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Physics of a random biological process

E. Canessa and A. Calmetta
International Centre for Theoretical Physics, Trieste, Italy
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We analyze the successive fluctuations of the daytime and nighttime sleep pattern of a newborn baby by using tools of far-from-equilibrium statistical physics. We find that this class of natural random biological process displays a remarkable long-range power-law correlation that extends for, at least, the first six months of life. Such a scaling behavior might help to characterize the underlying dynamics of the (early) growth and development of humans through analyzing the time series generated when asleep.

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The topic long-range "critical phenomena" type correlations in biological systems, using tools of nonequilibrium statistics, is of considerable current interest in the physics community. Of these we mention, e.g., the discovery of long-range correlations in several different DNA sequences when viewed as random processes [1–3] and the long-range anticorrelations generated by the human heartbeat time series [4]. Besides this, research on the pattern-recognition phenomenon in very young babies has continued to produce surprises [5]. In this context it is tempting to wonder if an investigation of the underlying dynamics of the early growth and development of humans might also be recognized by applying physics. This is so because this phenomenon must be closely related to the time series generated while asleep. In fact, throughout cycles of 24 h, young babies slept and woke up randomly so that they biologically generated another class of random temporal series that can also be analyzed via far-from-equilibrium statistical physics, similar to the studies in Refs. [1–4].

A first step towards understanding the dynamics of the process of human growth and development, at an early age, is to analyze the quantitative measure of the daytime and nighttime sleep of an infant. This is the aim of this work. Herein we shall use measurements of the sleep pattern of a newborn baby, named Maddalena, to construct a simple 1:1 map of the data onto an equivalent random "walk" in order to search for possible correlations. The sleep pattern is treated as a time series similar to that observed in nonlinear dynamical systems with complex feedback. We report that such a mapping of the newborn sleep pattern displays a remarkable long-range power-law correlation that is ubiquitous in nature [6–8], at least during the first six months of life.

Figure 1 shows the total number of sleeping hours against the day of the month taken right from the fifth day after birth (marked by an arrow) until six months and five days later, ranging from early spring to late autumn. The first five days were spent at the hospital in a common room with other babies. At delivery, and during the six-month neonatal period in question, the anatomic figures were just above normal average.

Newborn babies sleep on average about 16 h a day [9]. The measured random fluctuations at each displayed month in Fig. 1 fall around the extreme values of 8.17 and 17.75 h. In many babies, the minimum values are largely determined because of crying previously after coping with gastric colic, typical during the earliest days, and because of the effect of immunization toward the end of three and six months of age. The main peaks are the consequence of a need for longer sleep as a natural response to a young baby's interest in everything, especially so from the age of three months. We estimate the error of such measurements to be less than 5%.

It is in the sleep pattern of Fig. 1 that we encounter very interesting results. Following previous studies [1–4], this class of random temporal series also motivates the quantification of possible time correlations of a biological process by computing the average value of the total number of sleeping hours during a period of d number of days. We thus define

$$h(d,t)=\sum_{k=t+1}^{t+d} h_k. \tag{1}$$

Then

$$H(d)=\langle h(d,t)\rangle=\frac{1}{L-d+1}\sum_{t=0}^{L-d} h(d,t), \tag{2}$$

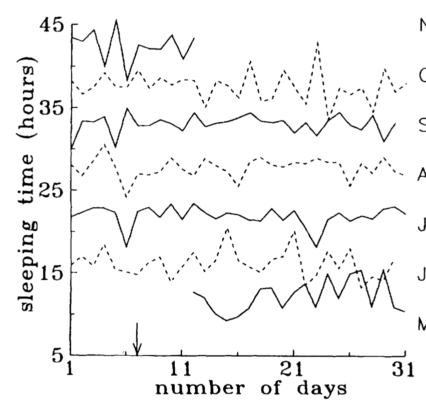

FIG. 1. The newborn sleep pattern along six months. The arrow indicates the date of birth. Monthly data above May are shifted by 5 h each.

