Graefe's Arch Clin Exp Ophthalmol
(2002) 240:765–770

CLINICAL INVESTIGATION

DOI 10.1007/s00417-002-0519-2

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Binocular quantification and characterization of microsaccades

Received: 7 March 2002
Revised: 6 June 2002
Accepted: 18 June 2002
Published online: 1 August 2002

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Abstract *Background:* The significance of microsaccades in the visual process has been discussed for more than 50 years. However, only a few studies have measured microsaccades binocularly, and detailed quantification and characterization of these small movements are needed in order to further understand their nature. *Method:* The amplitude, velocity, acceleration and direction of microsaccades were quantified binocularly in 10 normal test persons during a 40-s fixation task, using an infrared recording technique. *Results:* All microsaccades for all test persons were performed simultaneously and individually with an almost identical amplitude in the right and left eye (a range of 0.003–0.042 deg between right and left eye mean values). The mean microsaccadic amplitude for the test persons was within a range of 0.223–1.079 deg. The directional difference between simultaneously-performed right and left eye microsaccades was less than 22.5 deg for 84.8% of the saccades, indicating that the majority of microsaccades are conjugated. Three different fixation patterns were identified and characterized: (1) a classic interplay between easily identified drifts and medium-sized microsaccades (mean amplitude range 0.328–0.413 deg); (2) long intersaccadic intervals (4–5 s) with almost absent drifts, followed by three or four large microsaccades (mean amplitude range 0.755–1.079 deg); and (3) low-amplitude drift movements interrupted by low-amplitude microsaccades (mean amplitude range 0.231–0.265 deg). *Conclusion:* Microsaccades are involuntary, predominantly conjugated, simultaneously performed, and of almost identical amplitude in the right and left eye, suggesting a central control mechanism for microsaccades at subcortical level.

Introduction

The complex structure of the human retina requires large eye movements in order to place the object of interest in the foveal region. When the object of interest is located in the fovea, as during steady fixation, the eye is not at rest, because small fixation eye movements are constantly performed in order to avoid the receptor cell adaptation that would occur in a stabilized retinal image [5, 10, 19]. Fixation eye movements are characterized by three different movements:(1) high-frequency small amplitude tremor, (2) slow drifts, and (3) fast microsaccades (duration about 25 ms) [6, 7, 18, 22]. Microsaccades are different from voluntary saccades with respect to both amplitude, which is smaller (ranging between 5 and 20 arcmin), and overshoot, which is relatively larger in microsaccades (Fig. 4 a). These amplitude values are, however, measured with the position of the head fixed by means of a bite board. When the head is supported by a chin rest or free to move, the mean amplitude is 2–3 times larger [4, 17]. Microsaccades are typically performed at a frequency of 0.1–5 Hz [2, 6, 11], and be-

