



The pupil is faster than the corneal reflection (CR): Are video based pupil-CR eye trackers suitable for studying detailed dynamics of eye movements?



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ABSTRACT

Most modern video eye trackers use the p-CR (pupil minus CR) technique to deal with small relative movements between the eye tracker camera and the eye. We question whether the p-CR technique is appropriate to investigate saccade dynamics. In two experiments we investigated the dynamics of pupil, CR and gaze signals obtained from a standard SMI Hi-Speed eye tracker. We found many differences between the pupil and the CR signals. Differences concern timing of the saccade onset, saccade peak velocity and post-saccadic oscillation (PSO). We also obtained that pupil peak velocities were higher than CR peak velocities. Saccades in the eye trackers' gaze signal (that is constructed from p-CR) appear to be excessive versions of saccades in the pupil signal. We conclude that the pupil-CR technique is not suitable for studying detailed dynamics of eye movements.

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1. The introduction

Eye tracking has become broadly applicable since the introduction of high quality video-based eye-trackers. Older eye-tracking techniques such as scleral coils (Collewijn, van der Mark, & Jansen, 1975) and the dual purkinje eye-tracker (Cornsweet & Crane, 1973) provide superior data quality in terms of signal to noise ratio but are much harder to use with patients, babies, impaired and even inexperienced participants and operators. Eye-tracking became even easier and less invasive with the introduction of commercial remote eye tracking (Applied Science Laboratories, Sensomotoric Instruments and Tobii). This also enabled researchers to conduct eye tracking without bite-bars, headsets and chin-rests. Many researchers switched from the old to the new technique and also many new researchers were attracted to the field of eye-tracking. The switch from one measurement technique to another may have consequences. An example of this is found in the study of Nyström, Hansen, Andersson, and Hooge (2016). They write: "We conclude that one reason to why the reported size of micro-saccades has increased is due to the larger overshoots produced by the modern pupil-based eye-trackers compared to the systems used in the classical studies, in combina-

tion with the lack of a systematic algorithmic treatment of the overshoot."

In the present study we evaluate the dynamics of video eye-tracker signals using the p-CR (Pupil minus CR) method. Before we go into the research questions, what is the p-CR method? Pupil based video eye-trackers use the pupil position in their camera image to determine gaze position. The pupil position in the camera image moves when the eye rotates. Usually larger eye rotation results in a larger shift in the camera image. However, the pupil centre may also move in the eye-image when the eye translates. Eye translations may occur when the head moves with respect to a (world fixed) camera. Merchant, Morrisette, and Porterfield (1974) writes: "One of the main difficulties of measuring eye direction optically is that of distinguishing between lateral motion of the eye relative to the eye direction sensor and rotary motion of the eye relative to the sensor". To compensate for the effects of small relative eye camera movements one may use the p-CR method. In the p-CR method, the pupil centre and the centre of the corneal reflection (CR, Fig. 1) are measured and subtracted from each other (Hutchinson, White, Reichert, & Frey, 1989). The CR is also referred to as P₁ reflection or glint. Fig. 1 shows a high resolution close up infra-red picture of the eye and the CR is the white spot on the left side of the pupil (marked with an arrow). The p-CR technique was applied for the first time in the oculometer of Merchant (1967) and nowadays the majority of the video

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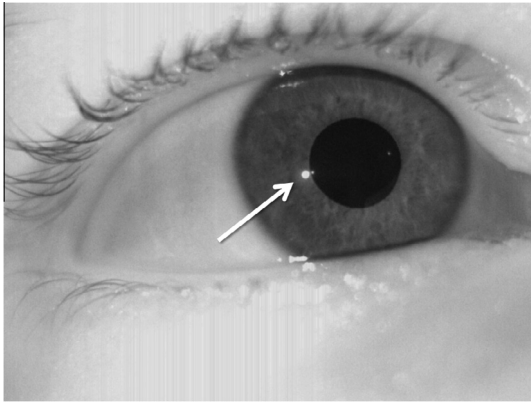


Fig. 1. High definition infra-red Eye image. The bright white spot marked with a white arrow left of the pupil is the corneal reflection (CR). The resolution of the eye image used in this study is much lower than of this eye image, SMI's eye image measures 224 by 160 pixels.

eye-trackers use the p-CR method. Many eye trackers do not even have the option to measure in pupil only modus or CR only modus.

