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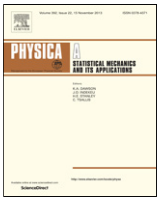

Assessment of long-range correlation in animal behavior time series: The temporal pattern of locomotor activity of Japanese quail (*Coturnix coturnix*) and mosquito larva (*Culex quinquefasciatus*)

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HIGHLIGHTS

- Fractal analysis resulted successful at characterizing temporal patterns of quail and mosquito larvae locomotion.
- Detrended Fluctuation Analysis found trends in quail time series data.
- Larvae presented crossovers in fluctuation function.
- Confidence intervals calculated for the estimation of autosimilarity parameter asserted the quality of results obtained.
- Effects of test duration on parameter estimation were observed.

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ABSTRACT

Detrended Fluctuation Analysis (DFA) is a method that has been frequently used to determine the presence of long-range correlations in human and animal behaviors. However, according to previous authors using statistical model systems, in order to correctly use DFA different aspects should be taken into account such as: (1) the establishment by hypothesis testing of the absence of short term correlation, (2) an accurate estimation of a straight line in the log–log plot of the fluctuation function, (3) the elimination of artificial crossovers in the fluctuation function, and (4) the length of the time series. Taking into consideration these factors, herein we evaluated the presence of long-range correlation in the temporal pattern of locomotor activity of Japanese quail (*Coturnix coturnix*) and mosquito larva (*Culex quinquefasciatus*). In our study, modeling the data with the general autoregressive integrated moving average (ARFIMA) model, we rejected the hypothesis of short-range correlations ($d = 0$) in all cases. We also observed that DFA was able to distinguish between

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the artificial crossover observed in the temporal pattern of locomotion of Japanese quail and the crossovers in the correlation behavior observed in mosquito larvae locomotion. Although the test duration can slightly influence the parameter estimation, no qualitative differences were observed between different test durations.

1. Introduction

Fractal analysis, such as Detrended Fluctuation Analysis (DFA), has successfully been applied in biology to diverse fields of interest including DNA [1], heart rate dynamics [2–4], neuronal discharges [5], human gait [2,6–8], and animal behavior [9–18]. In particular, fractal analysis has been used to evaluate the temporal dynamics of animal behavior in a wide variety of situations and species, ranging from the swimming patterns of Copepoda [19] and surface behavioral patterns of dolphins [13] to social behavior of chimpanzees [9] and even human walking patterns [2,6–8]. Various animal behaviors have been shown to present long-range correlations (i.e. for large time lags, the autocorrelation function of such long-memory processes decays according to a power-law and hence exhibits scaling with a characteristic scaling exponent [20]; see below). In this context, DFA has emerged as an effective tool to measure the temporal organizational complexity of animal behavior [12,16], mainly because it could be applied to non-stationary time series and it is able to eliminate trends in data. For example, DFA has been found useful to detect subtle changes in behavioral patterns due to sublethal doses of a toxic compound [15], or stressful events [12,16,17,21] that could go undetected by conventional behavioral analyses which are often limited to measures of the mean duration or frequency of particular behaviors [12].

Although DFA is used to evaluate temporal patterns of animal behavior, there are some important considerations that must be taken into account for the correct interpretation of results. It is crucial to understand the intrinsic dynamics of the system under study when applying DFA. First, it should be considered that one of the common challenges is the existence of crossovers in the fluctuation function (i.e., a change in the value of α for different ranges of scales) [5,22]. A crossover may arise from actual changes in the correlation properties of the signal at different time scales (i.e., two levels of complexity), or from trends (a smooth and monotonic or slowly oscillating pattern caused by external effects) that were not correctly eliminated by the DFA [23,24]. The existence of trends in time series generated by biological systems is very common and almost unavoidable. Thus, efforts should be made to systematically study the trends in time series data (for complete review see Refs. [23,24]). However, most of the biological studies that use DFA do not appear to consider the presence of trends of orders higher than one in their time series.

Second, Maraun et al. (2004) [20] proposed that when using DFA, long-memory should not be assumed a priori but must be established. To reliably infer power-law scaling of the fluctuation function, a straight line in the log–log plot has to be established. This requires the investigation of the local slopes [20]. However, finite datasets bring along natural variability. To decide if a fluctuating estimation of the slope should be considered as being constant, empirical confidence intervals must be calculated for a long-range and a simple short-range correlated model [20]. To the authors' knowledge, this has never been applied to animal behavior time series.

Third, the duration of the test and sampling frequency are of vital importance in animal behavioral studies. Many animal behavioral studies last only five or ten minutes. Longer durations are not always possible because behavioral pattern and experimental conditions can change through time. For example, behavioral studies often focus on studying animals in novel, stressful environments where the animal can adapt over time, or they evaluate response to a drug or toxin which metabolizes in the organism resulting in the blood concentration of the substance changing over time. In addition, animal behavior is subject to circadian rhythms, and exhaustion if forced to perform a certain behavior over a prolonged period of time. The sampling frequency of the behavior also has limitations. In the case of evaluating locomotor activity, the sampling interval cannot be shorter than the time it takes the animal to take a step. Hence, there are empirical limitations on the number of data points a behavioral time series can have. Studies that use DFA to evaluate changes in the correlation properties of a behavior due to stressors or age frequently have around 1400–7200 data points [6,7,11,12,25,26,17,18], representing test durations no longer than 1 h, with sampling intervals between 0.3 and 1 s. The length of the time series is also important in order to accurately estimate the scaling parameters and to evaluate whether the process presents short-range or long-range correlation. In short-memory processes, the slope of the fluctuation function converges to $\alpha = 0.5$ for large enough time scales. However, for a finite set of data, a priori one cannot be sure that the series is long enough to show this plateau. Therefore, for a process with unknown correlation structure, it is misleading to use $\alpha > 0.5$ as evidence for long memory (see Section 3.2 for further details) [20], especially when the time series is short. In other words, it might be possible that the record is too short to exhibit a plateau with $\alpha = 0.5$. Herein, the effect of the duration of the behavioral time series on the estimation of scaling parameters will be evaluated.

Fourth, in a previous study [15] on Japanese quail, we have shown that long periods of inactivity (relative to the total duration of the test), at the beginning of a time series (latency to ambulated), caused by a heighten fear response can result in a loss of the typical monofractal pattern. Thus, it is important to consider this factor when evaluating behavioral time series with DFA. In this regard, it should also be taken into account that elimination of data under certain circumstances does not affect global scaling properties. Ma et al. (2010) [27] showed, using DFA, that the removal segments of data points