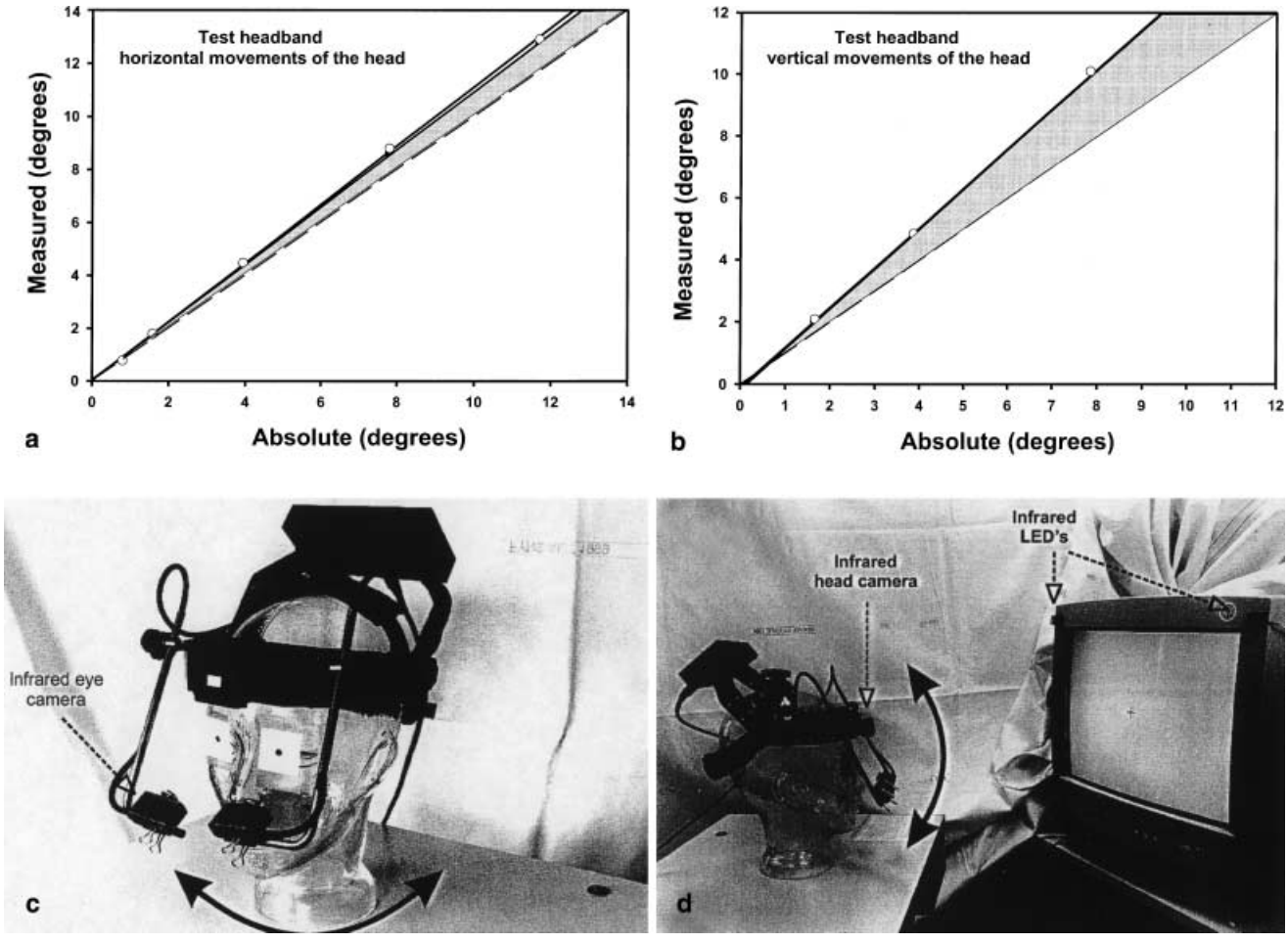

Fig. 1a–d **a, b** The precision (*solid lines*) of the Eye-Link System in tracking the position of the head. *Shaded areas* represent the measurement bias. The head band was mounted on a head model, and the infrared cameras were focused on two black circles (imitating the pupils) printed on white paper which were attached to the head model (**c**). Head movements were measured with the head camera with reference to the four infrared light-emitting diodes (*LED's*) placed on the monitor. The head model was then rotated in predefined angles in the horizontal (**c**) and vertical meridian (**d**), and these absolute values (depicted on the *x*-axis) were compared to the values measured by the Eye-Link System (depicted on the *y*-axis). *Open circles* represent right eye values, *filled circles* left eye values

tween two microsaccades the eye performs slow drifting movements (Fig. 4a) with a mean amplitude within a range of 1.2–9 arcmin [6]. Microsaccades and drifts are superimposed on a 50- to 100-Hz tremor with an average amplitude of 5–30 arcsec [22].

