Power-Law Functional Organizations of the Brain in Wake, Anesthesia, and Vegetative State

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Introduction: The healthy human brain is a classic example of a complex, self-organizing system in wake and consciousness-reduced conditions, such as sleep and anesthesia. The theory of self-organized criticality (SOC) proposed by Bak *et al.* (1987) [1] represents an attractive model for describing human brain dynamics that operates in a critical state, determining necessary neural processes and conditions that underlie brain state transitions, and understanding comprised self-organizing capability of the brain in pathological conditions, such as the vegetative state (VS). Across the description of biological systems, from the cellular to ecosystem level, one most commonly-sought empirical signature of self-organization is the manifestation of power-law distribution regarding principal variables of a complex system [2]. To date, the power-law distribution has been identified with healthy brains in a series of neurophysiological processes measured by multi-electrode arrays (MEA), electroencephalography (EEG), and magnetoencephalography (MEG) [3], suggesting self-organized criticality as an emergent property of the brain leading to optimal information processing and performance. However, only a handful of studies have investigated the possible power-law distribution in different aspects of the brain's functional organizations using neuroimaging techniques. The reported neuroimaging studies adopted either region- or voxel-based approaches for characterizing functionally connected brain networks; however, the results have been inconsistent and inconclusive with respect to the manifestation of power-law distributions. The present study proposes a novel algorithm that determines functional partitions (FPs) of the brain by taking into account both their anatomical and functional significances. We then show its effectiveness in demonstrating robust power-law distributions in healthy brains and discuss the implications of power-law manifestations in wake, anesthesia, and VS as related to self-organization.

Methods: Imaging data were drawn from our two previous publications on functional imaging investigations of propofol sedation and VS [4, 5]. Analysis first involves obtaining an arbitrary number of FPs in a participant-specific manner, following the rationale that, at the most fundamental level, anatomical structure underlies the distribution and diversity of functional modules of the brain. Accordingly, a hierarchical clustering algorithm was performed with voxel-wise imaging time courses within each of the 116 anatomically-defined regions [6]. Next, a global threshold was applied to all the obtained dendrograms to create an arbitrary number of FPs (Fig. 1A). We then compared the power-law probability distribution of the size and the number of connections (degrees, above a threshold) of FPs based on the neuroimaging data obtained in wake, propofol sedation, and VS.

Results and Conclusions: With healthy brains, the proposed algorithm is capable of revealing anticipated power-law functional organizations of the brain in a robust manner, as the number of FPs increases for observing the brain at a greater detail, e.g., at 2000 FPs. (Fig. 1B, show degree distribution only). Moreover, healthy brains still maintained power-law distributions in deep sedation (loss of consciousness, Fig. 1C) and recovery (Fig. 1D), consistent with previous EEG findings of human brain in propofol anesthesia. It also suggests a persistent self-organizing brain functioning in anesthesia, as it is in sleep [7]. In contrast, the power-law degree distribution, which was universally observed in healthy brains, was severely distorted in patients of well-diagnosed vegetative state (Fig. 1E), in which the self-organizing capability of the brain is most certainly compromised. Together, these findings confirm the validity of the method, suggest appropriate scales at which the self-organizing processes of the brain should be observed, and reveal the maintenance or disruption of self-organization in healthy and pathological conditions of the brain.

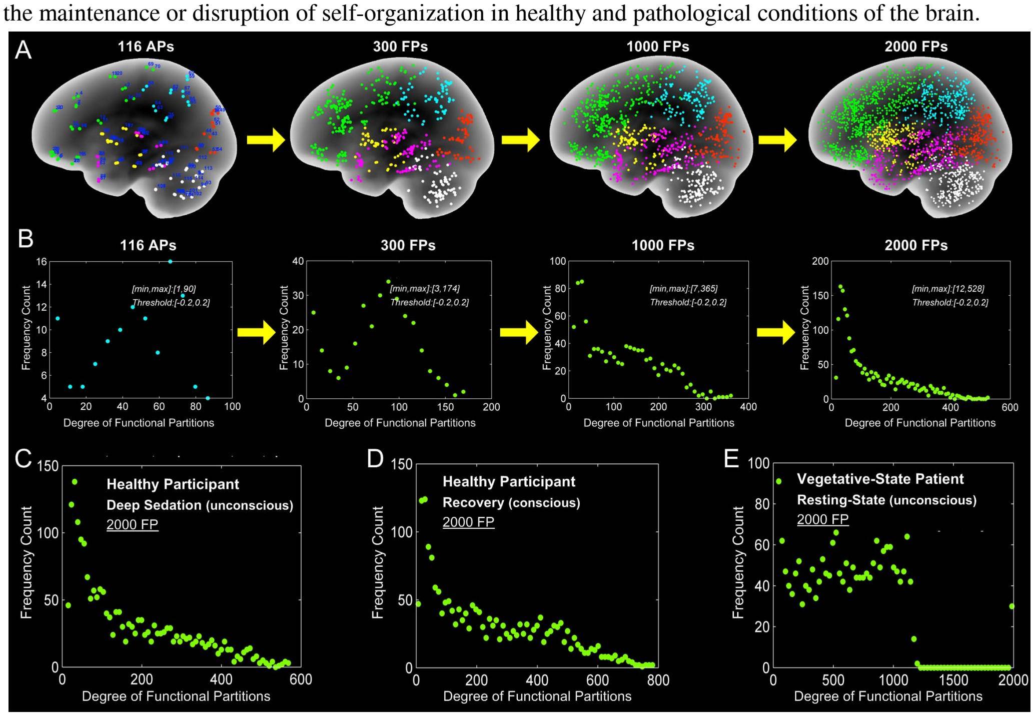

Figure 1. (*A*) Functionally partitioning the brain starts with a predefined 116 anatomical partitions (APs), and globally thresholding all dendrograms generates an arbitrary number of FPs, as illustrated for an example, from 300 to 2000 FPs. (*B*) Power-law degree distribution becomes evident and persistent with an increase of FPs with a healthy brain in wake. (*C*) Power-law degree distribution in deep sedation. (D) The same in recovery. (E) Disrupted distribution pattern in a VS patient.

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