Complexity measures based on intermittent events in brain EEG data

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Abstract. In this work we discuss the application of the *complexity* approach to the study of physiological signals. In particular, a theoretical framework based on the ubiquitous emergence of fractal intermittency in complex signals is introduced. This approach is based on the ability of complex systems' cooperative micro-dynamics of triggering meta-stable self-organized states. The meta-stability is strictly connected with the emergence of a intermittent point process displaying anomalous non-Poisson statistics and driving the fast transition events between successive meta-stable states. As a consequence, the estimation of features related to intermittent events can be used to characterize the ability of the complex system to trigger self-organized structures.
We introduce an algorithm for the processing of complex signals that is based on the fractal intermittency paradigm, thus focusing on the detection and scaling analysis of intermittent events in human ElectroEncephaloGrams (EEGs). We finally discuss the application of this approach to real EEG recordings and introduce the preliminary findings.

Keywords: signal processing, complexity, fractal intermittency, brain, electroencephalogram (EEG), disorders of consciousness

1. Introduction

Human physiology is a prototypical example of complexity and the brain is surely the most important one. The brain is composed of elementary units, the neurons, that are strongly connected with many other neurons with highly nonlinear interactions, given by chemically activated electrical signals traveling along the inter-neuron links (axons and dendrites). The nonlinear dynamics at the level of single neurons (i.e., the threshold mechanism for the electrical discharges generating spikes and bursts) are highly enhanced by the complex link topology, but at the same time some kind of ordering, or self-organizing, principle triggers the formation of global cooperativity. The overall picture is that of a complex network with a huge number of nodes (the neurons) and links with a very complicated topology. It is then not surprising that brain dynamics display a very rich landscape of different behaviors and a very efficient plastic behavior, characterized by a rapid and efficient capability of response to rapid changes in the external environment. Due to this variety, the attempt of characterizing the brain functioning with a relatively low number of parameters is a very fascinating problem and a very hot topic in brain research. This topic involves different disciplines, spanning from biology and medicine to non-equilibrium statistical physics of complex systems, network analysis and information science.

2. The complexity paradigm

The *complexity* paradigm involves a modeling approach that is complementary to the *microscopic* approach based on extending the micro-dynamics of single units to the network level via properly modeled node-node interactions. Following the paradigm of *emerging properties*, the complexity approach simply focuses on the modeling of self-organized large scale structures emerging from the cooperative dynamics of the complex network. The main idea is that self-organized structures are the essential actors in the global dynamics of complex systems and play a crucial role in the response of the system to external stimuli. As a consequence, also the statistical indicators extracted from the data analysis usually refer to some global property associated with the large scale, global, dynamical evolution of coherent or self-organized structures.

2.1. Complexity and fractal intermittency

Even if a universally accepted definition of a complexity does not yet exist, complex systems often display the following features:

(1) a complex system is multi-component with a large number of degrees of freedom, i.e., many functional units or nodes. As said above, these units interact with each other and their dynamics are strongly nonlinear;
(2) non-linearity and multi-component is not enough to define complexity: the dynamics must be cooperative and trigger the emergence of self-organized structures;
(3) self-organized states display long-range space-time correlations (slow power-law decay);
(4) self-organized states are meta-stable, with relatively long life-times and fast transition events between two successive states, denoted in the following as *crucial events*.

Crucial events determine a fast memory drop, while the self-organized structures remain strongly correlated until their decay. The sequence of crucial events, marking the transition among self-organized states, is an emergent dynamics described as a a birth-death point process of self-organization. Then, the feature (4) in the above list is the basic property allowing for a description of complexity in terms of intermittent signals. Due to the fast memory drop occurring during the fast transitions, each self-organized state is often independent from each other, as such as the crucial transition events. This is denoted as *renewal condition.* In this case, the sequence of crucial events is described by a renewal point process. A very general observation is that a complex (cooperative) system is characterized by long life-times that are statistically distributed according to a inverse

power-law. The life-times correspond to the time between two successive crucial events and are also denoted as inter-event times or Waiting Times (WTs).
In this work we discuss an approach to complexity based on the modeling of time intermittency emerging by the underlying cooperative dynamics. In particular, the emergence of a renewal point process whose WT distribution is a inverse power-law: $\psi(\tau) \sim 1/\tau^{\mu}$ is denoted as *fractal intermittency* [9, 14, 15, 8, 6] The distribution $\psi(\tau)$ and the exponent μ are *emerging properties* and, thus, a signature of complex behavior. In Fig. 1 we report a synthetic scheme qualitatively explaining the connection between self-organization, cooperation and non-Poisson renewal processes. Poisson renewal processes always emerge in the case of independent systems, whatever the micro-dynamics of the single nodes. As a consequence, a departure from the Poisson statistics reveals some kind of cooperation among the nodes of the network. For power-law distributed WTs,

