Entropy Production and Functional Asymmetry in rs-fMRI Dynamics

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Many stochastic processes have a preferred time direction, which means that they evolve in time with a certain probability, and by inverting the arrow of time it becomes less probable. This time asymmetry is a hallmark of irreversible dynamics. Recently, the study of non-equilibrium dynamics has shown that the brain alters the entropy production levels depending on the conscious state or task performed. Interestingly, it suggests that the more the brain is engaged with a task, the more irreversible its dynamic is, while the opposite occurs during sleep states. In these approaches, researchers have used probabilistic models to describe Functional Magnetic Resonance Imaging (fMRI) signals whose inferred parameters are used to extract how far from equilibrium it is. However, very little is known about the sources of irreversibility in the brain. In multivariate systems, the different degrees of freedom can interact in a non-reciprocal way. As an example, a certain brain region A can have a functional interaction with another region B, such that a disturbance in A might lead to a lagged correlation in B with a certain strength, while the opposite do not happen with the same intensity. Furthermore, for high-dimensional systems, the matrix encoding this interaction between different components – here called coupling matrix – can be studied as a random matrix. This suggests that non-equilibrium dynamics in the brain might be related to an intrinsic functional asymmetry between different regions, which might be regarded to biological variability in the subjects' brain performing the same activities. As a matter of fact, recent works have shown that the level of irreversibility is intimately connected to the variance of the coupling matrix.

Due to the slow sampling rate, resting-state (rs-) fMRI data can be modeled using discrete-time stationary stochastic processes, and one difficulty in this approach is selecting an appropriate model to describe the data. Complex models tend to capture more features about the underlying dynamics, but are often hard to interpret; while simple models tend to not consider important sources of irreversibility. One possible approach is to keep track of a certain source of irreversibility and use the simplest model possible by employing a Maximum Caliber Approach (MCA) using appropriate constraints. The simplest statistical quantity that encapsulates asymmetric interactions between different brain regions lag-1 correlations.

In this work, we derive a model to describe rs-fMRI using MCA taking second momentum and lag-1 correlations as constraints. This leads us to a minimum model to studying irreversible dynamics - the Vector Autorregressive (VAR1) model - where the source of entropy production comes from the asymmetry in the coupling matrix between different stochastic components. By fitting the model in the data, we show a positive correlation between the entropy production rate and the variance of the coupling matrix, reinforcing our thesis that subjects under the same resting-state condition show variable degrees of irreversibility levels due to biological variability in the brains.