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Technical Note

COMPARING EYE MOVEMENTS RECORDED BY SEARCH COIL AND INFRARED EYE TRACKING

Kai-Uwe Schmitt, PhD[1], Markus H. Muser, PhD[2], Christian Lanz, MD[2], Felix Walz, MD[2] and Urs Schwarz, MD[3]

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ABSTRACT. Objective. The performance of a new video-based infrared eye tracker (IR) was compared to the magnetic search coil technique (SC). Since the IR offers interesting possibilities as a diagnostic tool in neuro-ophthalmology, it was investigated whether the new device has overcome shortcomings that were reported from former IR systems. **Methods.** Horizontal saccades were recorded using the IR and the SC. The IR allowed eye movement recordings at different sampling rates ranging from 250 Hz to 1000 Hz while the SC recorded at 1000 Hz. **Results/Conclusions.** The results show that the IR and the SC were in good agreement and produced similar results. In contrast to other studies, the influence of the sampling rate of the IR was small. The saccade main-sequences did not show significant differences. The latency times observed for both systems were mainly in the short-latency range.

KEY WORDS. eye movements; human; magnetic search coil; saccade; video; infrared; eye tracking.

INTRODUCTION

Precise recording and detailed analysis of eye movements has become an important diagnostic tool in neurology [1, 2]. Due to its very high spatial and temporal resolution, the magnetic search-coil technique (SC) is regarded as the gold standard for recording these movements [3, 4]. However, since this method is invasive, it has significant disadvantages. In contrast, video-based systems for recording eye movements are non-invasive and, therefore, are a desirable alternative to the SC.

In the past, several studies have compared the two methods [3–6]. Van der Geest and Frens [6], for instance, compared a video system (sampling rate 250 Hz) and the SC (500 Hz) using saccadic eye movements and concluded that the main disadvantage of the video method is its low sampling rate, which was thought to be responsible for noisier estimates of all parameters. Nonetheless, they report that the main sequence was similar for both systems and that its peak velocity saturation level was only slightly overestimated by the video system. The SC, however, was suspected to inhibit viscoelastic coupling between the annulus and the cornea, i.e., the SC motion produces a filtered version of the actual eye movement with underestimation of the true peak velocity. A similar explanation was given by Träisk et al. [7] who analysed saccades using the SC and video-based device both sampling at 500 Hz and found significant differences between the two methods. A slower peak velocity was recorded for the SC

From the [1]Institute for Biomedical Engineering, ETH Zurich and University of Zurich, Gloriastrasse 35, 8092 Zurich, Switzerland; [2]AGU Zürich, Winkelriedstrasse 27, 8006 Zurich, Switzerland; [3]Department of Neurology, University Hospital Zurich, Frauenklinikstrasse 26, 8091 Zurich, Switzerland

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Address correspondence to Kai-Uwe Schmitt, Institute for Biomedical Engineering, ETH Zurich and University of Zurich, Gloriastrasse 35, 8092 Zurich, Switzerland.
E-mail: schmitt@ethz.ch

and explained by a slippage of the SC on the surface of the eye, hence inducing a low-pass filter. Furthermore, it was suggested that the presence of the SC alters the oculomotoric command signal. The finding that the video-based results show a higher variability was explained by reduced alertness of the volunteers, i.e., a subject is more alert when wearing the uncomfortable device.

This study further investigates the differences between the SC and a video-based infrared eye tracker (IR). Using a more advanced IR system with adjustable sampling rates up to 1000 Hz, it was possible to elaborate on the frequency dependence in more detail. Additionally, the IR was used to record the SC in the eye of the volunteers while performing saccades. As a result, it was possible to analyse the behaviour of the SC during eye movements.

METHODS (INCLUDING ETHICS ASPECT)

Subjects

A total of 5 healthy subjects (3 women, 2 men, age 29–50 years, including the male author US) participated in this study. All of them gave informed consent and had normal or corrected-to-normal vision. Three of the five subjects were familiar with wearing SCs.

Eye movement recordings

Eye movements were recorded with two different systems:

1. A typical SC set-up (SKALAR Medical, Delft, The Netherlands) with a sampling rate of 1000 Hz of the horizontal and vertical positions of the centre-aligned right eye and a nominal spatial resolution of 30 sec arc. The stimulus was back-projected onto a translucent tangent screen (viewing distance 1 m, subtending ±42° horizontally and ±26° vertically, pixel size 0.2°) using an active-matrix LCD video projector (SHARP). The frame rate of the display system was 70 Hz.
2. A table-mounted IR prototype (OCULOMETRICS, Zurich, Switzerland) with an adjustable sampling rate between 250 and 1000 Hz. The stimulus was presented on a 18-inch LCD monitor (Belinea 101920, 1280 × 1024 Pixel, 60 Hz) positioned 490 mm from the right eye and aligned the same way as the SC system. Eye movement traces were evaluated by tracking both the pupil and the corneal-scleral junction. Tracking was performed by first determining the centre of the pupil using a modified circular Hough transform, and subsequently detecting the left and right pupil edges as well as the left and right border of the iris using an adaptive edge detection algorithm. Because of the spherical shape of the eye, the attainable angular resolution depends on the rotation of the eye, i.e. a rotational displacement smaller than 10° can be tracked with a resolution of 0.1° approximately, while a larger displacement will yield a resolution of 0.2°.

