

## **Complexity, Health and Aging**

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## Complexity, coordination and health

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Fractal fluctuation is a very specific pattern of variability over time, characterized by properties of self-similarity and long-range correlation. These fluctuations have been often observed in the series of performances produced by living systems in repetitive tasks. Fractal fluctuations are also often referred to as  $1/f^\beta$  noise, in reference to the typical power scaling observed in the frequency domain.

Fractal fluctuation is closely related to health. Its presence is considered the hallmark of young, healthy and adaptive systems, and typically an extinction of long-range correlation is observed in elderly and in patients suffering from neurodegenerative diseases.

The real origin of fractal fluctuation remains in debate. The most convincing point of view states that long-range correlation reflects the presence of complex interdependence within the system under study, between a wide number of sub-systems acting at different time scales. This so-called interaction-dominant view suggests that fractal correlation emerges from the coordination between these different time scales, and as such signs the complexity of the system (Kello et al., 2007).

As a consequence, one could conceive a direct link between health, coordination and complexity. A healthy system is supposed to present this complex coordination between its constitutive components. Deficiency could then express following two opposite ways: (1) The system presents a number of *independent* sub-components. In this case the outcome series become random, less ordered over time. (2) The system is dominated by a restricted set of sub-components: the outcome series become more ordered and predictable.

Fractal fluctuation has been often described as an optimal compromise between disorder and order. Considering the  $1/f^\beta$  model,  $\beta = 1$  corresponds to perfect  $1/f$  noise, often considered a “magical” threshold, characterizing optimal functioning. A decrease of  $\beta$  towards 0 is conceived as a deviation towards disorder and randomness, and an increase towards 2 is analyzed as a deviation towards order and predictability.

Empirical results, however, should be interpreted with caution. It is important to keep in mind that serial correlations in empirical series reflect both long-range correlations, arising from the functional complexity of the system, and short-range correlations that could be induced, for example, by local corrective processes. An increase or conversely a decrease in correlation can be due to the presence of such short-range processes (e.g. Delignières, Torre & Lemoine, 2009).

Moreover the strength of correlations, as measured by classical methods, is not predictive of the genuine presence of long-range correlation. Specific methods, such as ARFIMA modelling, allow to detect the effective presence of long-range correlations in the signals. Sometimes systems can present moderate levels of effective long-range correlations, whereas in others cases, series can present high correlation levels but are not long-range correlated.

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Kello, C. T., Beltz, B. C., Holden, J. G., & Van Orden, G. C. (2007). The emergent coordination of cognitive function. *Journal of Experimental Psychology: General*, 136, 551-568.

# **Aging and loss of complexity in the neuro-musculo-skeletal system**

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Understanding age-related changes of the neuro-musculo-skeletal system ranks high on the agenda of gerontological research. Since numerous age-related phenomena are simultaneously observed at multiple levels, across different domains and in various task conditions, this challenge has been predominantly declined in separate sub-domains. The dominant idea underlying this approach is that age effects are complex and vary erratically from tasks to task in a way that depends on the processes involved. As a consequence, a large number different theories, methods and task paradigms co-exist, thereby making aging research a puzzle of knowledge and an example of disunity in terms conceptualization, levels of analysis, methods and measurements.

For a long time, cognitive psychology, behavioral neurosciences and human movement sciences have been illustrative examples of subdivisions into separate sensory, cognitive and sensorimotor sub-domains, leading to the striking situation that researchers in one domain often ignored the research questions, methods and findings of the other domain. However, during the last decade, the classic separation between sensory, cognitive and sensorimotor aspects of CNS functioning has been however challenged on the basis of both behavioral and neuro-imaging data. The issue of the (missing) link between cognition and action also motivated a recent transition in developmental and aging research. The results of these studies supported the view that aging as an integrated process, which may affect the different components of the neuro-musculo-skeletal system in a global and interacting way, thereby resulting in correlated changes between different domains of functioning. Accordingly, it has been suggested that a deeper understanding of aging of the neuro-musculo-skeletal system could emerge from attempts to explore the underlying mechanisms of coupling between temporal changes in the different domains of functioning.

