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Title: Learning, Motor Skill and Long-Range Correlations.

Déborah Nourrit-Lucas.<sup>1</sup>, Adaté Olivier Tossa<sup>1</sup>, Grégory Zélic <sup>2</sup> & Didier Delignières<sup>2</sup>

<sup>1</sup> UMR 7349; MAPMO, UFR Sciences, Orléans University, France

<sup>2</sup> EA 2991 Movement to Health, Montpellier University 1, France

Abstract: Long-range correlations have been evidenced in a number of experiments, generally using over-learned and over-practiced tasks. We hypothesized that long-range correlation could represent the byproduct of learning. We analyzed the series of periods produced by a group of expert and a group of novices during prolonged trials on a ski-simulator. Results showed a very low variability in expert's series, as compared to novices. Fractal analyses showed that fluctuations were significantly more structured and correlated in experts. These results suggest that learning could be conceived as the progressive installation of complexity in the system.

Key-words: Motor skills, motor learning,  $1/f$  noise, long-range correlations, degeneracy

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<sup>1</sup>Corresponding author: D. Nourrit-Lucas, UMR. 7349 "Mathématiques-Analyse, Probabilités, Modélisation-Orléans", Département de Mathématiques, Université d'Orléans, Rue de Chartres, B.P. 6759-F-45067 Orléans cedex 2 France Tel: +33 2 38 49 46 81. Fax: +33 2 38 41 72 05. E-mail: [deborah.lucas@univ-orleans.fr](mailto:deborah.lucas@univ-orleans.fr)

## *Introduction*

Fractal fluctuations have been recently evidenced in series of performances collected in cyclical or repetitive tasks, such as serial reaction time [1], finger tapping [2,3], circle drawing [4], forearm oscillations [5], reciprocal aiming [6], bimanual coordination [7], walking, running [8,9], or in bimanual coordination tasks [10].

These fluctuations are characterized by specific properties, namely self-similarity, or scale invariance, meaning that statistical features in the series are similar whatever the scale of observation, and long-range correlation, revealed by the presence of positive serial correlations between successive values, which persist over time, often over dozens, sometimes over hundreds of observations [11,12].

These ubiquitous and amazing statistical properties present a special interest for behavioral scientists, as they are conceived as theoretically closely linked to complexity, adaptability and health [13]. Long-range correlated series represent the typical output of complex and healthy organisms, characterized by essential properties of robustness and adaptability. In contrast, aging and disease seem marked by a loss of complexity, which is typically revealed by a decrease of long-range correlations in output series [8]. These close relationships between long-range correlations, robustness and adaptability are of special importance here, as the two latter represent the main properties of the skilled behavior, and the essential by-products of learning.

Importantly, long-range correlations have been essentially evidenced in overlearned tasks, such as tapping, circle drawing, reciprocal aiming, walking or running. In all cases these tasks required the exercise of basic skills, acquired from years and extensively practiced. Obviously, seeking for long-range correlation in performance series requires the collection of very long time series of hundreds successive data points, supposing that participants are sufficiently familiar with the task at hand. One could hypothesize, however, that the presence

of such fractal fluctuation could be related to the fact that performance is underlain by a well established skill.

An interesting result supporting the present claim has been reported by Wijnants, Bosman, Hasselman, Cox and Van Orden [14]. The authors analyzed serial correlations in series of movement times in a reciprocal aiming task. The task was performed with the non-dominant hand, and the experimental design included five successive blocks of 1100 trials. Results showed an increase of serial correlations in the series with practice, with a clearer evidence for  $1/f$  fluctuation in the last block.

It could be interesting here to clearly distinguish between learning and practice. Learning can be defined as the acquisition of a new skill, which is not initially present in the repertoire of the individual [15,16,17]. In contrast, practice refers to the repeated exercise of a task, leading to a refinement of an existing skill, but not necessarily to the adoption of a qualitatively modified behavior. Practice is essential for learning, but extensive practice is often required for an effective learning to occur [15]. From this point of view, the aforementioned results seem more related to the effects of practice and to those of effective learning.