Studies of fixation eye movements have been going on since the 1950s [7, 18], but the role of the drift and microsaccadic movements in the visual process is still not fully understood. Research on stabilized retinal images has shown that without performing drifts the object of interest fades [5, 10, 19], whereas the role of microsaccades is controversial. Steinman showed in 1973 [22] that a person may select not to make microsaccades, and still be able to see the object of interest, whereas Gerrits and Vendrik together with Clowes [3, 8] found that optimal viewing conditions were only obtained when both microsaccades and drifts were performed. All previous studies of test persons with no experience in oculomotor research have shown that microsaccades are performed involuntarily during fixation [1, 7, 6, 13, 17, 18, 22]. These studies included only a few test persons, and in only three studies [7, 20, 21] were fixation eye movements quantified binocularly. In order to understand the role of microsaccades in the visual process in both normal test persons and patients, it is important to have a detailed characterization of the microsaccades from a large number of normal individuals. In the present study microsaccades were quantified binocularly in 10 normal test persons during a 40-s fixation task.

Material and methods

Ten normal test persons (mean age 43.4 years, range 32–57 years), with a best-corrected visual acuity of 1.0 and no history of neurological or ocular disease, were investigated. All test persons had

given informed consent prior to their inclusion in the study. A 40-s fixation task was performed 3 times for each test person, during which the person was carefully instructed to fixate on the center of a black cross (diameter 1.7 cm) on a white background shown on a computer monitor at a distance of 70 cm. This relatively large fixation target, subtending 1.39 deg on the retina, was chosen so that the same experimental setup could be used for patients with reduced visual acuity. The head of the test person was placed on a chin rest, and the fixation eye movements were recorded by video-oculography using the Eye-Link System (Senso Motoric Instruments, Teltow, Germany). The Eye-Link System consisted of two head-mounted infrared video cameras which traced the position of each eye linearly within the range of ±20 deg horizontally and ±17 deg vertically with a precision of 0.005 deg [noise level 0.01 deg RMS (root mean squared)]. A third infrared camera traced the head position. The precision of these measurements depended on the amplitude of head movements (Fig. 1). Thus, it was possible binocularly to measure horizontal and vertical eye positions with an adjustment for moderate head movements. The position of both eyes was recorded linearly with a data transit delay of 6–12 ms at a sample rate of 250 Hz and stored on a computer hard disk. Eye positions were transformed into eye rotation values with the help of a computer software program (Senso Motoric Instruments), so that the amplitude and direction of the saccades could be assessed. Microsaccades were defined as movements with a minimum velocity of 5deg/s [12] accelerating at 2500 deg/s^2 and having a typical microsaccadic configuration with overshoot (defined as peak minus end microsaccadic amplitude), as shown in Fig. 4a. Microsaccadic amplitude was defined as maximum amplitude minus overshoot.

Results

A total of 1280 microsaccades were quantified.

Microsaccadic amplitude, velocity, peak velocity and mean acceleration

All microsaccades for all test persons were performed simultaneously in the right and the left eye. Table 1 shows for each test person the mean values ± SEM of the microsaccadic amplitude, velocity, peak velocity and acceleration for the three individual measurements for each eye. Differences (numeric) between right and left eye values for the 10 test persons ranged between 0.004 and –0.0740 deg for the mean amplitude, from 0.2220 to 2.8700 deg/s for the mean velocity, from 0.0660 to 5.8100 deg/s for the peak velocity and from 12.0710 to 508.9750 deg/s^2 for the mean acceleration. No correlation was found between the mean microsaccadic amplitude and the mean microsaccadic amplitude difference (correlation coefficients r=0.05).

