Long-range dependence in human movements: detection, interpretation, and modeling perspectives

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This symposium is conceived as a complement to the keynote proposed by Jeffrey Hausdorff, and focused on long-range dependence in human movement. 1/*f* noise, or fractal fluctuations, have been discovered in a number of empirical phenomena, and remain an intriguing property, characterized by long-range dependence and self-similarity. In the domain of motor behavior, fractals have been evidenced, for example, in tapping, forearm oscillations, bimanual coordination, or step duration during locomotion. This fractal dynamics was frequently presented as the natural outcome of complex systems, but the principles underlying its generation remain controversial (Wagenmakers, Farrell & Ratcliff, 2004).

During this symposium, Guy Madison (Umeå, Sweden), Kjerstin Torre (Montpellier, France), and Loic Lemoine (Montpellier, France) will present a series of experiments focusing on tapping. 1/*f* fluctuations were evidenced in the series of time intervals produced in continuation tapping, and in the series of errors in synchronization tapping (Chen, Ding, & Kelso, 1997; Gilden, Thornton & Mallon, 1995; Lemoine, Torre & Delignières, 2006; Madison, 2004). These communications present studies aiming at evidencing the origin of 1/*f* fluctuations in such tasks, the factors that could modulate the fractal properties of signals, and the models that could take account for their evidenced statistical properties. These experiments show that fractal analyses open a new window of observation on timing control, and allow a fruitful re-examination of classical theories. Finally Eric-Jan Wagenmakers (Amsterdam, The Netherlands) will discuss several hypotheses that have been proposed for explaining the universality of 1/*f* noise, and some general models that could be able to generate this kind of fluctuation over time.

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Exploring the origin of long-range dependence in human timing: Effects of sensory feedback and relations between synchronisation and production

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Sequences of intervals intended to be isochronous exhibit long-range dependence in terms of fractional Gaussian noise (fGn). The Hurst exponent is < 0.5 when synchronizing with physically isochronous sound sequences (Pressing & Jolley-Rogers, 1997), and > 0.5 for (internally paced) production, increasing for longer intervals. The origin of these dependencies is unclear, but they may obviously have something important to say about the underlying mechanisms for explicit timing, a matter of considerable controversy. It has been suggested that fGn might arise naturally from a timing mechanism in which each interval is determined by a few immediately preceding intervals (Madison, 2004), in line with a timing model that incorporates memory and habituation (Staddon, 2005). In contrast, there is no principled reason why fGn would emerge from the widely established pacemaker-counter clock.

The pacemaker-counter clock is an open-loop model in which sensory afference is not assumed to play any role, whereas memory is conceivably heavily dependent on sensory information. The purpose of the present study was therefore to compare conditions of facilitated vs. restricted sensory feedback from the participants' own movements. Furthermore, possible systematic relations between long-range dependence during production and a number of synchronization performance indices were examined.

Six experienced participants performed repeated sessions on different days, in total 10 trials for each condition comprising 4 inter onset intervals (500, 800, 1100, and 1500 ms) with either auditory feedback or no feedback. Finger movements were registered by breaking a beam of light.

Preliminary analyses of the production data indicate that auditory feedback led to slightly smaller Hurst exponents, in agreement with the hypothesis, but only for 500 ms. However, auditory feedback led to smaller variability for all interval durations. Analyses of synchronization data are in progress.

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Synchronisation and Syncopation: A common timing model.

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Chen, Ding and Kelso (1997) suggested that series of errors collected during tapping in synchronization presented fractal properties. Torre, Lemoine and Delignières (2006), using ARFIMA modeling, provided statistical evidence for the presence of long-range dependence in those series. They proposed a model, combining the shifting-strategy model (Wagenmakers, Farrell & Ratcliff, 2004) and a first-order auto-regressive correction (Vorberg & Wing, 1996). This model seemed able to account for the dynamical structure of errors and inter-tap intervals. The main element of this model is an activation-threshold timekeeper, whose threshold presents random shifts, leading to a plateau-like evolution over time. This evolution in threshold is supposed to be related to the successive adoption of different strategies for controlling duration. Simulations suggested that one key parameter for determining long-range dependence was the range of threshold shifting.