Practice and learning, however, often produce similar and related effects, such as the decrease of performance variability, an enhancement of efficiency, a better robustness facing external perturbations, and a better adaptation to related tasks [18]. As such, long-range correlation could be conceived a logical byproduct of practice and learning.

In the present experiment, we analyzed performance series collected in novice and expert participants in a complex task. We hypothesized to evidence stronger long-range correlations in experts, suggesting that the expert behavior was characterized by a higher level of complexity than the initial, novice behavior.

### *Material and Methods*

#### *Participants*

*Nine volunteered participants (two females, seven males) participated in this study. There were separated in two experimental groups. The expert group included one female and three males (mean age: 39.2 years  $\pm$ 6.3, mean weight: 73.2 kg  $\pm$  8.46; mean height: 179.6 cm  $\pm$  3.5). These participants were involved in a series of experiments on the ski-simulator task. Ten years ago, they were involved in a first longitudinal experiment including 390 1-min trials over 13 weeks, and were proven to have adopted a skilled behavior, qualitatively different than their initial behavior on the task [15]. They were also involved in two retention tests, the first one five months after the completion of the learning protocol [19], and the second ten years after [20]. In both cases the retention tests evidenced the persistence of the skilled behavior initially acquired by participants.*

The novice group (one female, four males, mean age: 23.2 years  $\pm$  2.5, mean weight: 70.5 kg  $\pm$  4.2; mean height: 1.80 cm  $\pm$  5.8) was composed of occasional skiers (with average three days of practice per year), but none had specific training on the ski-simulator. All participants signed a consent form, and were not paid for their participation.

#### *Experimental device*

The task was performed on a ski-simulator (Skier's Edge Co., Park City, UT), which consisted of a platform on wheels, which moved back and forth on two bowed, parallel metal rails (Figure 1). We used a modified version of the simulator by replacing the two independent feet supports of the original apparatus with a 30-cm wide board, in unstable balance over a sagittal rotation axis (for more details see [15])

- Insert Figure 1 -

#### *Procedure*

Participants were instructed to make cyclical sideways movements on the ski simulator, “as ample and frequent as possible”. They had to keep their hands behind their back at all times, and to fix their eyes on a point located on the floor, three meters in front of the apparatus.

They performed a unique session of 10 minutes, allowing the performance of approximately 550 complete oscillations on the apparatus.

#### *Data collection*

A passive marker was fixed in the front of the simulator platform. The displacement of this marker was recorded in three dimensions by a VICON motion analyzer (Biometrics) with seven cameras (100 Hz). Analyses focused on the series of positions of the platform, along the transverse axis, computed from the collected 3-D data.

The position time series were filtered with a dual-pass Butterworth filter with a cut-off frequency of 10 Hz. A peak-finding algorithm was used to localize the left reversal points of the platform motion and the period was calculated for each oscillation as the time interval between two successive reversal points. We retained for analysis the 512 last points of the series, for each participant.

#### *Statistical analysis*

We first characterized series in terms of descriptive statistics (mean and standard deviation). We then applied three analyses aiming at evidencing and measuring serial correlation in the series.

##### *Autocorrelation function*

Autocorrelation functions were computed up to lag 30. We extracted from these function two variables of interest: the lag-one autocorrelation [ $ACF(1)$ ], and the average autocorrelation for lags comprised between 10 and 30 [ $\langle ACF \rangle(10-30)$ ]. As long-range correlated series are characterized by the persistence of correlations over time,  $\langle ACF \rangle(10-30)$  was expected to be significantly higher in the expert group.