Raw CS and IR signals were stored for off-line analysis.

Paradigm

A standard paradigm to elicit visually guided saccades was used in all experiments. The stimulus (0.8 × 0.8°, target luminance 25 cd/m^2, background luminance 0 cd/m^2) was presented at 0°, 5°, 10°, 15°, and 20° eccentricity right- and leftwards with the same randomised sequence in all experiments and for all subjects. All subjects were familiarised with the experimental procedure before the first run.

Each subject performed the following set of consecutive experiments:

1. IR, sampling rate: 250 Hz
2. IR, 500 Hz
3. IR, 1000 Hz
4. SC, 1000 Hz
5. IR, coil in the eye, 500 Hz
6. IR, coil removed, eye still anaesthetised, 500 Hz

Data analysis

Data analysis was performed off-line using commercial software (MATLAB R2006a, The MathWorks Inc., Natick, MA) with a purpose-built toolbox (available upon request). Blinks and grossly abnormal eye traces were excluded. The saccade onset of the adaptive smoothing spline filtered raw eye position traces [8, 9] was determined by a velocity and acceleration threshold. Subsequently, latency, amplitude, duration, and peak velocity of all valid saccades as well as their main sequence were determined [5].

RESULTS

The main sequence was computed for each subject and for every experiment (Figure 1). Table 1 summarises the parameters.

The post-saccadic positions recorded for all measurements (Figure 2) showed a very small standard deviation.

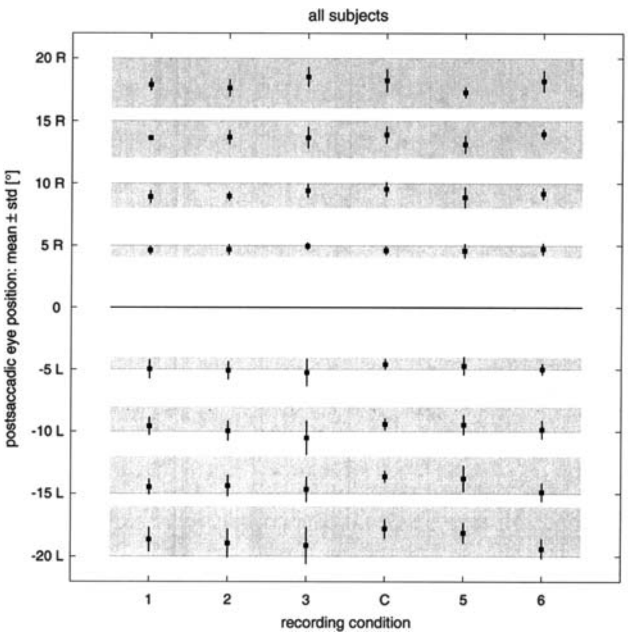

Fig. 1. Post-saccadic positions for all subjects and all conditions: IR 250 Hz (1), IR 500 Hz (2), IR 1000 Hz (3), SC 1000 Hz (C), IR 500 Hz and coil in place (5), IR 500 Hz eye still anaesthetised (6). The shaded area represents the normal position gain between 0.75 and 1.00 for each excursion.

At 1000 Hz sampling rate, the saccade parameters of the main sequences obtained from the SC and the IR system were in agreement. In general, the saccade latencies recorded by the SC system were slightly longer than those recorded by the IR system, but the difference was statistically not significant ($p > 0.05$).

Comparing the results from the IR system at sampling rates of 250 Hz, 500 Hz and 1000 Hz showed no systematic difference for the saccade main-sequence parameters and latencies ($p > 0.05$).

The outcome of the IR recordings before and after the SC experiments (both with the SC still in place and without the SC) did not reveal significant differences. Furthermore, the video sequences taken with the SC showed no movement at all of the SC relative to the eye.

In line with the literature, it was generally observed that the subjects performed slightly faster abducting saccades than adducting saccades.

DISCUSSION

Despite the limited number of tested subjects, the data presented in this study is of excellent quality (see Figures 1, 2). The derived parameters and their variance are well within the known range for horizontal saccadic eye movements (see Table 1).

