Scaling of Horizontal and Vertical Fixational Eye Movements

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\textbf{ABSTRACT}

Eye movements during fixation of a stationary target prevent the adaptation of the photoreceptors 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 the Detrended Fluctuation Analysis (DFA) 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 ballistics movements, i.e. micro-saccades, are removed, the scaling exponents in both directions become similar. Our findings suggest that micro-saccades 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 of continuously moving the eyes in the horizontal plane, in order to match the stereoscopic image for different viewing distance.

\textbf{I. INTRODUCTION}

When we view a stationary scene, our eyes perform extremely small autonomic movements. These fixational (or miniature) eye movements are produced involuntarily and are characterized by three different types of movements: (i) high-frequency small amplitude tremor, (ii) slow drift, and (iii) fast microsaccades [1,2]. Generally, they serve to counteract retinal adaptation by generating small random displacements of the retinal image in stationary viewing. Studies of fixational eye movements have been going on since the 1950s, but the role of the drift, tremor and microsaccadic movements in the visual process is not yet fully understood [2,3].

When fixating an object its image falls on the fovea, the region of highest visual acuity in the center of the visual field. Drifts are slow movements with a mean amplitude within a range of 1.2 – 9 min arc [2], 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 1\,' and 60\,' arc and occur at a typical mean rate of 1 to 2 per second [4]. Microsaccades seem to reposition the eye on the target. Tremor (or physiological nystagmus) is a high-frequency (ranging from 50 to 100 Hz [2]) oscillations of the eye typically less than 0.01 deg, i.e., less than the size of one photoreceptor, and is superimposed on drift. Tremor serves to continuously shift the image on the retina, thus calling fresh retinal receptors into operation. If an image is artificially fixed on the retina it fades and disappears within a few seconds [5]. Tremor causes every point of the retinal image to move approximately the distance between two adjacent foveal cones in 0.1 seconds and thus causes the image of an object to constantly stimulate new cells in the fovea [6]. Drift and tremor movements are rather irregular and show statistical properties of a random walk [7]. Microsaccades, however, create more linear movement segments embedded in the eyes’ trajectories during fixational movements. There is evidence that microsaccades are (i) persistent and anti-persistent at different time scales [3], (ii) show a characteristic signature of suppression and overshoot in response to visual change [4,8], and (iii) orient themselves according to covert shifts of attention [1].

Although finding the specific function of fixational eye movements has been a long-standing and controversial topic in eye movements research [9], our concern is not the purpose of such movements but rather the dynamical behavior of fixational eye movements and if there is some difference between horizontal and vertical fixational eye movements. In this article we mainly investigate these questions using the detrended fluctuation analysis [10,11], 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 pronounced 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 [12]. 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 microsac-
cades on perception and attention [3,4,8] and their role in the neuropysiology 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 was collected from five normal subjects. 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°. The subjects were required to fixate a small stimulus with a spatial extent of 0.12° or 7.2 arc min (3 x 3 pixels on a computer display, black square on a white background). Each participant performed about 100 trials with a duration of 3 seconds and total of 474 trials were obtained [3]. The recording of each trial includes position trajectories of horizontal and vertical components of left eye and right eye movements.

![Image](image-url)

FIG. 1. Eye position simultaneous recording of horizontal and vertical components 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.

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 the detrended fluctuation analysis (DFA) which was developed to quantify long-term power-law correlations embedded in a nonstationary time series [10]. The DFA method has been successfully applied to research fields such as cardiac dynamics [17,11,18–20], 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 $x_i$, $i = 1, \cdots, N + 1$, 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 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

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

Subtraction of the mean $\langle v \rangle$ of the whole series is not compulsory since it would be eliminated by the detrending in the third step [25]. Thus $Y(k)$ in Eq.(1) represents actually the “position”.

We then divide the profile $Y(k)$ of $N$ elements into $N_t = \text{int}(N/t)$ non-overlapping segments of equal length $t$, where $\text{int}(N/t)$ 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 opposite end. Therefore, $2N_t$ segments are obtained altogether.

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

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

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

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

for $\nu = N_t + 1, \cdots, 2N_t$, where $y_{\nu}$ is the fitting polynomial in segment $\nu$. 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 profiles on scales larger than the segment [10]. In general, in the nth order DFA (DFAn), yν 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 root-mean-square of the variance

\[
F(t) = \left( \frac{1}{2N_t} \sum_{\nu=1}^{2N_t} F^2(\nu, t) \right)^{1/2}.
\]

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 \( t \geq n + 2 \). 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 \( \alpha \) 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 anti-correlated; if \( \alpha > 0.5 \), the series is correlated or persistent.

### IV. ANALYSIS OF FIXATIONAL EYE MOVEMENTS

We applied DFA1-4 to all velocity records derived from the horizontal and vertical components. Since the scaling exponents of the fluctuation functions obtained by DFA1-4 are similar, we show here the DFA2 results as a representative of the DFA analysis.

As can be seen from Figs.2 (a) and (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 horizontal, also show a broader range compared with the vertical. Moreover, the scaling exponents at short time scales (between 12 milliseconds and 40 milliseconds) for horizontal, are typical larger than the corresponding exponents for vertical. However, if we remove microsaccades [26] the fluctuations of both components, the corresponding crossovers and the exponents at small time scales become similar (Figs. 2(c) and (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 seconds trials, in particular after removing the microsaccades, indicates that 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 (see Figs.2 (b) and (d); and Figs.3 (b) and (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.

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 the short time scales. At the long time scales both horizontal and vertical components are anti-persistence and 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 be seen also 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 (b) where the microsaccades are included. The power spectral density of horizontal and vertical components are found to be different (Figs.4 (a) and (b)). After removing the microsaccades the components become similar (Figs.4 (c) and (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 clearer in the DFA curves where only a few trials (of 3 sec) are sufficient to distinguish between the horizontal and vertical eye movements.

We find that at long time scales (between 300 and 600 milliseconds), the horizontal and vertical components show anti-persistence behaviour ($\alpha < 0.5$) (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 anti-persistent than vertical (see Table I(A)).

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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 long standing controversy in eye-movements research. Steinman [27] showed that a person may select not to make microsaccades, and still be able to see the object of interest, whereas Gerrits & Vendrik [28] and Clowes [29] found that optimal viewing conditions were only obtained when both microsaccades and drifts were present. Since microsaccades can be suppressed voluntarily in high acuity observation tasks [30,31], it was concluded that microsaccades serve no useful purpose and even that they represent an evolutionary puzzle [4,9].

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 [3]. Moreover we show that due to microsaccades there is also different scaling behaviour 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 the 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 also show that the role of microsaccades in horizontal movements are more dominant. These findings may provide better understanding of the recent neuro-physiological findings on the effects of microsaccades on visual information processing [13–16].

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