##### *Detrended Fluctuation Analysis (DFA)*

DFA is a widely used method that allows to quantify correlation in time series [21]. The series  $x(t)$  is first integrated, by computing for each  $t$  the accumulated departure from the mean of the whole series:

$$X(t) = \overset{t}{\underset{i=1}{\dot{\Delta}}} [x(i) - \bar{x}] \quad (1)$$

This integrated series of length  $N$  is divided into  $k$  non-overlapping intervals of length  $n$ . The last  $N - (kn)$  data points are excluded from analysis. In each interval, a least squares line is fit to the data (representing the trend in the interval). The series  $X(t)$  is then locally detrended by subtracting the theoretical values  $X_n(t)$  given by the regression. For a given interval length  $n$ , the characteristic size of fluctuation for this integrated and detrended series is calculated by:

$$F(n) = \sqrt{\frac{1}{N - (kn)} \overset{N-kn}{\underset{t=1}{\dot{\Delta}}} [X(t) - X_n(t)]^2} \quad (2)$$

This computation is repeated over all possible interval lengths. Typically,  $F$  increases with interval length  $n$ . A power law is expected, as

$$F(n) \propto n^\alpha \quad (3)$$

$\alpha$  is expressed as the slope of the double logarithmic plot of  $F(n)$  as a function of  $n$ . The value  $\alpha = 0.5$  indicates the absence of correlations (white noise),  $\alpha > 0.5$  indicates persistent long-range correlations, meaning that large (small) values are more likely to be followed by large (small) values.

We considered interval lengths ranging from  $n = 10$  to  $n = N/2$ . In order to avoid any bias due to the logarithmic distributions of the points in the diffusion plots, we divided the abscissa into intervals of  $0.1(\log_{10}\Delta t)$ , and computed the average points within each interval (13 points were obtained for an initial series length of 512 data points). Finally, in order to control for the effects of noisy perturbations that mainly affect short-term fluctuations and tend to flatten the diffusion plot, we focused on the long-term slope (i.e. the 6 last points [22]).

### *Power spectral density analysis (PSD)*

This method works on the basis of the periodogram obtained by the Fast Fourier Transform algorithm. In the frequency domain, long-range correlated series are characterized by the following scaling law:

$$S(f) \propto 1/f^\beta \quad (4)$$

where  $f$  is the frequency and  $S(f)$  the correspondent squared amplitude.  $\beta$  is estimated by calculating the negative slope ( $-\beta$ ) of the line relating  $\log(S(f))$  to  $\log f$ .

We also used the improved version of PSD proposed by Eke et al. (2000)[12], which uses a combination of preprocessing operations: First the mean of the series is subtracted from each value, and then a parabolic window is applied: each value in the series is multiplied by the following function:

$$W(j) = 1 - \left(\frac{2j}{N+1} - 1\right)^2 \quad \text{for } j = 1, 2, \dots, N. \quad (5)$$

Thirdly a bridge detrending is performed by subtracting from the data the line connecting the first and last point of the series. Finally the fitting of  $\beta$  excludes the high-frequency power estimates ( $f > 1/8$  of maximal frequency). This method was proven to provide more reliable estimates of the spectral index  $\beta$ , and was designated as  $^{\text{low}}\text{PSD}_{\text{we}}$ .

### *Group comparisons*

Considering the low sample sizes and the strong inhomogeneity of variances, we used nonparametric Mann-Whitney U tests for comparing central tendencies between groups. The significance threshold was set at 0.05.

### *Results*

#### *Descriptive statistics*

We present in Figure 2 two example series obtained with a novice (top panel) and an expert (bottom panel). The samples of mean periods were as follows: Novices : {0.87, 1.13, 1.02,



0.96, 0.81} ; Experts : {0.82, 0.93, 0.87, 0.84}. There was no difference between the two groups (Experts: 0.87 sec  $\pm$  0.04; Novices: 0.96 sec  $\pm$  0.13;  $U = 6$ ;  $Z = 0.98$ ;  $p = 0.327$ ; *exact p* = 0.413).

This figure, however, suggests evident differences in terms of variance. Indeed, the samples of standard deviations were the following: Novices : {0.17, 0.24, 0.39, 0.10, 0.25} ; Experts : {0.02, 0.04, 0.04, 0.03}. There was a statistical difference between the two groups (Experts: 0.03 sec  $\pm$  0.01; Novices: 0.23 sec  $\pm$  0.11;  $U = 0$ ;  $Z = -2.45$ ;  $p = 0.014$ ; *exact p* = 0.016). As expected, experts performed the task with a very low variability, as compared with novices.

