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# Strong anticipation and long-range cross-correlation: Application of detrended cross-correlation analysis to human behavioral data

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## HIGHLIGHTS

- We apply cross-correlation analysis to series accounting for coordination processes.
- In the long term, series present similar long-range correlation properties.
- The matching of long-term fluctuations could result from short-term coupling processes.

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## ABSTRACT

In this paper, we analyze empirical data, accounting for coordination processes between complex systems (bimanual coordination, interpersonal coordination, and synchronization with a fractal metronome), by using a recently proposed method: detrended cross-correlation analysis (DCCA). This work is motivated by the strong anticipation hypothesis, which supposes that coordination between complex systems is not achieved on the basis of local adaptations (i.e., correction, predictions), but results from a more global matching of complexity properties. Indeed, recent experiments have evidenced a very close correlation between the scaling properties of the series produced by two coordinated systems, despite a quite weak local synchronization. We hypothesized that strong anticipation should result in the presence of long-range cross-correlations between the series produced by the two systems. Results allow a detailed analysis of the effects of coordination on the fluctuations of the series produced by the two systems. In the long term, series tend to present similar scaling properties, with clear evidence of long-range cross-correlation. Short-term results strongly depend on the nature of the task. Simulation studies allow disentangling the respective effects of noise and short-term coupling processes on DCCA results, and suggest that the matching of long-term fluctuations could be the result of short-term coupling processes.



## 1. Introduction

Synchronization with the environment has often been described in terms of anticipation. For example, when participants have to synchronize finger taps with the beats emitted by a metronome, a mean negative asynchrony is consistently reported, suggesting that participants do not react to auditory stimuli, but rather anticipate their occurrence. Such anticipatory behavior can be underlain by the formation of an internal model that allows short-term predictions about the time of occurrence of the next metronome signal. A number of representational models, based on phase correction [1] and/or period correction [2], have been proposed for explaining synchronization in tapping tasks [3]. This kind of local short-term anticipation, based on internal models and corrective processes, is referred to by Dubois [4] as *weak anticipation*.

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Dubois [4] evoked a second kind of anticipative behavior, which he called *strong anticipation*, which is supposed to occur without reference to any internal model [5,6]. Strong anticipation is based on the embedding of the organism within its environment, creating a new organism–environment system, which possesses lawful regularities that allow the emergence of anticipation.

Stephen and Dixon [7] noted that two divergent approaches to strong anticipation have to be distinguished. The first one suggests that strong anticipation results from an appropriate local coupling between the organism and its environment. For example, the synchronization of the rhythmic oscillations of a limb with a periodic metronome has been successfully accounted for by a model of coupled oscillators, including a parametric driving function [8,9]. More sophisticated models in physics have shown that, during the synchronization between a slave and a master system, the presence of time delays in the master system yields the slave system to synchronize with future states of the master [10]. These models of coupled oscillators suggest that anticipation could emerge from the macroscopic properties of the organism–environment system. This conception supposes that anticipation is based on local time scales [6].

A second approach considers that strong anticipation could be based on a more global coordination between the organism and its environment. Stephen, Stepp, Dixon, and Turvey [5] analyzed synchronization with a chaotic metronome: In that case, local predictions are difficultly conceivable, because of the intrinsically unpredictable nature of the pacing signal. Indeed, the authors showed that tapping behavior in this situation exhibited a mix of reaction, proaction, and synchrony to metronome signals. Importantly, they observed a close matching between the fractal exponents of the chaotic signals and those of the corresponding inter-tap interval series. In this kind of strong anticipation, the organism is not adapted to the states of the environment but to their statistical structure. The presence of $1/f$ scaling in the environment is essential in this coordination process: the organism exploits the complexity of the environment, and especially the long-range correlated structure of its evolution over time, as a resource for a more adaptive and efficient behavior [5,7].

Note that the concept of strong anticipation was primarily introduced to account for the adaptation of (complex) organisms with their (complex) environment. Anticipation suggests a directional relationship, with a slave system attempting to anticipate the future states of a master system. The principles that underlie strong anticipation, however, can be extended more generally to coordination processes between equivalent systems [11]. In that case, systems mutually adapt, with a kind of bidirectional anticipation. Strong anticipation, in this context, suggests that the complexity of both systems is an essential resource for their effective coordination. For example, Marmelat and Delignières [11] analyzed interpersonal coordination in a task where participants had to move pendulums in synchrony. Results revealed a poor local correlation between the series of oscillation periods produced by the two participants of each dyad. The authors analyzed the scaling properties of the series of periods produced by participants, separating short-term and long-term scaling behaviors. They evidenced a close correlation between long-term fractal exponents, but, in the short term, series behaved more independently.

The hypothesis that coordination could occur not only on local and short-term scales but following multiple and interpenetrated scales suggests that strong anticipation should be revealed by the presence of long-range cross-correlations between the series [12]. Long-range cross-correlations can occur between two series that both present long-range correlations. In that case, each series has long memory of its previous values, and additionally each series has also a long memory of the previous values of the other.

Podobnik and Stanley [13] introduced detrended cross-correlation analysis (DCCA) for analyzing long-range cross-correlations between two simultaneously recorded non-stationary time series. This method is an extension of the well-known detrended fluctuation analysis (DFA), which was initially proposed by Peng et al. [14–16], as a method for quantifying serial correlations in non-stationary time series. To date, DCCA has essentially been applied to artificial series, and to some real-data sets related to stock markets [17–19], road traffic [20–22], climate [23], or encephalography [24]. In this paper, we analyze some data sets collected in experiments about synchronization processes in human behavior, with the aim of seeking for statistical signatures of strong anticipation.

We first present the algorithms of DFA and DCCA, and we briefly discuss some formal properties of their expected results. Then we examine the results obtained with experimental series collected in situations that could be considered as emblematic of strong anticipation processes in human behavior: inter-limb coordination, interpersonal synchronization, and synchronization with fractal metronomes. Then we analyze some results obtained with simulated data sets, especially for evidencing the effects of short-term autoregressive processes.

## 2. Methods

### 2.1. Detrended fluctuation analysis (DFA)

DFA has been successfully applied to various processes, including physiological processes [25], psychological [26], sensorimotor [27–29], geophysical [30], climate [31] or financial [32,33]. DFA exploits the diffusion property of fractional Brownian motions, stating that in such processes the variance is a power function of the time interval over which it is computed [34]:

$$\mathrm{Var}\, x(t) \propto \Delta t^{2H}, \tag{1}$$

where $H$ is the Hurst exponent.