Voluntary saccades are characterized by a strict peak velocity/amplitude correlation which often is referred to as the main sequence [23]. The main sequence has been proven correct previously also for involuntary microsaccades [20, 24], and the present study confirmed these results (Fig. 2) for test persons with mean saccadic amplitude larger than 0.40 deg. Fig. 3 shows the main sequence for the right and left eyes in each of the three individual experiments for all 10 test persons as a function of the mean saccadic amplitude. The figure shows that

Table 1 For each of the 10 test persons, the mean values ± standard error of mean (SEM) of the three individual measurements: microsaccadic amplitude (degrees), microsaccadic velocity (degrees/second), microsaccadic peak velocity (degrees/second), and microsaccadic acceleration (degrees/second^2). *n* number of microsaccades performed for each individual (total 1280 microsaccades)

Test person	Mean amplitude (degrees ± SEM)		Mean velocity (degrees/second ± SEM)		Peak velocity (degrees/second ± SEM)		Mean acceleration (degrees/second^2 ± SEM)	
	Right eye	Left eye	Right eye	Left eye	Right eye	Left eye	Right eye	Left eye
EBK (n=122)	0.307±0.056	0.349±0.028	20.787±0.664	21.986±0.651	33.200±1.987	37.671±1.326	3030.770±50.459	3539.745±77.235
KDE(n=82)	0.386±0.285	0.409±0.390	26.116±7.879	25.331±18.449	51.683±16.460	48.715±18.449	4154.205±1182.042	3937.938±958.217
BB (n=196)	0.438±0.059	0.388±0.048	26.668±1.204	23.798±2.241	49.741±4.479	44.510±4.780	4228.882±182.413	3853.097±269.276
NL (n=142)	1.060±0,105	1.098±0.105	39.680±3.077	39.902±2.951	76.442±5.089	77.803±5.855	5001.089±205.455	5078.689±220.410
GA (n=134)	0.775±0.112	0.734±0.087	40.130±1.666	38.431±1.126	97.518±6.152	91.708±3.830	6439.625±98.356	6050.184±236.142
ML (n=48)	0.270±0.032	0.242±0.021	20.467±1.266	19.033±0.613	33.886±3.939	29.957±1.671	3413.633±235.212	3113.700±197.217
FM (n=134)	0.212±0.017	0.250±0.026	21.067±2.074	21.533±1.518	37.233±5.082	39.667±3.501	3619.233±306.757	3483.000±252.774
KAF (n=136)	0.251±0.041	0.278±0.029	15.154±2.405	15.671±1.588	27.976±3.376	28.042±1.601	2349.076±388.587	2321.795±229.887
HR(n=108)	0.336±0.088	0.255±0.058	24.288±2.852	24.894±1.739	44.650±7.234	47.715±6.700	3945.760±425.229	4335.065±278.422
SJ (n=178)	0.375±0.041	0.378±0.058	25.821±2.002	24.647±0.901	46.601±3.106	44.661±2.422	3554.705±45.647	3566.776±94.254

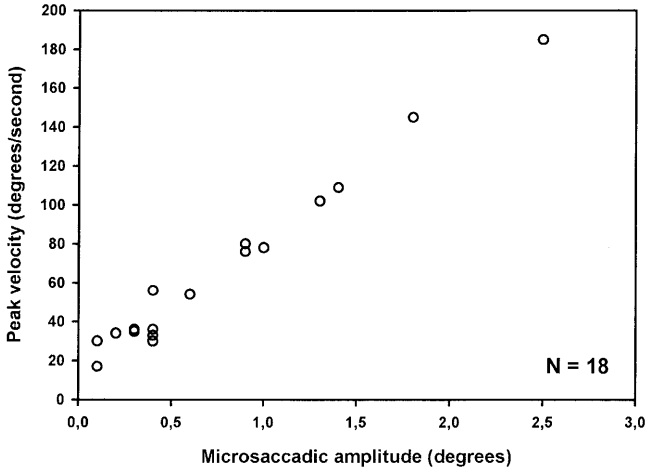

Fig. 2 An example of the microsaccadic peak velocity versus amplitude relationship for the right eye of test person KDE during the first fixation procedure. Correlation coefficient r=0.99. n number of microsaccades