- Insert Figure 2 -

### *Autocorrelation functions*

We present in Figure 3 the point-by-point average autocorrelation functions for the two groups. There were evident graphical differences between these two average functions. In the novice group, the autocorrelation function present just significant values for the three first lags, and then reaches very quickly values close to zero. This kind of auto-correlation function is typical of short-range correlated processes [22]. In contrast, the average autocorrelation function of the expert group present presents a very slow decay, with significant values up to the 30<sup>th</sup> lag. This kind of auto-correlation function corresponds to those obtained with long-range correlated series.

The following values were observed for ACF(1): Novices : {0.38, 0.03, 0.28, 0.11, 0.07} ; Experts : {0.40, 0.27, 0.38, 0.23}. There was no difference between the two groups, however, because of the large variability in the novice group (Experts: 0.32  $\pm$  0.08; Novices: 0.17  $\pm$  0.15;  $U = 4$ ;  $Z = -1.47$ ;  $p = 0.142$ ; *exact p* = 0.190).

<ACF>(10-30) values were the following: Novices : {0.01, 0.02, 0.03, 0.00, 0.00} ; Experts : {0.31, 0.09, 0.24, 0.04}. There was a significant difference between the two groups (Experts: 0.17  $\pm$  0.12; Novices: 0.01  $\pm$  0.01;  $U = 0$ ;  $Z = -2.45$ ;  $p = 0.014$ ; *exact p* = 0.016).

- Insert Figure 3 -

#### *Detrended Fluctuation Analysis*

We present in Figure 4 the point-by-point average diffusion plots, for the two groups. In both case, the diffusion plots present a global linear shape. A clear flattening appears for the Expert group, suggesting the influence of a white noise component in the series. This influence is less apparent for the Novice group, essentially because the global shape is close to that expected for white noise processes ( $\alpha = 0.5$ ).

The individual values were the following: Novices : {0.69, 0.63, 0.65, 0.53, 0.45} ; Experts : {1.30, 0.69, 1.16, 1.08}. There was a significant difference between the two groups (Expert:  $1.06 \pm 0.26$ ; Novices:  $0.59 \pm 0.10$ ;  $U = 0$ ;  $Z = -2.45$ ;  $p = 0.014$ ; *exact p* = 0.016).

- Insert Figure 4 -

#### *Power Spectral Density analysis*

We present in Figure 5 the point-by-point average bi-logarithmic power spectra, for the two groups. The flattening of the spectra in the high g-frequency region revealed for both group the influence of a white noise component. The individual values of the  $\beta$  exponent, computed over the low-frequency region, were: Novices : {-0.16, 0.24, 0.74, 0.14, 0.17}; Experts : {1.57, 1.04, 1.55, 1.14}. There was a significant difference between groups (Experts:  $1.32 \pm 0.28$ ; Novices:  $0.23 \pm 0.33$ ;  $Z = -2.45$ ;  $p = 0.014$ ; *exact p* = 0.016).

- Insert Figure 5 -

#### *Discussion*

Motor learning has been classically assumed to be characterized by the selection of the most efficient behavioral solutions, a decrease of performance variability, and an increase of smoothness in movement trajectories [18]. This point of view tends to induce the idea that

learning yields a kind of simplification of the system, through the selection of proper procedures and the elimination of errors.

The present results confirm these classical assumptions, and especially the very low variability of cyclical performance in experts. The most important result, however, is the increase of serial correlations in experts, with regards to the levels observed in novices. Expert performance seems characterized by a more complex and structured dynamics than that of novices.

