Scaling of horizontal and vertical fixational eye movements

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(Received 16 July 2004; published 21 March 2005)

Eye movements during fixation of a stationary target prevent the adaptation of the visual system to continuous illumination and inhibit fading of the image. These random, involuntary, small movements are restricted at long time scales so as to keep the target at the center of the field of view. Here we use detrended fluctuation analysis in order to study the properties of fixational eye movements at different time scales. Results show different scaling behavior between horizontal and vertical movements. When the small ballistic movements, i.e., microsaccades, are removed, the scaling exponents in both planes become similar. Our findings suggest that microsaccades enhance the persistence at short time scales mostly in the horizontal component and much less in the vertical component. This difference may be due to the need for continuously moving the eyes in the horizontal plane, in order to match the stereoscopic image for different viewing distances.

DOI: 10.1103/PhysRevE.71.031909 PACS number(s): 87.19.La, 05.45.Tp, 89.75.Da

I. INTRODUCTION

Images stabilized on the retina of awake humans soon fade and are no longer seen. This is in line with the general principle that the nervous system responds to change and eschews constant stimulation, to which it readily adapts. In order to prevent fading, the oculomotor system has evolved three different movements that occur during visual fixation that have the effect of preventing perceptual fading. Those movements are: (i) high-frequency small-amplitude tremor, (ii) slow drift, and (iii) fast microsaccades [1]. These movements are generally assumed to counteract the adaptation of the visual system by their small random displacements, although their role in the visual process is not yet fully understood [2].

Tremor (or physiological nystagmus) is high-frequency (about 90 Hz [1]) oscillations of the eye, typically less than 0.01 deg, and thus causes the image of an object to constantly stimulate new cells in the fovea [3]. Drifts are slow movements, with a mean amplitude within a range of 0.04 to 0.13 deg on average [1], away from a fixation point.

Each instance of drift is necessarily terminated by a microsaccade (cf. Fig. 1). Microsaccades are rapid small-amplitude movements ranging between 0.02 and 1 deg and occur at a typical mean rate of 1 to 2 per second [4]. Microsaccades seem to reposition the eye on the target.

Drift and tremor movements are rather irregular and show statistical properties of a random walk [5]. Microsaccades, however, create more linear movement segments embedded in the eyes' trajectories during fixational movements. There is evidence that microsaccades (i) are persistent and antipersistent at different time scales [2], (ii) show a characteristic signature of suppression and overshoot in response to visual change [4,6], and (iii) orient themselves according to covert shifts of attention [1].

Herein we do not address the longstanding question of the purpose of these miniature eye movements [7], but rather our concern is their dynamical behavior and if there is any difference in scaling between horizontal and vertical fixational eye movements [8]. We investigate these questions using detrended fluctuation analysis (DFA) [9,10], a technique used to detect possible long-term correlations in time series. We find that the persistence of horizontal and vertical fixational eye movements exhibit pronouncedly different behavior mostly due to the effect of the microsaccades. This result is in good agreement with the neurophysiological fact that horizontal and vertical components of saccades are controlled by different brain stem nuclei [11] and are known to have different behavioral properties. These differences exist even

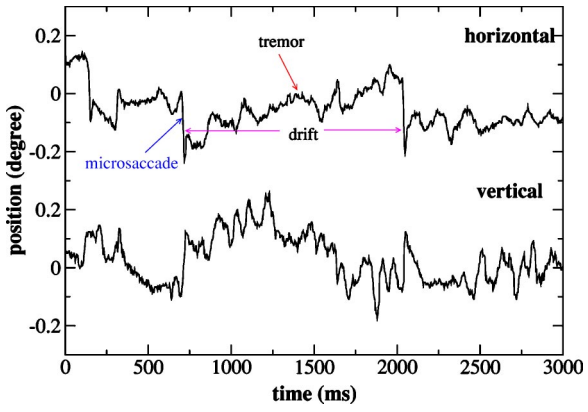

FIG. 1. Simultaneous recording of horizontal and vertical position of left eye movements. The traces show microsaccades, drift, and tremor in eye position. In the horizontal tracing, up represents right and down represents left; in the vertical tracing, up represents up and down represents down movements.

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during oblique saccades [12]. Indeed, many of the microsaccades seen were oblique. We have thus quantified one more difference between the two planes that occurs during diagonal movements.

Our study indicates that after removing the microsaccades, the scaling behavior of both components becomes similar. These findings may further elucidate the mechanisms underlying effects of microsaccades on perception and attention [2,4,6] and their role in the neurophysiology of vision [13–16]. In addition, in many pathological states the fixation system can be disrupted by slow drift, nystagmus, or involuntary saccades. However, because all three of these occur in healthy individuals, it may be difficult to determine if there is truly an abnormality present. Thus, further characterizing of the fixational system may be useful in clinical evaluation of such dysfunction.