Why senescent changes are functionally coupled across cognitive and sensorimotor domains and what is the exact nature of their shared dynamics, if exist, remains however largely unknown. In particular, even though the issue of common causes is frequently evoked in the cognitive literature, the question of whether manifestations of behavioral aging in both cognitive and sensorimotor domains could be reduced to a few common causal mechanisms acting as pacemakers of changes has been scarcely addressed.

In this presentation, we explore a new research direction to further address the issue of common causes to cognitive and sensorimotor aging. This approach is grounded on repeated observation, in a number of experimental studies, of similar behavioral phenomena in both the cognitive and sensorimotor domains, namely: 1) general slowing of behavioral responses, 2) increase in intra-individual variability of performance and 3) changes in complexity of behavioral outputs. These striking observations can be interpreted as neuro-behavioral markers that capture the relationships between neural, information processing and behavioral levels across lifespan. They suggest that dimensional reduction of aging process is possible as soon as one accepts to consider that common age-related effects could exist on domains that are classically considered as composed of specific and independent processes.

# Stability and stabilization, adaptability and adaptation: An analysis of the variability in rhythmic coordination

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The variability, stability, and adaptability observed in biological systems and human sensorimotor behavior are three highly entangled properties. A common but simplified assumption is that stability and variability are roughly inversely related. However, when a system is subjected to changing constraints, behavioral *stability* relies on its capacity to adapt to different conditions, thereby implying a certain variability. Clarifying such complex relationships constitutes a challenge for deepening the understanding of the conditions of systems health/disease, adaptability/inflexibility. There has been accumulating evidence for the idea that, instead of the magnitude of fluctuations, the presence of long-range correlations, or *1/f noise*, in psycho-biological variables may be the warranty for systems health and adaptability. However, to appraise the respective meanings of the two aspects of variability, it is necessary to assess the magnitude of fluctuations and their correlation structure as two independent parts of the global variability of the time series.

Here we address the mechanisms of stability and stabilization, adaptability and adaptation, by analyzing two essentially independent ingredients of the global variance of time series: the local variance (LV) and the serial long-range correlations. These two properties are mutually independent, but both affect the series global variance: for a same LV, an increase of the intensity of long-range correlations causes an increase of the series variance, and conversely. Basing on this observation, we hypothesized that a negative correlation between the LV and the intensity of the long-range correlations in serial performances may constitute a resource for the system to adapt to critical conditions, where the maintenance of the required behavior needs the performance to be stabilized, *i.e.*, its global variance to be minimized.

To test our hypothesis, the bimanual coordination paradigm provides an appropriate experimental framework. It has been well established that the coordinative system is characterized by different intrinsic stabilities, as a function of the coordination pattern and the tempo of the oscillations performed: anti-phase coordination is intrinsically less stable and more variable than in-phase coordination, and this relative stability decreases as the required movement frequency increases so that anti-phase at high oscillation frequency constitutes a “critical” condition. Moreover, a nonlinear transition appears with increasing movement frequency: individuals spontaneously switch from anti-phase to in-phase coordination. Finally, this phase transition is thought to be partly due to the increasing magnitude of the fluctuations affecting the coordination pattern.

We show that a negative correlation between the LV and the persistence of long-range correlations in the relative phase series emerges despite the essential independence of these two properties. This correlation increased gradually with the decrease of the intrinsic stability of the coordination performed, to reach significance only in the critical condition. This result thus supports the idea that the appearance of a negative correlation between the LV and the intensity of long-range correlations allows for the *stabilization* of the outcome behavior. While the presence of *1/f noise* might indeed be a signature of systems *adaptability*, the emergence of a co-adjustment between the LV and the long-range correlation structure may be a sign of effective *adaptation*.