This result could be interestingly related to a recent work that linked long-range correlation and degeneracy [24]. Degeneracy is a design principle of complex systems which has been proposed for explaining the co-existence of the a priori paradoxical properties of robustness and evolvability [25]. Robustness refers to the capacity to maintain a function despite internal or external perturbations, and evolvability to the capacity to adapt to perturbations by adopting new behavior and functions. The concept of degeneracy refers to a *partial overlap* in the functions of the multiple components within the system. In degenerate systems, structurally different components can perform similar functions under certain conditions, but can also assume distinct roles in others conditions [26,27].

Delignières and Marmelat [24] propose a model of degenerate neural network composed of a chain of partially overlapping pathways. They manipulated degeneracy through the number of alternative pathways in the model. A simulation study showed that (1) such a degenerate model produces long-range correlated series, (2) the strength of correlations in the output depends on the level of degeneracy in the model, and (3) a minimal threshold in degeneracy is necessary for producing long-range correlations.

The present experiment suggests that learning could be understood as the progressive installation of degeneracy in the system. Learning is not the selection of the most appropriate solution, but the coordination of a complex network composed of multiple, alternative and

overlapping pathways for producing a given outcome. Learning can then be conceived as an increase in complexity of the neural networks that underlie performance, and the overlapping between alternative pathways explains the presence of long-range correlations in output series. This enrichment of neural networks could explain the property of robustness of motor skills, essentially revealed in retention tests, but also the properties of generalizability and transfer, which are considered essential for the completeness of learning [18].

Schöllhorn, Hegen, and Davids [28] recently developed innovative ideas about learning that could be in resonance with the previous finding. They proposed a so-called *differential learning approach*, that explicitly aimed to exploit the system's complexity by its confrontation to complex and changeable environments and constraints. It is noteworthy to note, however, that this enrichment in complexity also occurs during the practice of very close and simple tasks, such as the reciprocal aiming task used by Wijnants and coll. [20].

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## Figure Captions

Figure 1: The ski simulator

Figure 2: Example period series. Top: novice participant; Bottom: Expert participant.

Figure 3: Mean autocorrelation functions. Top: Novice group ( $N = 5$ ); Bottom: Expert group ( $N = 4$ ). The dashed line represents the level of significance ( $p < 0.05$ ).

Figure 4: Mean DFA diffusion plots for the Novice (grey) and Expert (white) groups. Dashed lines represent the mean slopes of the long-term region of the diffusion plots.

Figure 5: Mean Log-log power spectra for the Novice (top) and Expert (bottom) groups. Dashed lines represent the mean negative slopes in low frequency-region of the power spectrum.



