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Dynamic functional connectivity and brain metastability during altered states of consciousness

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ABSTRACT

The scientific study of human consciousness has greatly benefited from the development of non-invasive brain imaging methods. The quest to identify the neural correlates of consciousness combined psychophysical experimentation with neuroimaging tools such as functional magnetic resonance imaging (fMRI) to map the changes in neural activity associated with conscious vs. unconscious percepts. Different neuroimaging methods have also been applied to characterize spontaneous brain activity fluctuations during altered states of consciousness, and to develop quantitative metrics for the level of consciousness. Most of these studies, however, have not explored the dynamic nature of the whole-brain imaging data provided by fMRI. A series of empirical and computational studies strongly suggests that the temporal fluctuations observed in this data present a non-trivial structure, and that this structure is compatible with the exploration of a discrete repertoire of states. In this review we focus on how dynamic neuroimaging can be used to address theoretical accounts of consciousness based on the hypothesis of a dynamic core, i.e. a constantly evolving and transiently stable set of coordinated neurons that constitute an integrated and differentiated physical substrate for each conscious experience. We review work exploring the possibility that metastability in brain dynamics leads to a repertoire of dynamic core states, and discuss how it might be modified during altered states of consciousness. This discussion prompts us to review neuroimaging studies aimed to map the dynamic exploration of the repertoire of states as a function of consciousness. Complementary studies of the dynamic core hypothesis using perturbative methods are also discussed. Finally, we propose that a link between metastability in brain dynamics and the level of consciousness could pave the way towards a mechanistic understanding of altered states of consciousness using tools from dynamical systems theory and statistical physics.

Introduction

The character, variety and intensity of the conscious content that constitutes our everyday experience represent some of the most puzzling questions faced by modern neuroscience. The ubiquity of consciousness in our first-person perspective of the world challenges a definition in terms of more primitive notions (Chalmers, 1995). Operationally, conscious content can be defined as information processing in the brain that is accompanied by subjective and reportable experience; in contrast, unconscious or subliminal information processing can influence cognition and behavior without reportability (Dehaene et al., 2006). Consciousness as a temporally extended brain state can be defined as a set of conditions in the brain that are compatible with conscious content (Bayne et al., 2016). Such conditions are modified during altered states of consciousness such as deep sleep, anesthesia or in disorders of consciousness (DOC). To answer the question as to whether the state and the content of consciousness can be fully dissociated, one must first find an empirical approach to investigate them independently. This is highly challenging by the very definition of both concepts, since the state of consciousness is defined precisely based on its capacity for sustaining conscious content. Current research is being carried out on the possible divergence between these concepts (see Bayne et al., 2016 for an example), but more studies are needed to settle this issue.

The contemporary recognition of consciousness as a neurobiological phenomenon requiring scientific explanation can be traced to the fundamental articles by Bachmann (1984) and Crick and Koch (1990). These articles proposed the search of neural correlates of consciousness, understood as the minimal set of neural events associated with a certain

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