II. DATA

Data were collected from five normal subjects from the University of Potsdam. All procedures were in accordance with the Helsinki Declaration. All subjects gave written informed consent, had normal or corrected to normal vision, and are experienced participants in eye-tracking experiments. Eye movements for these participants were recorded using an EyeLink-II system with a sampling rate of 500 Hz and an instrument spatial resolution <0.005 deg. The subjects were required to fixate a small stimulus with a spatial extent of 0.12 deg or 7.2 arcmin (3×3 pixels on a computer display, black square on a white background). This stimulus produced a rate of microsaccades similar to those obtained with a wide variety of other stimuli used in the same laboratory. Each participant performed 100 trials with a duration of 3 s, well longer than the currently accepted time for visual fading of a stabilized image. During off-line processing, some of the trials were discarded; for example, if they contained saccades greater than 1 deg, leaving us a total of 474 trials for further analysis [2]. All trials were identical—simple fixation—and thus the absence of a few trials for any one subject is inconsequential. The recording of each trial includes position trajectories of horizontal and vertical components of left eye and right eye movements.

Figure 1 shows a typical simultaneous recording of horizontal and vertical miniature eye movements for the left eye from one subject. The horizontal and vertical movements (upper and lower traces in the figure, respectively) exhibit an alternating sequence of slow drift and resetting microsaccades. Usually, the subjects show an individual preponderance regarding the direction of these drifts and resetting microsaccades. In this subject, for example, the drift in the horizontal movement occurred typically to the right and the microsaccades to the left (Fig. 1).

III. METHODS OF ANALYSIS

To study the dynamical behavior of fixational eye movements we employ DFA, which was developed to quantify long-term power-law correlations embedded in a nonstationary time series [9]. The DFA method has been successfully applied to research fields such as cardiac dynamics [10,17–20], human gait [21], climate temperature fluctuations [22,23], and neural receptors in biological systems [24]. Here we apply this method to the velocity series derived from the position series of fixational eye movements.

For a position series x_i, $i=1,\ldots,N+1$, of a horizontal or vertical movement, we first calculate its velocity series v_i by $v_i=T_0(x_{i+1}-x_i)$, where T_0 is the sampling rate; in our experiments $T_0=500$ Hz. We chose to use a two-point velocity in order to avoid any smoothing and to clearly characterize the direction and magnitude of a movement. For other definitions of velocity, see [4].

We first calculate the integrated series as a profile

$$Y(k)=\sum_{i=1}^{k}[v_i-\langle v\rangle],k=1,\ldots,N. \tag{1}$$

Subtraction of the mean $\langle v\rangle$ of the whole series is not compulsory since it would be eliminated by the detrending, which will be calculated in the next steps [25]. Thus, $Y(k)$ in Eq. (1) actually represents the "position."

We then divide the profile $Y(k)$ of N elements into $N_t=\mathrm{int}(N/t)$ nonoverlapping segments of equal length t, where $\mathrm{int}(N/t)$ denotes the maximal integer not larger than N/t. Since the length N of the series is often not a multiple of the considered time scale t, a short part at the end of the profile may remain. In order not to disregard this part of the series, the same procedure is repeated starting from the end (of series) to the beginning. Therefore, $2N_t$ segments are obtained all together.

Next, we determine in each segment the best polynomial fit of the profile and calculate the variance of the profile from these best polynomials fit

$$F^2(\nu,t)\equiv\frac{1}{t}\sum_{i=1}^{t}\{Y[(\nu-1)t+i]-y_v(i)\}^2 \tag{2}$$

for each segment $\nu,\nu=1,\ldots,N_t$, and

$$F^2(\nu,t)\equiv\frac{1}{t}\sum_{i=1}^{t}\{Y[N-(\nu-N_t)t+i]-y_\nu(i)\}^2 \tag{3}$$

for $\nu=N_t+1,\ldots,2N_t$, where y_ν is the fitting polynomial in segment ν. If this fitting polynomial is linear, then it is the first-order detrended fluctuation analysis (DFA1). This eliminates the influence of possible linear trends in the profile on scales larger than the segment [9]. In general, in the nth-order DFA (DFAn), y_ν is the best nth-order polynomial fit of the profile in segment ν. Therefore, linear, quadratic, cubic, or higher-order polynomials can be used in the fitting procedure. Since the detrending of the original time series is done by the subtraction of the polynomial fits from the profile, different-order DFA differ in their capability of eliminating trends of order $n-1$ in the series.