Among other things p-CR eye-trackers are used to estimate gaze direction during fixation. This may already be problematic because the pupil size may change due to arousal or changing light conditions and therefore the mapping between the p-CR vector and gaze direction may be disturbed (Choe, Blake, & Lee, 2016; Drewes, Zhu, Hu, & Hu, 2014; Merchant et al., 1974; Wildenmann & Schaeffel, 2013; Wyatt, 1995, 2010). In case of a fixed pupil size and as long as CR and pupil position are monotonically increasing (or decreasing) functions of viewing direction the p-CR may be effective to compensate for some relative movements between the eye and the camera. In the present study we want to focus on another

potential pitfall of the p-CR technique. P-CR video eye-trackers are also used to investigate saccade properties (Buonocore, McIntosh, & Melcher, 2016; DiStasi et al., 2012; Engbert & Kliegl, 2003; Frens & Van der Geest, 2002; McSorley, Haggard, & Walker, 2004; Otero-Millan, Troncoso, Macknik, Serrano-Pedraza, & Martinez-Conde, 2008; Smeets & Hooge, 2003; van Beers, 2007; Van der Geest & Frens, 2002). Saccade properties involve peak velocity, acceleration, curvature, exact start and endpoint, saccade duration. Measuring gaze direction during fast eye rotation (up to 500°/s; Collewijn, Erkelens, & Steinman, 1988) by subtracting 2 separate signals is potentially problematic. The pupil-CR technique may only deliver a valid gaze signal when the pupil and the CR signals have at least similar timing (meaning that there is a negligible time lag between the two signals). For the p-CR technique to be as effective during saccades as during fixation the latter condition is met when the rigid eye assumption holds (Nyström, Hooge, & Andersson, 2016). In the rigid eye condition there is no relative motion between different parts of the eye. We already know from the literature that this is not the case, since the eye deforms during fast eye movements. From recent research we know that the pupil (the inner iris border) moves and oscillates relative to the outer iris border during and after saccades (Drewes, Montagini, & Masson, 2011; Hooge, Nyström, Cornelissen, & Holmqvist, 2015; Kimmel, Mammo, & Newsome, 2012; Nyström, Andersson, Magnusson, Pansell, & Hooge, 2015; Nyström, Hooge, & Holmqvist, 2013; Nyström, Hansen, et al., 2016; Nyström, Hooge, et al., 2016). The question remains how that affects the relative timing between the CR and pupil signals. And in addition, how would a deforming eye affect the shape of the pupil and CR tracker signals? The ocular bulge also oscillates after saccades, and this may affect reflections of the IR-illuminator on the cornea and thus the position of the corneal reflection in the eye image. As a nice illustration to the previous Fig. 2 of Taberner and Artal (2014) shows how different eye