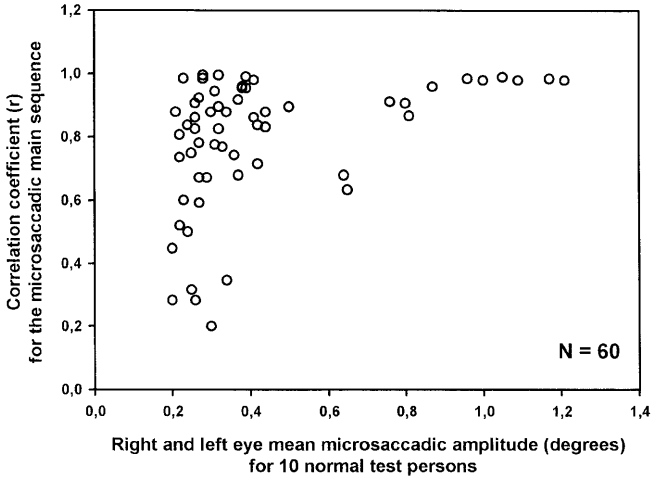

Fig. 3 The individual mean microsaccadic amplitude for each eye, for each of the three fixation procedures, as a function of the main sequence (microsaccadic amplitude versus peak velocity) for all 10 test persons. n number of fixation procedures

the correlation coefficient for the main sequence is more than 0.6 for mean amplitudes larger than 0.40 deg, whereas it may be as low as 0.20 for mean amplitudes less than 0.30 deg. The mean velocity/amplitude as well as the mean acceleration/amplitude correlations were also estimated, but the main sequence correlations remained higher for low-amplitude microsaccades.

Microsaccadic direction and intersaccadic interval

Table 2 shows that the directional difference between simultaneously performed right and left eye saccades was