The comparison of the data and parameters from the IR and the SC system at 1000 Hz sampling rate showed very good agreement without statistically significant differences. This finding indicates that both methods are capable of reliably recording horizontal saccades. Hence, the IR system exhibits a quality that allows recordings at a spatial and temporal resolution that is comparable to the SC.

Furthermore, these findings are comparable with those published by van der Geest and Frens [6] who compared the two methods at lower sampling rates. They concluded that the main disadvantage in their study was the low sampling rate of their video system.

However, there are several disagreements with the results of Träisk et al. [7]: In our set-up, IR measured peak velocities of 20° saccades varied on average by 10% compared to the SC measurements. Träisk et al. reported that their video system resulted in a 31% higher maximum velocity at 20°. Moreover, we did not observe a slippage of the coil as they did. Also, we could not confirm a higher variability of the IR parameters derived in our study; and the order of the experiments (IR first, then SC) was not important either since we did not find significant differences between the results of the measurements taken before and after the SC experiment. There is no satisfactory explanation of these differences. However, some of them might be due to simple technical differences of the systems (e.g., head vs. table mounted video systems) rather than the recording methodology itself.

Because it was hypothesised in several studies that the sampling rate of the video system might be a critical factor with great impact on the results, we compared IR eye movement recordings at sampling rates ranging from 250 to 1000 Hz. Our results revealed only minor differences, which did not show a systematic pattern. This excludes a methodological or technical error in these recordings and must therefore be attributed to biological variance. In fact, independence of the sampling frequency is to be expected, since a sampling rate of 250 Hz is sufficient for recording saccades with a velocity range as employed here, according to the Whittaker–Shannon sampling theorem. We therefore conclude that the range of frequencies used in our study is sufficient to analyse horizontal saccades, and a lower spatial resolution (compared to the SC) is not a limiting factor for the video systems.

Unfortunately, the methods of saccade identification and parameter computation were not always sufficiently presented in some other studies, although they play an important role (e.g., filtering, threshold values, fitting technique). Different SC systems as well as different video systems might have used different methods to analyse the data, which would explain some discrepancies in other reports. In addition, the experimental set-up could be a

Table 1. Summary of the saccade main-sequences and latencies from all subjects for all conditions

Subject	Condition		tc	Conf	Lim	Conf	r^2	Latency	Std
1	1	video, 250 Hz	8.85	0.71	390.48	15.46	1.00	154.67	27.42
	2	video, 500 Hz	7.54	0.56	398.56	13.22	1.00	156.29	25.59
	3	video, 1000 Hz	5.79	0.70	379.11	16.85	0.99	160.22	25.60
	C	MSC, 1000 Hz	7.10	0.21	396.17	4.56	1.00	182.31	29.88
	5	video, 500 Hz	7.01	0.62	364.66	13.85	0.99	159.42	29.57
	6	video, 500 Hz	5.13	0.42	356.05	9.44	0.99	151.65	17.80
2	1	video, 250 Hz	13.89	1.00	538.86	23.55	1.00	153.61	35.43
	2	video, 500 Hz	10.79	0.74	492.70	18.09	1.00	157.67	25.67
	3	video, 1000 Hz	9.67	1.20	479.04	29.47	1.00	168.40	23.55
	C	MSC, 1000 Hz	11.47	1.01	517.42	24.78	0.99	186.99	25.31
	5	video, 500 Hz	3.26	4.34	333.57	107.22	0.44	157.84	25.69
	6	video, 500 Hz	11.37	0.80	501.70	19.52	1.00	160.47	21.75
3	1	video, 250 Hz	9.80	1.27	424.39	28.89	0.99	111.55	15.43
	2	video, 500 Hz	6.77	1.12	398.83	28.19	0.98	120.20	17.27
	3	video, 1000 Hz	5.99	1.11	427.41	30.56	0.99	118.08	10.54
	C	MSC, 1000 Hz	7.04	0.36	384.34	8.49	1.00	147.16	18.87
	5	video, 500 Hz	7.68	0.78	383.47	17.93	0.99	119.47	21.34
	6	video, 500 Hz	9.80	1.88	456.53	45.48	0.98	111.94	10.98
4	1	video, 250 Hz	10.69	1.50	570.76	41.89	0.99	218.56	63.78
	2	video, 500 Hz	11.00	1.18	599.64	33.23	0.99	200.14	50.18
	3	video, 1000 Hz	10.42	1.70	604.43	49.94	0.99	176.52	46.17
	C	MSC, 1000 Hz	9.22	0.40	517.48	10.34	1.00	222.48	56.63
	5	video, 500 Hz	9.52	1.69	540.09	47.17	0.98	202.15	68.44
	6	video, 500 Hz	10.22	1.10	560.51	30.23	0.99	182.14	57.32
5	1	video, 250 Hz	6.65	0.88	417.71	21.42	0.99	128.75	36.45
	2	video, 500 Hz	7.07	0.42	449.89	10.70	1.00	124.94	20.59
	3	video, 1000 Hz	7.09	1.04	459.29	25.86	0.99	137.75	20.23
	C	MSC, 1000 Hz	6.34	0.34	383.60	7.16	0.99	165.93	24.46
	5	video, 500 Hz	6.70	0.64	394.06	14.44	0.99	132.00	17.67
	6	video, 500 Hz	7.14	0.39	427.30	9.53	1.00	125.64	22.29