Finally, the fluctuation $F(t)$ over the time windows of size t is determined as a rms of the variance

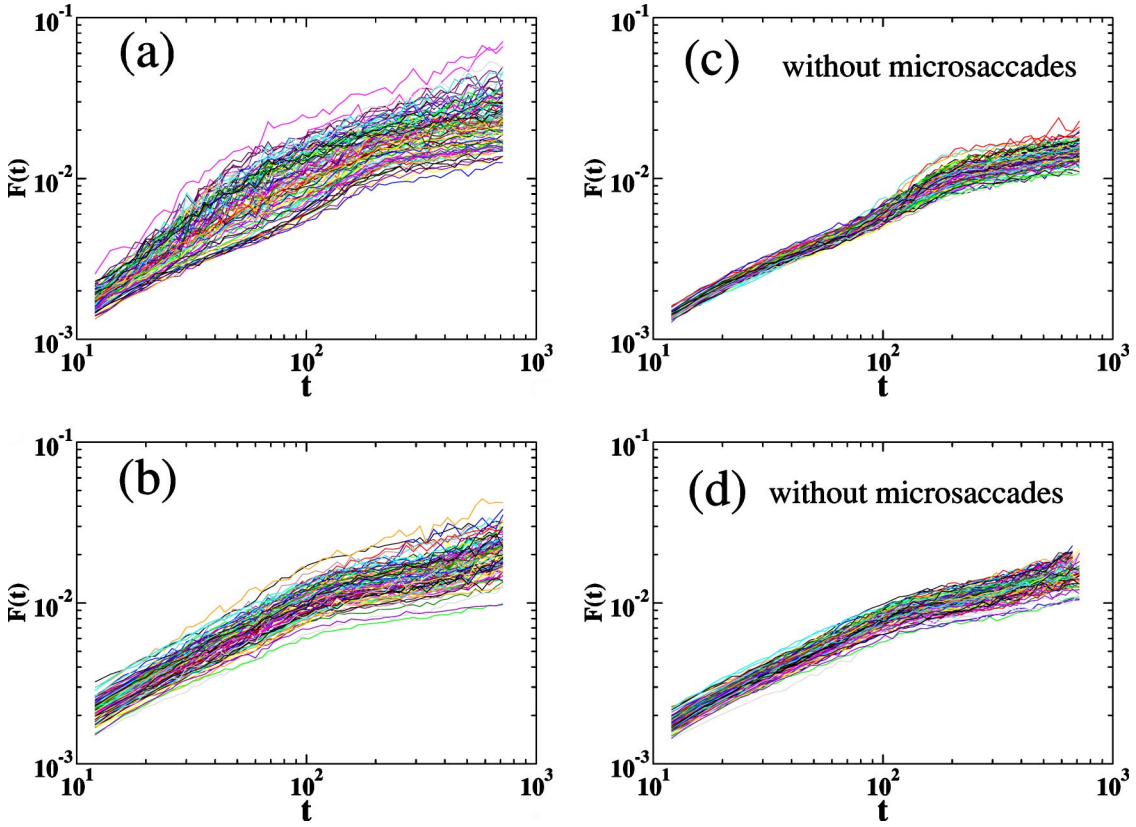

FIG. 2. Detrended fluctuation analysis (DFA2) of velocity records of horizontal and vertical eye movements, from the right eye of a typical participant; the time units are milliseconds while $F(t)$ units are in degrees: (a) horizontal, (b) vertical, (c) horizontal [same data as (a)] after removing microsaccades, and (d) vertical [same data as (b)] after removing microsaccades.

$$F(t) = \sqrt{\frac{1}{2N_t}\sum_{\nu=1}^{2N_t} F^2(\nu,t)}.$$

This computation is repeated over all possible interval lengths. Of course, in DFA, $F(t)$ depends on the DFA order n. By construction, $F(t)$ is only defined for $t \geqslant n+2$. For very large scales, for example, for $t > N/4$, $F(t)$ becomes statistically unreliable because the number of segments N_t for the averaging procedure becomes very small. We therefore limit our results to $[n, N/4]$.

Typically, $F(t)$ increases with interval length t. We determine the scaling behavior of the fluctuations by analyzing log-log plots of $F(t)$ versus t. A power law $F(t) \propto t^{\alpha}$, where α is a scaling exponent, represents the long-range power-law correlation properties of the signal. If $\alpha = 0.5$, the series is uncorrelated (white noise); if $\alpha < 0.5$, the series is anticorrelated; if $\alpha > 0.5$, the series is correlated or persistent.