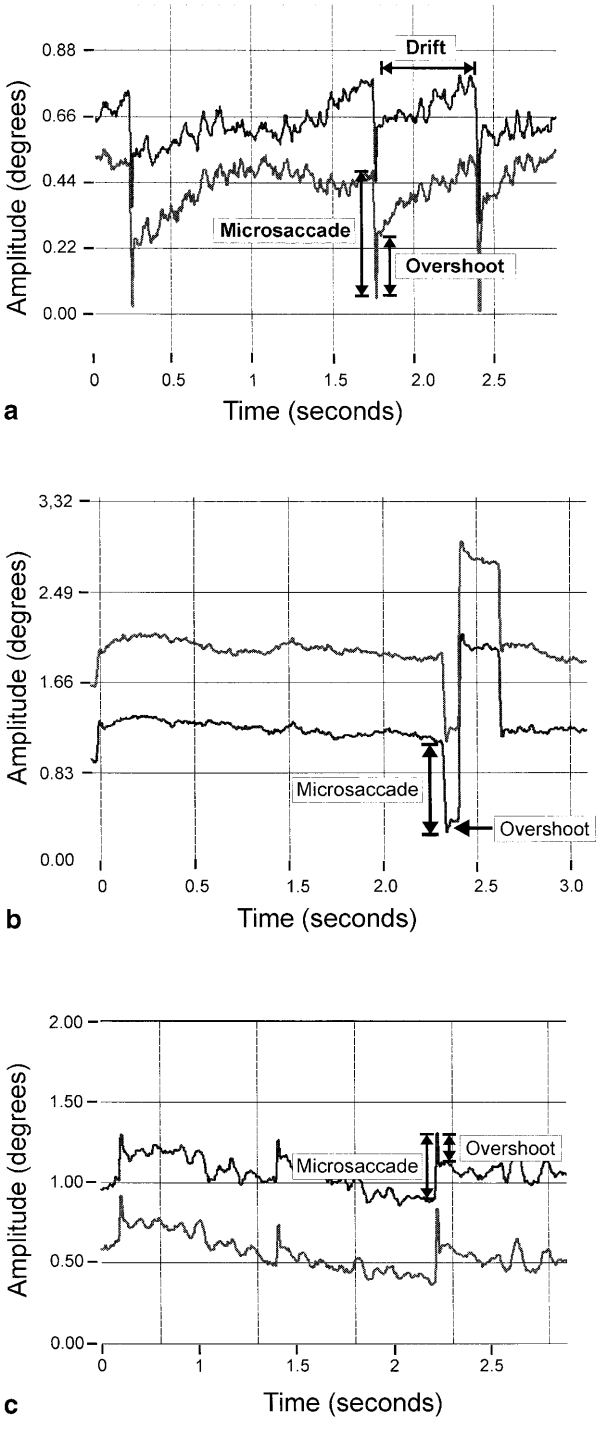

Fig. 4a–c Plots of horizontal fixation eye movements. Time is plotted in milliseconds on the x-axis, horizontal eye position in degrees on the y-axis. **a** A classic fixation pattern with fast microsaccades interrupted by easily identified drifts. Notice the large overshoot. **b** A fixation pattern with a long intersaccadic interval as seen on the x-axis (time in milliseconds), followed by three high-amplitude microsaccades. **c** This fixation pattern was characterized by low-amplitude microsaccades interrupted by low-amplitude drifts

Table 2 The directional difference (in degrees) of simultaneously-performed right and left eye microsaccades. Zero degrees corresponds to a perfect match in right and left eye direction; 180 deg corresponds to microsaccadic movements in opposite direction (*n*pair number of paired right and left eye microsaccades)

0–22.5 deg	22.6–45 deg	45.1–67.5 deg	67.6–90 deg	90.1–145 deg	145–180 deg
84.8% (range 60–100%) (*n*pair=543)	7.8% (range 0–36%) (*n*pair=50)	3.8% (range 0–10.2%) (*n*pair=24)	1.4% (range 0–6.9%) (*n*pair=9)	1.9% (range 0–5.8%) (*n*pair=12)	0.3% (range 0–2.1%) (*n*pair=2)

less than 22.5 deg for 84.8% of the saccades, indicating that the majority of microsaccades are conjugated. No correlation was found between the mean saccadic amplitude and the mean directional difference of simultaneously-performed microsaccades (correlation coefficients r=0.26), which indicates that small microsaccades are just as conjugated as large microsaccades.

The mean intersaccadic interval was 0.61 saccades/s (range 0.23–0.93 saccades/s).

Fixation pattern

Evaluation of the fixation plot for each test person revealed three different fixation patterns. Test persons EBK, KDE and BB showed a classic fixation pattern with easily identified drift and medium-sized microsaccadic movements with large overshoot (mean amplitude range 0.328–0.413 deg) (Fig. 4a), whereas test persons NL and GA were characterized by several large intersaccadic intervals (4–5 s) where the drift movement was almost absent, followed by three or four large microsaccades (mean amplitude range 0.755–1.079 deg) within approximately 1 s (Fig. 4b). The large microsaccades were different from the classic microsaccades with respect to overshoot, which was relatively smaller. Finally, test persons ML, FM and KAF showed low-amplitude drift movements, interrupted by low-amplitude, large-overshoot microsaccades (mean amplitude range 0.231–0.265 deg) (Fig. 4c). Combinations of these three fixation patterns were found for the last two test persons (SJ and HR).

Discussion

The mean microsaccadic amplitudes found in the present study are in general larger than the previously reported amplitude data assembled by Ditchburn and Foley-Fischer [6]. Consequently, it might be argued that our recordings do not include microsaccades. However, the data in the paper by Ditchburn and Foley-Fischer were all obtained during steady-fixation experiments where movements of the head were minimized by use of a dental bite board. This procedure is known to reduce microsaccadic amplitude 2–4 times compared with situations where the head is either supported by a chin rest [17] or free to move [4]. In the present study a chin rest was used during fixation, and microsaccades with the classic large-overshoot configuration were recorded. Furthermore, the intersaccadic intervals were found to lie within the previously reported range [2, 6, 11], which indicates that the fast movements in our recordings are microsaccades.