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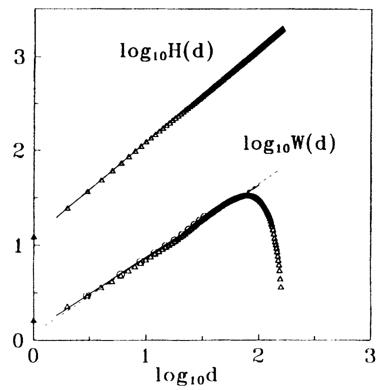

FIG. 2. Scaling behavior of the random pattern of Fig. 1. For large d values, deviations from a linear behavior arise because of the data size effects. The slope of 0.763 characterize "a class of natural random biological process" as discussed in the text.

where L is the total number of days in the observation period ($L=185$). From a statistical physics viewpoint, the above might be equivalent to calculate the total displacement of a one-dimensional random walker mapped 1:1 from the measurements of Fig. 1. In the present work such an imaginary walker moves upwards only, i.e., a *directed* random walk in the time domain [1–10]

We characterize this peculiar random walk by the variance

$$W(d)=\left\{\frac{1}{L-d+1}\sum_{t=0}^{L-d}[h(d,t)-H(d)]^2\right\}^{1/2} \quad (3)$$

or

$$W(d)=\langle[h(d,t)-H(d)]^2\rangle^{1/2}. \quad (4)$$

This second calculation enables us to see if fluctuations of the random pattern generate a linear (power-law) behavior [1].

Figure 2 shows the double logarithmic plots of the mean H and root mean square W as a function of d. From the slopes of the straight, full lines in this figure, calculated by a least-squares fit, it can be visualized how H and W indeed increase with the d amount of days as power laws. To a good approximation, for the case of considering d to represent a complete day cycle (i.e., 24 h), H nicely scales with d as

$$H\sim d^{\nu}, \quad \nu=1.001 \quad (5)$$

such that the exponent ν is pretty close to unity.

From Fig. 2 we also have that W scales with d as

$$W\sim d^{\mu}, \quad \mu=0.763 \quad (6)$$

which is an indication that the daytime and nighttime sleep of human infants might be correlated. As shown in this figure, these results for H and W extend for several days. For large d, deviations from a linear behavior arise because of the data size effects.

As seen in Fig. 1 the minima in sleeping time (given in h) are followed by maxima for the reasons explained above. In statistical terminology this means that the data for a short time scale of the order of 2 d is anticorrelated, implying an initial value of the $W(d)$ slope in Fig. 2: $\mu_i\sim 0.485<0.5$. Two basic statistical quantities are the average daily sleeping time $H(d=1)$ and its standard deviation $W(d=1)$ which we give next. For $H(1)$ we obtain 12.29 h and for $W(1)$ we find it to be 1.64 h.

The present correlations seem to be truly long and independent of the details of any set of days chosen within the six month period at hand. In fact, we also have to check the cases for d representing cycles of more than a day (e.g., 48, 72, . . ., h). In all such calculations we obtain similar results. The dotted line results shown in Fig. 2 (which are obtained by fitting the open dots) correspond to the case of measurement cycles of 72 h (i.e., d equals every 3 d). Thereafter we derive a $W(d/3)$ slope of $\mu=0.787$, which when averaged to the above value of $W(1)$ gives an estimation for the statistical error of the real data at large time intervals to be less than 3%.

In passing we also mention that we also attempted to calculate the Fourier spectrum of the data in Fig. 1 [4,8]. But because of the relatively small amount of days in a semester, the spectral data obtained could not be smoothed simply because of the impossibility of averaging. Though we still notice a sort of $1/f$-like behavior (not shown).

Measurements were extended for six months because of many reasons. Around this date several new variables appear in the life of a baby which lead to different behavior for the data as in Fig. 2. This is essentially the consequence of the rather different criteria needed to quantify a 24 h cycle since from about six months, babies start to sleep until morning without (solid) food and adopt a rather sociable sleep pattern with a longer sleep at night and a regular daytime sleep giving them energy for their active life [9].

In this way, according to the unexpected results of Fig. 2, it is tempting to believe in the existence of long-range power-law correlations for the random sleep patterns of humans based solely on their statistical properties. Such scalings might help to characterize the underlying dynamics of the (early) growth and development of humans by analyzing the time series generated when asleep, similar to those observed in nonlinear dynamical systems with complex feedback. However, before making any firm conclusion, it is certainly necessary to recognize more evidence and see if this interesting finding is universal. The difficulty in repeating this investigation on several young babies, to average the data, is, as for Maddalena, on recording random daytime and nighttime sleep patterns and following these measurements closely for at least six months. Of course, this requires one to spend 185 broken and noisy nights uninterruptedly.

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