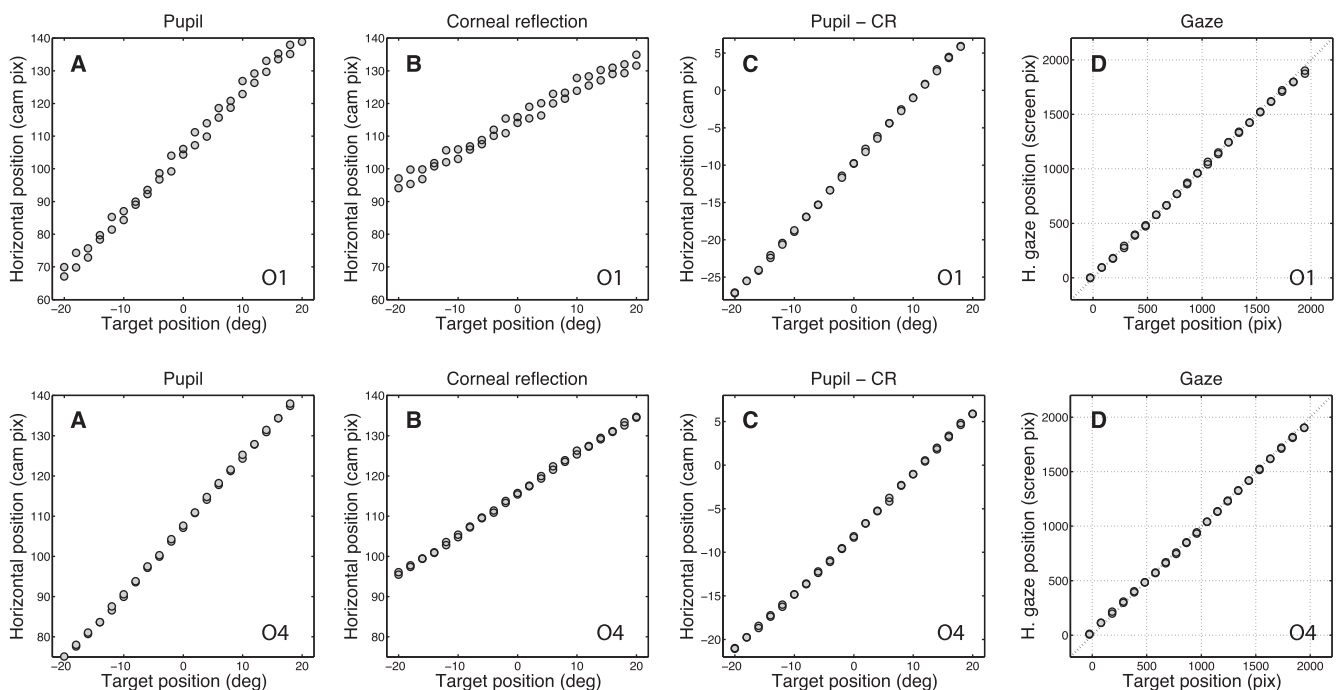


Fig. 2. Horizontal component of four different eye tracker signals as function of target position. The top panels represent data from observer O1; the bottom panels represent data from observer O4. The differences in data of observer 1 and observer 4 are mostly due to head movements made by observer 1, observer 4 sat completely still during the experiment. The jitter in the data of observer 1 is gone in the pupil-CR panel, showing effective compensation for small head movements. In panels A, B and C the target position is represented in degrees. To show the quality of the gaze signals, panels D show both target and gaze position in pixels. The horizontal resolution of the screen was 1920 pixels.

tracker signals (cornea- p_1 , pupil and lens p_4) differ in shape and timing.

In the present study we ask how saccade dynamics of the eye-tracker signal depends on the dynamics of the underlying signals, namely the pupil and the CR signal. This is an exploratory study that will give us insight into the nature of the eye-tracker signal. We refer to this signal as eye-tracker signal instead of eye movement signal because we do not know whether the p-CR eye-tracker signal validates as eye movement during saccades (Hooge et al., 2015). Most eye-tracker manufacturers keep their recipes for how to achieve their eye-tracker signal secret.

Why is it important to investigate how the gaze signal depends on the pupil and the CR signals?

1. Video eye-tracker signals are known to yield higher velocities during saccades than coil signals (Frens & Van der Geest, 2002; Kimmel et al., 2012). This may be due to coils but it has never been investigated how the shape of the video eye-tracker signal depends on the shapes of the underlying CR and pupil signals. Probably coils underestimate velocity; there is still the possibility that p-CR eye-trackers overestimate velocity. This is important information when data obtained with old and new eye-trackers are compared.
2. To what extent does the p-CR eye-tracker signal represent eye movements (eyeball rotation). Here we hypothesize that the putative temporal shift between the pupil and the CR signal is partly responsible for the size of the overshoots in the gaze signal. If the previous hypothesis holds, the huge overshoots in the p-CR eye-tracker signal are partly an artefact of the p-CR technique.
3. The p-CR technique was developed to increase data quality (accuracy) of the video eye tracker under the condition of relative movements between head and camera. Is the p-CR technique effective when the eye is rotating at high speed? If not, the p-CR technique is not the ideal tool to study eye movement dynamics.