Chen, Ding & Kelso (2001) analyzed the fractal properties of series of errors in two contrasted conditions: synchronization and syncopation to the metronome. They showed that the fractal exponent was higher in syncopation than in synchronization. Moreover, they showed that providing participants with efficient control strategies for syncopation (e.g. extending the finger on the beep) induced a decrease of fractal exponents, which reached the level observed in synchronization. One could then suppose that the difference in exponents observed between synchronization and syncopation is related to the difficulty to adopt a consistent strategy in syncopation. The aim of this study was then to test this hypothesis and the ability of the model to account for differences between conditions.

9 participants were tested in both tasks at a timing frequency of 1.25Hz. Results confirmed the significant effect of task on fractal exponents. Simulation with the model showed that setting a higher range of threshold shifting allowed producing series statistically similar to those experimentally observed.

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Fractal modeling of synchronization tapping in line with continuation tapping

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In continuation tapping, participants produce self-paced inter-response interval series presenting $1/f^{\beta}$ structure. When tapping is performed in synchronization, the inter-response interval series appear as differenced series with a positive spectral slope, while the produced asynchronies present the typical $1/f^{\beta}$ structure.

Characteristic inter-response interval series in continuation tapping can be well modeled by providing the internal timekeeper *C* of the Wing and Kristofferson model with $1/f^{\beta}$ noise (Delignières, Torre & Lemoine, submitted), using the *shifting strategy* model (Wagenmakers, Farrel & Ratcliff, 2004).

For synchronization timing, Vorberg and Schulze (2002) proposed to extent the original Wing and Kristofferson model with an auto-regressive correction of asynchronies, accounting for Gaussian properties and short-range correlation in series. However, with regard to long-range correlation, the hypothesis of simple auto-regressive synchronization processes has been opposed, arguing that such a mechanism can not account for the $1/f^{\beta}$ structure observed in asynchronies (see for example Ding, Chen & Kelso, 2002).

We propose to combine the modified continuation tapping model with the auto-regressive extension for synchronization. This combined model allows to reproduce the features evidenced in experimental synchronization tapping, notably the negative lag1 auto-correlation in inter-response intervals, a positive and persistent auto-correlation function in asynchronies, and the characteristic power spectra of both inter-response intervals and asynchronies. So, a comprehensive regard on both continuation and synchronization processes allows to live up to Gaussian, short-range and long-range correlation properties of inter-response interval series and asynchronies in synchronization tapping.

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Models for 1/*f* Noise in Psychological Time Series

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Stock market fluctuations, neuronal spike trains, network traffic, and sunspot activity; these are all examples of physical systems that display persistent temporal correlations, long-range dependence, or $1/f^{\alpha}$ noise. What this means is that the above systems are self-similar and scale-invariant, that they operate in between the randomness of white noise and the predictability of Brownian motion, and that they have autocorrelations that decay relatively slowly.

In the last decade, $1/f^{\alpha}$ noise has also been detected in a wide variety of psychological time series (see Wagenmakers, Farrell, & Ratcliff, 2004, for a critical review). The phenomenon of $1/f^{\alpha}$ noise is of scientific interest not just because of its ubiquity and its fractal features, but also because the origin of $1/f^{\alpha}$ noise is not easy to explain. In this presentation I will discuss several models that generate $1/f^{\alpha}$ noise. All of these models come from econometrics and physics but can be easily recast in psychological terms.

One of the more popular theories for $1/f^{\alpha}$ noise is self-organized criticality (e.g., Bak, 1996). I will argue by example that this theory is only useful when it is instantiated in a concrete model for performance. Other models that will be discussed are regime switching models (e.g., Gourieroux & Jasiak, 2001), point process models (e.g., Kaulakys, Gontis, & Alaburda, 2005), and fluctuating-threshold models (Davidsen & Schuster, 2002). The study of $1/f^{\alpha}$ noise as a kind of "psychomythics" (Uttal, 2003) will be briefly discussed.

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