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Effects of lesions on synchrony and metastability in cortical networks

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ABSTRACT

At the macroscopic scale, the human brain can be described as a complex network of white matter tracts integrating grey matter assemblies — the human connectome. The structure of the connectome, which is often described using graph theoretic approaches, can be used to model macroscopic brain function at low computational cost. Here, we use the Kuramoto model of coupled oscillators with time-delays, calibrated with respect to empirical functional MRI data, to study the relation between the structure of the connectome and two aspects of functional brain dynamics — synchrony, a measure of general coherence, and metastability, a measure of dynamical flexibility. Specifically, we investigate the relationship between the local structure of the connectome, quantified using graph theory, and the synchrony and metastability of the model's dynamics. By removing individual nodes and all of their connections from the model, we study the effect of lesions on both global and local dynamics. Of the nine nodal graph-theoretical properties tested, two were able to predict effects of node lesion on the global dynamics. The removal of nodes with high eigenvector centrality leads to decreases in global synchrony and increases in global metastability, as does the removal of hub nodes joining topologically segregated network modules. At the level of local dynamics in the neighbourhood of the lesioned node, structural properties of the lesioned nodes hold more predictive power, as five nodal graph theoretical measures are related to changes in local dynamics following node lesions. We discuss these results in the context of empirical studies of stroke and functional brain dynamics.

Introduction

The ensemble of macroscopic white matter brain connections can be described as a complex network, the structural connectome, consisting of nodes corresponding to grey matter assemblies and edges, or connections, corresponding to structural white matter pathways between them (Hagmann, 2005; Sporns et al., 2005). Besides enabling a holistic characterization of the brain's architecture, the structural connectome, combined with a suitable model, enables the simulation of whole-brain dynamics at low computational cost (Honey et al., 2009). Simulated time-courses can then be compared to empirical functional data (Honey et al., 2009; Cabral et al., 2011; Deco et al., 2013) or analyzed using mathematical tools from dynamical systems theory, to quantify properties such as entropy or synchrony of the simulated neural activity (Honey and Sporns, 2008; Shanahan, 2010).

A notable application of such tools concerns the stability of brain dynamics. Within the brain, communication between neural ensembles is hypothesized to occur through coherence, whereby two neural assemblies whose activity fluctuates in synchrony can exchange information (Fries, 2005). However, a consistently coherent, stable state would be pathological. Thus, for efficient, flexible communication, variability of coherence is equally important. Accordingly, the healthy brain exhibits features of *multistability*, comprising multiple stable states but requiring external input to shift between them (Friston, 2001; Ashwin et al., 2007; Freyer et al., 2011, 2012) as well as *metastability*, spontaneously shifting between transient attractor-like states (Kelso, 2012; Shanahan, 2010; Tognoli and Kelso, 2014).

The notion of metastability is highly relevant to brain activity, which even in the so-called "resting-state" is a dynamic process. The brain in the absence of a specific task, alternating between temporarily stable states, has been compared to a tennis player, hopping on their two feet in preparation to hit the ball regardless of its incident direction (Deco et al., 2009). Besides providing a fast response to any stimulus, resting-state dynamics have been hypothesized to consolidate past events and stabilize neural ensembles (Buckner and Vincent, 2007). Whilst the relevance of metastable processes to cognition is beginning to be directly addressed (Deco et al., 2013; Hellyer et al., 2014), and a

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