To answer our research question we need an eye-tracker that produces separate pupil and CR signals in the data output. At the moment we were conducting our experiment we only knew of two commercially available p-CR eye-trackers that report CR and pupil signals in their native data export, namely the SMI Hi-Speed tower and the Arrington Research 400 Hz Binocular USB. We have access to an SMI Hi-Speed 1250. However, the majority of the eye-tracker manufacturers (ASL, SR Research and LC technologies) use the pupil-CR technique and report that they do not support export of the CR signal in their default recording mode.

We will conduct two experiments to investigate how 1) the gaze signal depends on the p-CR vector during eye movements and 2) whether the gaze signal is veridical during eye movements. The latter means whether the gaze signal validates as an eye movement signal during saccades. An example of an eye tracker signal that is not veridical is found in Deubel and Bridgeman (1995) who compared the coil signal with the dpi signal during saccades. They write about the dpi eye tracker signal: "Our data demonstrate that even for small saccades the difference between eye rotation and tracker signal is considerable". As pointed out in Nyström, Hansen, et al. (2016) and Nyström, Hooge, et al. (2016) there is no direct information whether estimated gaze direction during saccades is correct because there is no comparison target during saccades. The only way to check for the validity of the gaze signal is letting subjects fixate a point in space and compare the real gaze direction with the gaze signal. Therefore, in the first experiment, we ask subjects to fixate several horizontal targets. By comparing the pupil, CR and gaze signals during fixation we should be able

to reveal the transformation from p-CR signal to gaze signal. The SMI eye tracker may be a straightforward p-CR eye-tracker using a scaling factor and offset to transform p-CR to gaze.

$Gaze = C_1(pupil-CR) + C_2$ (with C_1 and C_2 calibration factors).

Or the SMI Hi-Speed may use more sophisticated methods to transform the p-CR signal into the gaze signal (for example a physical eye model or nonlinear fitting). The second experiment is designed to investigate the timing and shapes of the pupil and CR signals before, during and after saccades. We will measure saccades ranging in size from 5 to 35°. We varied saccade size because various dynamic properties such as velocity, acceleration (Collewijn et al., 1988) and amplitude of the post saccadic oscillation (Hooge et al., 2015) differ between large and small saccades. Firstly, we will provide a description of the (relative) dynamics of the CR and pupil signals. Secondly, we will use the p-CR to gaze transformation found in the first experiment to understand the nature of the gaze signal obtained during saccades. Thirdly we will discuss whether the gaze signal of p-CR eye-trackers is suitable to study saccade dynamics.

2. Experiment 1

2.1. Methods

2.1.1. Observers

We engaged two male observers in experiment 1 (O1, age 49 years and O4, age 37 years). Written informed consent was provided by the observers, and the experiment was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.1.2. Set up

Binocular eye movements were recorded with an SMI Hi-Speed 1250 Tower mount eye-tracker operating at 500 Hz. Only eye-tracker signals of the left eye were used. Visual stimuli were presented on a ASUS VG248QE monitor (measuring 530 mm × 300 mm, refresh rate of 144 Hz) placed at a distance of 76 cm from the eye. The resolution of the monitor was set to 1920 pixels by 1080 pixels (16:9 ratio). We used the default binocular 13-point calibration iView X (version 2.8.26).

2.1.3. Stimulus and task

The stimulus consisted of one white circular dot (diameter 0.2°) placed on a black background. The dot was presented in semi random order at 21 different locations for a period of 2 s. The 21 horizontal positions ranged from −20° to 20° with intervals of 2°. Each dot was shown two times. The observers were asked to fixate the dot carefully while sitting as still as possible.

3. Results & discussion

Panels A and B of Fig. 2 show the horizontal position of pupil and CR as function of target position on the screen. It is immediately clear that for the range of targets fixated (−20° to 20°) the pupil centre moves over a bigger distance (±70 pixels) in the eye image than the CR (±35 pixels). To relate these numbers to the eye-tracker; the resolution of the eye-tracker's CCD chips measures 224 by 160 pixels. The top 4 panels of Fig. 2 contain data of Observer O1. From the different positions of both the pupil and CR for similar target positions (vertical jitter in the figure) we conclude that this observer did not manage to keep his head completely still and made small head movements. Observer O4 managed to fixate his head much better and he produced less jitter than observer O1. Panel C contains the p-CR signal on the vertical axis. Two things