IV. ANALYSIS OF FIXATIONAL EYE MOVEMENTS

Micro eye movements (as mentioned before) are generally assumed to prevent the adaptation of the visual system by their small random displacements [2]. Early experiments dating back over 50 years discovered this phenomenon and detected fading on the time scale of several seconds. More recent studies have found that even much briefer periods of visual stabilization lead to a significant decrease in visibility [1]. Coppola and Purves [26] found that some images can disappear in less than 80 ms.

We applied DFA1–DFA4 to all velocity records derived from the horizontal and vertical micro eye movement components. Since the scaling exponents of the fluctuation functions obtained by DFA1–DFA4 are similar, we show here the DFA2 results as representative of the DFA analysis.

As can be seen from Figs. 2(a) and 2(b), the fluctuation functions of horizontal components have pronounced differences from the fluctuation function of vertical components. This is expressed by several characteristics, which can be observed. There is a broader range of exponents in the horizontal compared to the vertical. The crossover times, from large exponents (at short time scales) to smaller exponents (at large time scales) in the horizontal, also show a broader range compared with the vertical. Moreover, the scaling exponents at short time scales (between 12 and 40 ms) for horizontal are typically larger than the corresponding exponents for vertical. However, if we remove the microsaccades [27], the fluctuations of both components, and the corresponding crossovers and the exponents at small time scales become similar [Figs. 2(c) and 2(d)]. This result indicates that microsaccades strongly influence the horizontal components in fixational eye movements. Note, the close similarity of the fluctuation function $F(t)$ in the different 3 s trials, in particular after removing the microsaccades, which indicates that

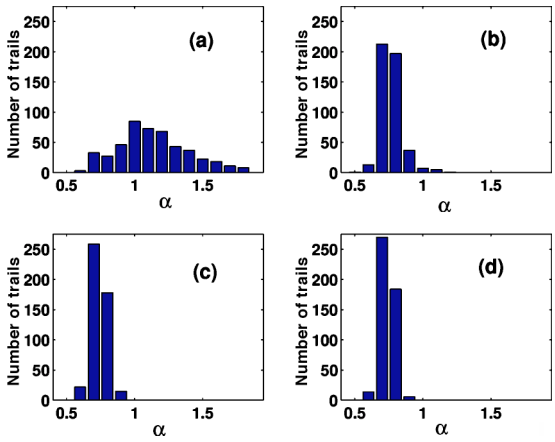

FIG. 3. Histograms of the number of trails having an exponent α, obtained by DFA2 at the short time scales (between 12 and 40 ms) for all the horizontal and vertical trials (with duration of 3 s) with and without microsaccades from the left eyes of all participants: (a) horizontal, (b) vertical, (c) horizontal without microsaccades, and (d) vertical without microsaccades.

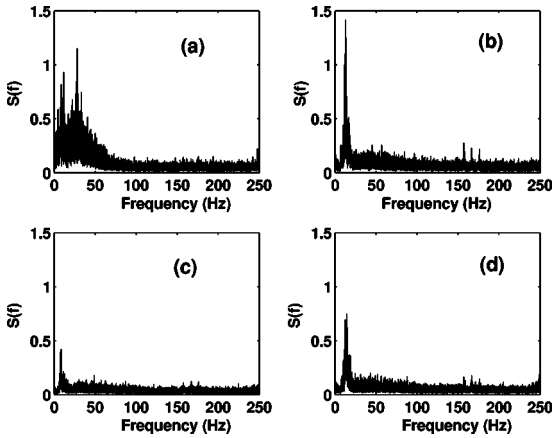

FIG. 4. Power spectral density $S(f)$ for the velocity series derived from the horizontal and vertical components from the right eye of one typical participant: (a) horizontal with microsaccades, (b) vertical with microsaccades, (c) horizontal after removing the microsaccades, and (d) vertical after removing the microsaccades.

the scaling exponent is a stationary and significant characteristic of the eye movement.

In Fig. 3 we show the histograms of the scaling exponents for the short time scales, for all trials with and without microsaccades from the left eyes of all participants. From this plot we notice that, at the short time scale, the horizontal and vertical components exhibit persistent behavior ($\alpha > 0.5$), where the horizontal components are much stronger correlated than the vertical. The average value of the scaling exponents for all trials is 0.76 for the vertical components and 1.1 for the horizontal components [see Table I(a)]. The scaling exponents of horizontal components show a broader distribution than the vertical components. However, after removing microsaccades, the fluctuations of horizontal components and the corresponding scaling exponents have a pronounced change to a narrow distribution, while the vertical components change very little [Figs. 2(b) and 2(d); 3(b) and 3(d)]. When comparing the scaling exponents for the original horizontal series with the scaling exponents for the horizontal removed microsaccades series, we find that the scaling exponents decrease from an average value around 1.1 to 0.74, while for the vertical components the scaling exponents decrease from an average value around 0.76 to 0.74 (Table I). Horizontal and vertical become similar after removing microsaccades.