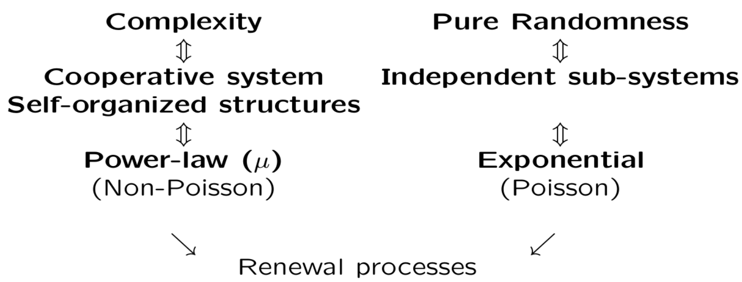

Fig. 1. Comparison of Poisson (non-complex) and non-Poisson (complex) processes.

μ is then used as an indicator of complexity, essentially being a measure of the ability of the system's dynamics to trigger global self-organized structures. In particular, complexity is identified with a condition of very slow decay in $\psi(\tau)$, corresponding to the range $\mu < 3$.
Conversely, the feature (3) is the starting point for a description of complexity in terms of spatial and topological indicators (e.g., the degree distribution of a complex network, avalanche size distribution).

3. Crucial events and fractal intermittency in the brain

Meta-stability is a basic feature of the information processing in the brain neural network. Fingelkurts and Fingelkurts recognized that rapid changes in the ElectroEncephaloGram (EEG), called Rapid Transition Processes (RTPs), mark passages between two quasi-stationary periods, each one corresponding to different neural assemblies, [1, 2] and are the signature of brain self-organization. RTPs and neural assemblies are then a prototype of crucial events and meta-stable self-organized states, respectively. The algorithm for the automatic detection of RTP events in EEG data was developed in Ref. [2] and exploited by the authors of Refs. [3–5, 7, 9, 10, 16] to characterize the complexity of the intermittent events. By exploiting a scaling detection method, the EDDiS method ([14] and references therein), these authors found that brain dynamics display fractal intermittency. In particular, it was shown that the fractal intermittency approach

is able to reveal the integrated (Rapid Eye Movement, REM) and segregated (Non-REM) stages during sleep, thus in agreement with the consciousness state of the subjects [9, 10, 16].
In the intermittency-based analysis here proposed, a key aspect is the definition of events, which needs to be further studied in order to extend the above analysis to different experimental and clinical conditions.

4. Signal processing for intermittent complex systems

The results obtained by applying the algorithms cited above and, in particular:
(i) the RTP event detection algorithm [2];
(ii) the EDDiS method for the evaluation of the diffusion scaling H, whose relationship with the index μ is known when renewal condition is positively validated [3, 6, 8, 14];
are very promising in the perspective of potential applications in the clinical activity of neurological disorders. However, RTP events are defined only for some experimental conditions.
In this work we investigate the key aspect of the event definition. We propose an algorithm involving a more general definition of event and being able to detect and discriminate events with different neuro-physiological origins. The proposed method essentially extends the technique introduced and applied in Refs. [11–13]. This method allows to extract different kind of crucial events marking the sudden increases of activity in given frequency bands. This allows to derive different definitions of events and to build a very flexible algorithm to be exploited in different experimental conditions.
We assume that the signals were already pre-processed for the artifact cleaning. Then, the software tool is divided into different modules:

(1) splitting of the single EEG channel into different frequency bands;
(2) detection of crucial events and high-activity epochs in the different frequency bands by using a thresholding method;
(3) building of a spatio-temporal map of events;
(4) extraction of some specific kind of events from the event map;
(5) estimation of the complexity of these events of interest, both for single EEG channels and for global events.

Despite its apparent simplicity, this algorithm is very flexible and powerful. Being based on the classical Fourier approach and on splitting the EEG signal into standard frequency bands, this approach allows for a more clear link between the event detection algorithm and its neuro-physiological interpretation. In this sense, a particular kind of brain events should be recognized to be a neural correlate of some increased neuro-physiological activity.

Finally, we will discuss some applications on real EEG data in different conditions (wake, sleep). Some preliminary results on subjects with disorder of consciousness will be presented.

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