Data for right- and leftward eye movements are merged (conf represents the 95% confidence interval, r^2 gives an estimate on the quality of the exponential fit, and std denotes for the standard deviation).

cause for differences, in particular higher variability, in results obtained by some other assessments [video results, 6, CS results, 4]. Some factors that possibly account for these inconsistencies are the positioning of the head, head movements, the alignment of the optical and the geometrical axes as well as differences in the eye tracking algorithms.

The interpretation of the saccade latencies, which were typically in the short-latency range, is somewhat difficult since they are not explicitly presented in similar studies [3–6]. In our view, the fact that two subjects (including one of the authors) were used to wearing a scleral SC restricts conclusions by other groups with respect to its influence on alertness.

We did not find systematic differences in the data before and after wearing the SC and with the SC in place. In particular, the comparison of the measurements before and after wearing the SC, but with the eye still anaesthesised, did not suggest that the behaviour was influenced by anaesthesia, which is in line with similar findings by Frens and van der Geest [10].

CONCLUSIONS

Modern IR systems can produce results of a quality comparable to SC systems. Furthermore, the influence of the sampling frequency is smaller than suggested in other studies, and its importance might be overestimated. A movement of the coil relative to the eye during saccades was not observed.

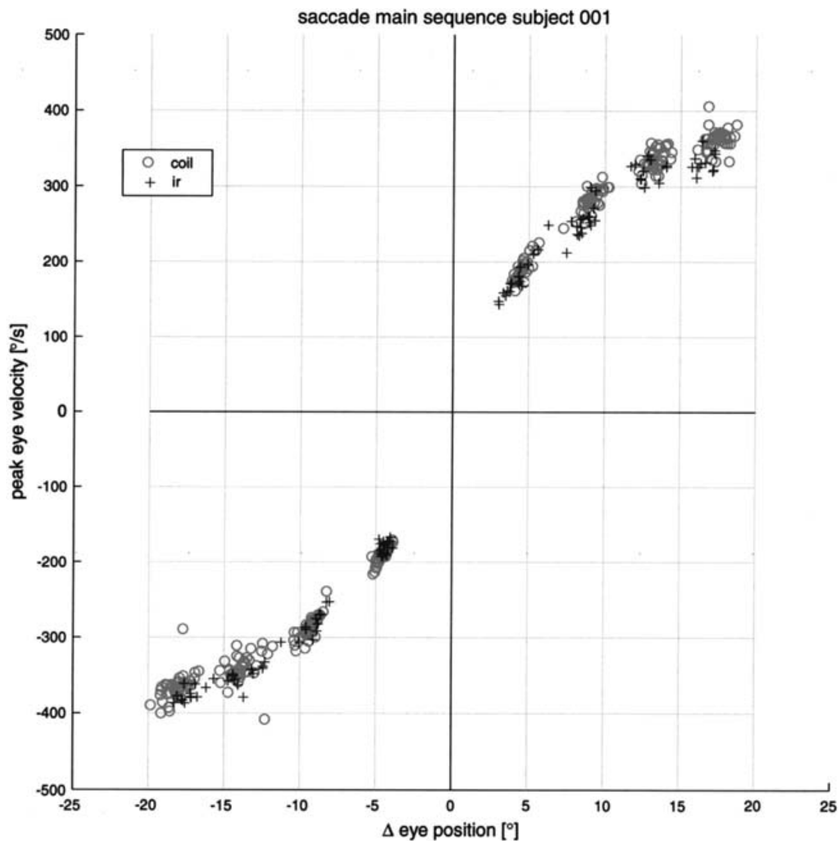

Fig. 2. Raw data, which was used to compute the main-sequences, of subject 1. All data points (Δ eye position vs. peak saccade velocity) for each condition are plotted. Note the similarity (+ excursion/velocity = movement to the right, − excursion/velocity = movement to the left).

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