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Relaxation and phase space singularities in time series of human magnetoencephalograms as indicator of photosensitive epilepsy

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Abstract

To analyze the crucial role of fluctuation and relaxation effects for the function of the human brain we studied some statistical quantifiers that support the information characteristics of neuromagnetic brain responses (magnetoencephalogram, MEG). The signals to a flickering stimulus of different color combinations have been obtained from a group of control subjects which is then contrasted with those of a patient suffering photosensitive epilepsy (PSE). We found that the existence of the specific stratification of the phase clouds and the concomitant relaxation singularities of the corresponding nonequilibrium dynamics of the chaotic behavior of the signals in separate areas in a patient provide likely indicators for the zones which are responsible for the appearance of PSE.

Keywords: Discrete non-Markov stochastic processes; Relaxation and phase space singularities; Magnetoencephalograms; Human brain; Photosensitive epilepsy

1. Introduction

The study of dynamical time series is gaining ever increasing interest and is applied and used in diversified fields of natural sciences, technology, physiology, medicine and economics [1–8], to name only a few. The majority of natural systems can be considered dynamical systems, whose evolution can be studied by time

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series related to relevant variables on a suitable time scale. These series are often characterized by a pronounced time and spatial synchronization or coherence, chaotic or robust behavior.

When analyzing time series data with linear methods, one can follow certain standard procedures. Moreover, the behavior may be described by a relatively small set of parameters. For a nonlinear time series analysis, this is not necessarily the case. While standardized algorithms exist for the analysis of the time series data with nonlinear methods, the application of these algorithms requires considerable knowledge and skills on the part of the user.

In a nonlinear time series analysis one starts out with a reconstruction of the state spaces from the observed data [8–12]. Although the embedding theorems [13] provide an important means of understanding the reconstruction procedure, likely none of them is formally applicable in practice. The reason is that they all deal with infinite, noise free trajectories of a dynamical system. It is not obvious that the theorems should be "approximately valid" if only the requirements are "approximately fulfilled", for example, if the data sequence is long, although finite and not completely noise-free.

A possible way to study the manifestation of physical properties of random processes (and the Markov random processes (MRP) in particular) in time series originates from the theory of nonequilibrium statistical physics. The history of the fundamental role of stochastic processes in physics dates back a century to the Markov representations [14] of random telegraphic signals. Such processes still find application in models of contemporary complex phenomena. A few typical examples of complex physical phenomena modeled by the Markov stochastic processes are: kinetic and relaxation processes in gases [15] and plasma [16], condensed matter physics (liquids [17], solids [18], and superconductivity [19]), astrophysics [20], nuclear physics [21], for certain quantum relaxation dynamics [22] and in classical [23] physics. At present, we can make use of a variety of statistical methods for the analysis of the Markov and the non-Markov statistical effects in diverse physical systems. Typical examples of such schemes are the Zwanzig–Mori's kinetic [24] generalized master equations and corresponding statistical quantifiers [25], the Lee's recurrence relation method [26], the generalized Langevin equation (GLE) [27], etc.

In this paper we shall study the crucial role of relaxation and kinetic singularities in brain function of healthy physiological and pathological systems for the case of photosensitive epilepsy (PSE). In particular, we seek marked differences in large space and times scales in the corresponding stochastic dynamics of discrete time series that could in principle characterize pathological (or catastrophic) violation of salutary dynamic states of the human brain. As a main result, we show here that the appearance of distinct differences in the relaxation time scales and extraordinary stratification of the phase clouds in the stochastic evolution of neuromagnetic responses of the human brain as recorded by MEG may yield evidence of pronounced zones responsible for the appearance of PSE.

2. Stratification in the phase space and stochastic processes in complex systems

The phase space plays a crucial role in determining the singularities of stochastic dynamics of the underlying system. A set of the dynamical orthogonal statistical variables describing the dynamical state of the complex system is a feature important in a proper construction of the phase space and analysis of the underlying dynamics. Let us consider an k-dimensional vector of the initial state $\mathbf{A}_k^0 = (x_1, x_2, x_3, \ldots, x_k)$ and an k-dimensional dynamic vector of the final state $\mathbf{A}_{k+m}^m = (x_{m+1}, x_{m+2}, x_{m+3}, \ldots, x_{m+k})$, where $k+m = N, k, m = N, N-1, N-2, \ldots, N/2-2, N/2-1, N/2$ and N denotes the sample length. From the discrete equation of motion

$$\frac{\Delta x_i}{\Delta t} = \frac{x_{i+1} - x_i}{t_{i+1} - t_i} = \frac{1}{\tau}\{\varDelta - 1\}x_i,$$

$$t_{i+1} - t_i = \tau, \tag{1}$$

we obtain the equation of motion of the dynamical vectors of state $\mathbf{A}_{m+k}^m$ as

$$\frac{\Delta \mathbf{A}_j^m}{\Delta t} = \mathrm{i}\widehat{L}A_j^m,$$