On the origins of 1/*f* noise in human motor behavior

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1/f fluctuations have been discovered in a number of time series collected in psychological and behavioral experiments (e.g. Beltz & Kello, 2006, Gilden, 2001; Torre, Lemoine & Delignières, 2007). This ubiquity is per se an intriguing phenomenon, and the origin of such fluctuations remains in question. One considers that this very specific kind of fluctuation plays an essential role in the stability of behavior, and in the adaptability and flexibility of organisms. A number of hypotheses have been proposed for accounting for this phenomenon. Currently, two categories of explanations can be discerned:

A first category of hypotheses seeks a general explanation for the existence of 1/*f* noise. For example Kello, Beltz, Van Orden, and Turvey (2007) consider 1/*f* fluctuations as the natural outcome of self-organization processes in complex systems. Cognitive functions are conceived as metastable patterns of neural and behavioral activity, and this metastability generates intrinsic fluctuations that universally exhibit the 1/*f* fluctuations. According to this point of view, 1/*f* noise is supposed to manifest in all aspects of behavior, so long as the same behavior is repeated consistently with minimal perturbation (Beltz & Kello, 2006).

A second line of reasoning seeks for domain-specific explanations. 1/*f* noise is supposed to emerge from specific underlying processes within the system, and consequently local models could be proposed that take into account the serial properties of behavior, and their alteration under various experimental conditions (Delignières, Torre & Lemoine, in press, West & Scaffeta, 2003).

This symposium will confront proponents of the two hypotheses, and will oppose epistemological approaches, modeling perspectives and experimental strategies.

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Nomothetic and mechanistic perspectives on $1/f^{\beta}$ noise

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$1/f^{\beta}$ noise or serial long-range correlation have been shown to be the typical statistical property of the outcome of many complex systems, including human motor behavior. Despite this ubiquity – or perhaps because of – the impact of the $1/f^{\beta}$ phenomenon on human movement research has remained rather modest and unclear, and so far current models of motor behavior have not been designed for accounting for long-range correlation.

In this communication we propose that the contribution of $1/f^{\beta}$ noise on human movement science depends to a large extent on the way one conceives this phenomenon. Especially, we contrast two current perspectives on $1/f^{\beta}$ noise. The nomothetic perspective gives general accounts of $1/f^{\beta}$ noise and refers to concepts such as complex systems, metastability, and self-organized criticality. The mechanistic perspective seeks domain-specific explanations for $1/f^{\beta}$ noise, by identifying concrete models of the underlying processes that are likely to be responsible for the correlation in the behavioral outcome. Thus, one may wonder whether the aim of serial correlation studies is to account for the prevalence of $1/f^{\beta}$ noise, or to account for the sensorimotor behavior under study, by taking the $1/f^{\beta}$ phenomenon into account.

We argue for the usefulness of domain-specific mechanistic models of $1/f^{\beta}$ noise for theories on sensorimotor behavior. The fact that $1/f^{\beta}$ noise in given sensorimotor behaviors is sensitive to particular experimental factors tends to support this claim. Mechanistic models present the advantage to be experimentally testable and thus falsifiable, and to allow establishing links to current models of sensorimotor behavior. We support our claim by outlining a mechanistic model of $1/f^{\beta}$ noise in the time interval series produced during self-paced tapping; we show how this model can be extended to synchronization and bimanual tapping, providing a unifying account of the specific serial correlation structures evidenced in self-paced, synchronization, and bimanual tapping tasks.

The Link Between Coordination and Pervasive 1/f Scaling

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It is readily apparent that physical activities are acts of coordination among bodily components and, by extension, component neural systems involved in the control of bodily movements. Sometimes coordination is simple in its regularity of movement as in the phase locking of musical activities set to a metronome. But more often, coordination is complex and irregular, as in a runner's gait over uneven terrain or an assisted play in basketball. These "rough and ready" coordinations appear to be as robust as they are ubiquitous: Neural and bodily components organize themselves temporarily to suit current intentions and conditions, but may quickly reorganize as intentions and conditions change.

In this communication, I propose that such coordinations have a common dynamical basis derived from three distinct but related bodies of work. Most directly related to physical activity, von Holst (1939) proposed *relative coordination* as a functional basis of movement coordination in biological models like the lipfish and centipede. Its functionality stems from a balance between independence versus interdependence among component activities, e.g., fin and leg oscillations, respectively. More generally, Ising (1925) proposed a model of ferromagnetism that has since been broadened to study how patterns organize and reorganize among many kinds of system components, e.g., electron spins. Most recently, Kelso (1995) proposed *metastability* as a key property of human neural and behavioral systems that requires a balance of independence versus interdependence among components, e.g., neurons.

These three perspectives on coordination and pattern formation are reviewed and synthesized to formulate a novel prediction. In particular, *1/f scaling* is predicted to be a pervasive property of *intrinsic fluctuations* produced in the balance of independence versus interdependence of component activities of many kinds. Evidence of pervasive 1/f scaling in human neural and behavioral activity is presented, and metastability is contrasted with alternate explanations that are specific to each domain in which 1/f scaling is observed.

Uncoordinated Action and the Breakdown of 1/f Scaling

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In the typical timing study that produces 1/f noise (Gilden, Thornton, & Mallon, 1995; Lemoine, Torre, & Delignières, 2006), a person taps out a continuous rhythmic beat without the aid of a synchronizing signal. In this paradigm the 1/*f* noise arises as a byproduct of the coordinated movement produced by the feeling of rhythm. Although it is not clear how the 1/f noise is itself generated or even what the feeling of rhythm is, the two phenomena are patently associated. In this communication I show how this association can be used to map out the temporal span of rhythmic feeling.

Quite a bit is known about the limits to rhythmic feel, and what is known is built into the design of metronomes. Metronomes typically do not have settings that go below 40 beats per minute. From a practical point of view there is no reason to build a metronome that beats much slower, because music at slower cadence could not be conducted or counted by the musicians. The metronome limit of 40 bpm suggests that the implicit working memory system that underlies rhythmic feel has a decay half-life in the neighborhood of 1.5 seconds.

In this communication I discuss timing behavior at very slow tempi, where the target beat-to-beat intervals extend beyond 1.5 s. The fluctuation spectra in these very slow regimes are not 1/*f*. The time series of beat-to-beat intervals shows a pronounced tendency to randomly walk when the interval exceeds 1.5 s. The random walk appears to arise as an explicit recency effect where past estimates serve as the basis for future estimates.

As a practical use of this observation I show that adults with diagnosed attention-deficit hyperactivity disorder (ADHD) have a shortened temporal span in the memory system that is used in making rhythm. This work shows how timing dynamics can be used to estimate what Fraisse termed the subjective present, and it suggests that the underlying core deficit in ADHD is related to perceptual mechanisms that create the present moment.