Multiscale information flow in complex brain networks

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The study of information flow and transport in complex biological networks by means of diffusion processes has attracted increasing interest in recent years. Random walks, the process by which randomly-moving objects wander away from where they started are commonly used to describe diffusion processes. In the past decade, there has been considerable progress in characterizing first passage times, or the amount of time it takes a random walker to reach a target. However, there is no work on characterizing the temporal dynamics of the information flow in the network, which depends on how the walkers move and not just when they arrive. Moreover, we lack knowledge about how the different temporal scales in the diffusion process, arise from the topological structure of the network, whether they interact, and how they do it.

Different complex networks may have associated different temporal scales. Unfortunately, for a general system, this information is usually unknown a priori. Popular methods such as Fourier transform allows for the identification of main oscillatory features of a system but struggle with nonlinear and nonstationary signals. To extract the different temporal scales, we use empirical mode decomposition (EMD), an adaptive and data-driven method that decomposes nonlinear and nonstationary signals (the movement of the random walkers in our case) into fundamental modes of oscillations called intrinsic mode functions (IMFs) without the need for a predefined model as is the case of Fourier and wavelet transforms. In this work we study the interaction between different IMFs. Since IMFs are associated with different oscillatory modes, their interaction corresponds to the phenomenon known as cross-frequency coupling (CFC) [1]. We focus on three types of CFC: phase-amplitude coupling (PAC), the phenomenon where the instantaneous phase of a low frequency oscillation modulates the instantaneous amplitude of a higher frequency oscillation, amplitude-amplitude coupling (AAC), which measures the co-modulation of the instantaneous amplitudes of two oscillations, and phase-phase coupling (PPC), which corresponds to the synchronization between two instantaneous phases.

We start by considering a complex network consisting of *N* nodes, and we place a large number *K* ($K \gg N$) of random walkers onto this network. In each time step the walkers move randomly between the nodes that are directly linked to each other. We allow the walkers to perform *T* time steps. As a walker visits a node, we record the fraction of walkers present at it, which we term the node activity. Thus, after *T* time steps, we obtain *K* time series (of length *T*) reflecting different realizations of the flow of information in the network. These time series are then decomposed into IMFs using EMD and CFC between them is computed. We apply this methodology to real brain networks. For this, a freely available (http://neurotycho.org/anesthesia-task) continuous electro-corticographical (ECoG) recording of monkey (Macaca fuscata) was used. Details of the surgery and recording protocol have been described elsewhere [2]. Briefly, subdural ECoG data of one monkey were recorded at 1 kHz from a bipolar-referenced array covering most of the lateral cortex, during awake and anesthetized states. We extracted one minute of continuous, artifact-free data. Data were notch-filtered around 50 Hz. Connectivity matrices for the anesthetized and awake states were constructed by computing the partial correlation between ECoG time series from 64 electrodes and taking the absolute value of the results. 5000 random walkers were placed onto these networks and the time series corresponding to their movement was recorded and decomposed into 7 IMFs. PAC interactions between these IMFs show two clusters: one cluster representing interaction between the instantaneous phases of IMFs 3,4 and 5, and the faster IMFs 1, and 2; the second cluster representing interactions between the phases of the slow IMFs 5, 6 and 7 with their instantaneous amplitudes. PAC and AAC values were stronger in anesthetized states than in awake states, while PPC didn't change significantly. Our results suggest the topology of brain networks facilitates the interaction between phases and amplitudes of slow and fast components, respectively, of the flow of information.

References

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[2] Yanagawa, T., Chao, Z. C., Hasegawa, N., & Fujii, N, Large-scale information flow in conscious and unconscious states: an ECoG study in monkeys. *PloS one*, *8*(11), e80845, 2013.