The gross variation in microsaccadic amplitude which has been reported in previous experiments [16, 13] may be explained by the three different fixation patterns (characterized by either high, medium or low microsaccadic amplitude) found in our study. Each fixation pattern was characterized by the interplay between microsaccades and drifts. In the high-amplitude fixation pattern, several long-lasting low-amplitude drift movements were followed by three or four high-amplitude microsaccades. These high-amplitude microsaccades were different from the classic microsaccades with respect to overshoot, which was relatively small (overshoot amplitude/microsaccadic amplitude). The medium-amplitude fixation pattern was “classic”, with easily identified drifts interposed by medium-amplitude microsaccades with large overshoot. Finally, low-amplitude microsaccades also with large overshoot, interposed at various intervals by low-amplitude drifts, were found in the low-amplitude saccadic pattern. Each test person was unaware of the microsaccades, and since all test persons had visual acuity of ≥1.0 the different fixation patterns do not seem to be influenced by visual acuity. These result are in accordance with our previous work, showing no correlation between changes in visual acuity and changes in microsaccadic amplitude after retinal photocoagulation for diabetic maculopathy [16]. However, Leopold and Logothetis, together with Martinez-Conde et al. [14, 15], found that the firing of many neurons in the striate and extrastriate cortex was profoundly influenced by the microsaccades. Therefore one may speculate that microsaccades are necessary in the visual process, but that the amplitude of these is of no importance.

The most striking characteristic of the microsaccades was the almost perfect watch in amplitude and direction in the left and right eyes of the same individual. The mean individual amplitude difference was within a range of 0.003–0.042 deg, and no correlation was found between the mean microsaccadic amplitude, the individual difference in amplitude, and the direction of simulta-

neously performed microsaccades. This shows that the programming of microsaccadic amplitude and direction is just as precise for small as for large microsaccades. These results suggest a central mechanism for the maintenance of binocular fixation.

A strict correlation between amplitude and peak velocity (main sequence) has been found for both voluntary saccades [23] and involuntary microsaccades [11, 20]. Our study confirmed these results, with main sequence correlation coefficients consistently larger than 0.60 for test persons with a mean saccadic amplitude >0.4 deg (Fig. 3). However, when the mean saccadic amplitude was <0.4 deg the variation in correlation coefficients was large (ranging between approximately 0.20 and 0.90). Zuber and Stark [24], who initially described the main sequence for the microsaccades, concluded that involuntary microsaccades and voluntary saccades were produced either by the same physiological system or by a single motor element. The results of the present study may indicate the presence of two different types of involuntary microsaccades, a hypothesis supported by the results of a recent study by Hamstra [12]. This study included experiments using two vertical bars separated by 4 arcmin as the fixation target. Microsaccades of less than 0.125 deg were found to make no contribution to overall fixation precision, whereas microsaccades of more that 0.25 deg did make such a contribution. The study used a dental bite board to reduce head movements during the fixation, a procedure known to reduce the microsaccadic amplitude two- to fourfold [4, 17]. Therefore, the microsaccades in the Hamstra et al. study with an amplitude of <0.125 deg may be similar to the low-amplitude, low-main sequence correlation microsaccades in our study.

The mean saccadic acceleration showed large variations among individuals. However, it should be taken into account that the Eye-Link System sample rate is 250 Hz, which is fairly low when measuring higher functions such as acceleration.

The present work is to our knowledge the largest study to quantify microsaccadic eye movements binocularly. The study revealed that the differences in microsaccadic amplitude among individuals could be explained, for 8 out of 10 test persons, by three different fixation patterns characterized by a high, medium or low microsaccadic amplitude, whereas the remaining 2 test persons did not follow any specific pattern. Within the same individual the right and left eye microsaccades were always initiated simultaneously, and the amplitude and the direction were almost identical. These results indicate a central control mechanism for the microsaccades which must be at a subcortical level, since microsaccades are performed involuntarily.

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