TABLE I. Average values of the scaling exponents obtained by DFA2 for all fixational eye movements we measured. HL=horizontal movements of the left eye, HR=horizontal movements of the right eye, VL=vertical movements of the left eye, and VR=vertical movements of the right eye.

Component	Short time scale	Long time scale
	(a) Microsaccades included	
HL	1.13±0.26	0.29±0.14
HR	1.05±0.25	0.31±0.14
VL	0.76±0.08	0.34±0.13
VR	0.76±0.09	0.30±0.12
	(b) Microsaccades removed	
HL	0.74±0.06	0.26±0.11
HR	0.73±0.05	0.26±0.10
VL	0.74±0.05	0.36±0.14
VR	0.74±0.04	0.35±0.13

We find that at long time scales (between 300 and 600 ms), the horizontal and vertical components show antipersistence behavior ($\alpha < 0.5$) [see Table I(a)], with no significant differences between them. After removing the microsaccades, the scaling exponents at the long time scales remain almost the same as before. The horizontal components become slightly less antipersistent than the vertical [see Table I(a)].

We thus conclude that microsaccades in the horizontal components are more dominant than in the vertical direction in fixational eye movements. The microsaccades enhance the persistence mostly in the horizontal components at short time scales. At the long time scales, both horizontal and vertical components are antipersistent and are less affected by the microsaccades.

To further test if the above results are indeed affected by microsaccades, we randomly removed parts of the series under study with the same length as the removed microsaccades and repeated the DFA analysis. We found that this procedure does not influence the scaling exponents. Thus, the scaling difference between the series with and without microsaccades is indeed due to microsaccades.

Finally, we tested if the effect of microsaccades can also be seen in the power spectral density. To this end, we analyzed the power spectra of the horizontal and vertical velocity series, for the right eye of a typical participant, for all trials with and without microsaccades. Results are shown in Figs. 4(a) and 4(b), where the microsaccades are included. The power spectral density of horizontal and vertical components are found to be different [Figs. 4(a) and 4(b)]. After

removing the microsaccades the components become similar [Figs. 4(c) and 4(d)]. This finding also indicates that the effect of the microsaccades in the horizontal component is stronger than in the vertical. Note that this effect is seen much more clearly in the DFA curves, where only a few trials (of 3 s) are sufficient to distinguish between the horizontal and vertical eye movements.

V. DISCUSSION

When the visual world is stabilized on the retina, visual perception fades as a consequence of neural adaptation. During normal vision, we continuously move our eyes involuntarily even as we try to fixate our gaze on a small stimulus, preventing retinal stabilization and the associated fading of vision [1]. The nature of the neural activity correlated with microsaccades at different levels in the visual system has been a longstanding controversy in eye-movement research. Steinman [28] showed that a person may select not to make microsaccades, and still be able to see the object of interest, whereas Gerrits and Vendrik [29] and Clowes [30] found that optimal viewing conditions were obtained only when both microsaccades and drifts were present. Since microsaccades can be suppressed voluntarily in high acuity observation tasks [31,32], it was concluded that microsaccades serve no useful purpose and even that they represent an evolutionary puzzle [4,7].

Our study using DFA suggests that microsaccades play different roles on different time scales in vertical and horizontal components in the correction of eye movements, consistent with [2]. Moreover, we show that due to microsaccades there is also different scaling behavior in horizontal and vertical fixational eye movements. Our results suggest that microsaccades at short time scales enhance the persistence mostly in horizontal movements and much less in vertical movements.

Our findings that the persistence in horizontal and vertical fixational eye movements, which are controlled by different brain stem nuclei, exhibit pronounced different behavior, and also show that the role of microsaccades in horizontal movements is the more dominant. These findings may provide better understanding of the recent neurophysiological findings on the effects of microsaccades on visual information processing [13–16].

ACKNOWLEDGMENTS

We thank Tomer Kalisky for his assistance in applying the DFA method, and Dr. Samuel Ron, Dr. Lance M. Optican, and Dr. Michael E. Goldberg for constructive suggestions on the manuscript. This work is supported in part by Grant Nos. KL955/6 and KL955/9 (Deutsche Forschungsgemeinschaft) and by NSFC (Nos. 10271031 and 10371043), and the Shanghai Priority Academic Discipline.

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