Figure 1



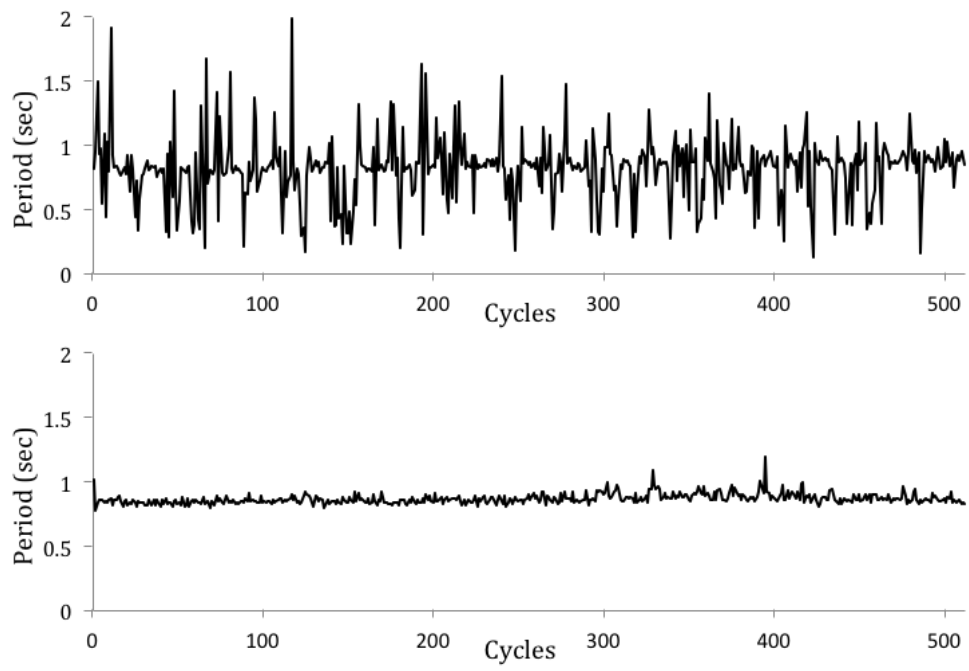


Figure 2

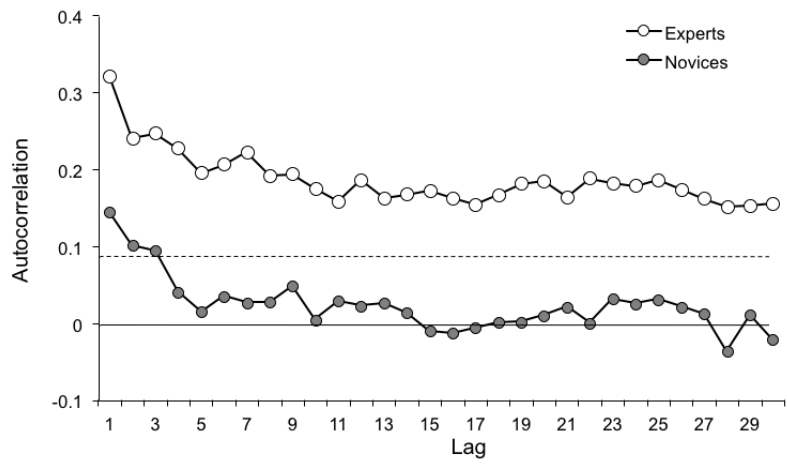


Figure 3

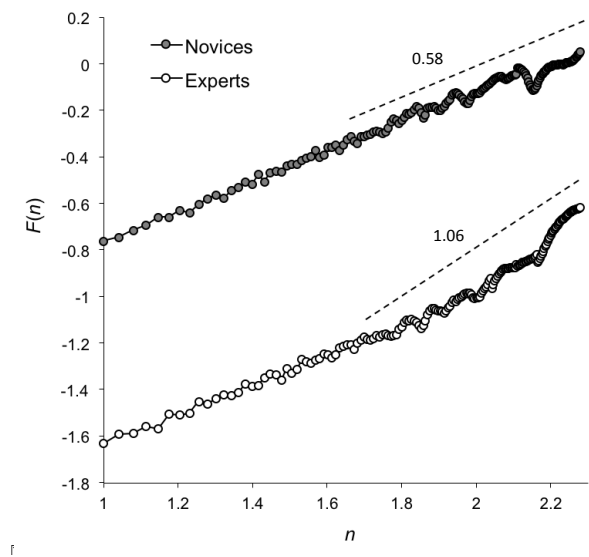


Figure 4

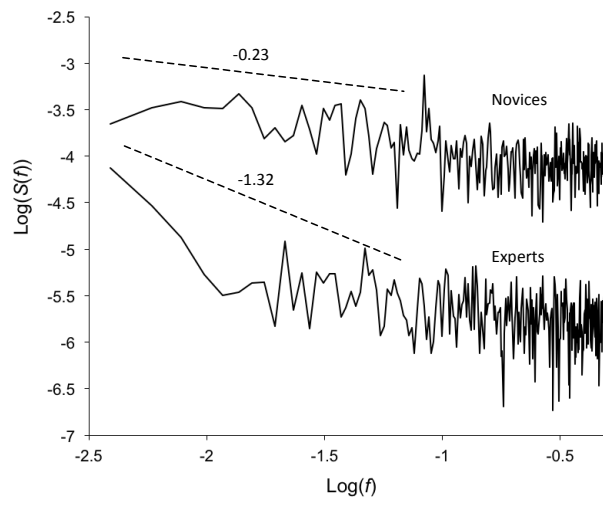


Figure 5