillations, Modular Models of Brain Function, Neuroimaging, Small-World Network

Sponsored by: Eugene M. Izhikevich, Editor-in-Chief of Scholarpedia, the peer-reviewed open-access encyclopedia


Reviewed by (http://www.scholarpedia.org/w/index.php?title=Neurocognitive_networks&oldid=32256) : Claus C. Hilgetag, Jacobs University, Bremen, Germany


Categories: Network Dynamics | Neuroscience | Computational Neuroscience | Cognitive Neuroscience
This page was last modified on 24 July 2012, at 00:13.

This page has been accessed 14,927 times.

Served in 0.938 secs.

"Neurocognitive networks" by Steven L Bressle is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 3.0 Unported License. Permissions beyond the scope of this license are described in the Terms of Use.