stand out: 1) the range of p-CR signal (± 35 pixels) is much smaller than the range of the pupil signal and the vertical jitter has disappeared. Panel C clearly shows why the p-CR method is applied in many pupil eye-trackers; the p-CR signal looks clean (no vertical jitter) for both observers. Here the p-CR technique shows to be effective to remove head movement related shifts of the pupil in the eye image. An important question remains: How does the p-CR signal relate to the gaze signal of the eye-tracker? Panel D shows the gaze signal, and both axes are in (screen) pixels, the horizontal axis shows positions of the targets, the vertical axis shows positions of the fixations. Again two things stand out:

- 1) Data points are located on the unity line. Under the assumption that the observers fixated the targets on the screen, this indicates that over a range of 40° (-20° to 20°) the eye-tracker delivers an almost veridical position signal. On the far left and the far right side there are slight deviations (under-estimation of position).
- 2) The shape of the p-CR signal (panel C) resembles the shape of gaze signal (panel D). We checked this by fitting the gaze position signal to the pupil-CR signal with a line for observers O1 and O2.

$$O1: \text{Gaze} = 53.868 * (p\text{-CR}) + 1481.6 \quad R^2 = 0.99978$$

$$O2: \text{Gaze} = 69.036 * (p\text{-CR}) + 1496.4 \quad R^2 = 0.99943$$

Based on the second observation we can conclude that the SMI Hi-Speed does not contain a sophisticated p-CR to gaze transformation. The gaze signal appears to be a shifted and scaled version of the p-CR signal.

The price for being less sensitive for the effects of relative movements between the camera and the head (causing higher accuracy) is lower precision. We computed sensitivity and RMS noise values for the pupil, CR, p-CR and gaze signals separately. Sensitivity expresses how many camera pixels are used for a certain eye rotation. From both Table 1 and Fig. 2 it is immediately clear that the sensitivity of pupil signal is higher than the sensitivity of the CR and p-CR signals. Surprisingly the RMS noise in the pupil signal is also larger (about 2 times) than that of the CR signal. The RMS noise in p-CR is even higher and is about the quadratic sum of the noise in the pupil and the CR signals indicating that the pupil noise is independent of the CR noise.

Kolakowski and Pelz (2006) state that the CR signal is a noisier signal than the pupil signal and therefore a limiting factor in the precision of the P-CR eye tracker signal. Surprisingly, for the SMI eye tracker in our set up, the RMS noise in the pupil signal is higher than that of the CR signal. This is not only true for pure camera signals (pupil, CR and p-CR in camera pixels); it is also true for

the calibrated versions of these signals. The absolute RMS noise in degrees (of eye rotation) can be computed by dividing the RMS noise by the sensitivity. For both observers the absolute RMS noise of the CR signal is about 15% lower than that of the pupil (Table 1). We also computed the absolute noise of our p-CR signal. If the gaze signal were an unfiltered transformed p-CR signal, the absolute RMS noise of the gaze signal should be equal to that of our p-CR signal. Table 2 shows that the precision of the gaze signal is about 3 times higher than the precision of the P-CR signal. We assume that the gaze signal contains less noise since in the default recording mode the bilateral filter is used (SMI manual 2.4 page 310). SMI claims that their bilateral filter does not cause delays in the gaze signal.

4. Experiment 2

4.1. Methods

4.1.1. Observers

We engaged four male observers in experiment 2 (O1, age 49 years, O2, age 50 years, O3, age 36 years and O4, 37 years). Written informed consent was provided by the observers, and the experiment was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

4.1.2. Set up

Binocular eye movements were recorded with the SMI Hi-Speed 1250 eye-tracker operating at 500 Hz. Visual stimuli were presented on a ASUS VG248QE monitor measuring 530 mm \times 300 mm) with a refresh rate of 144 Hz placed at a distance of 76 cm from the eye. The resolution of the monitor was set to 1920 pixels by 1080 pixels (16:9 ratio). We used a standard 13-point SMI calibration iView X (v. 2.8.26) that was carried out binocularly.

4.1.3. Stimulus and task

The stimulus consisted of one white circular dot (diameter 0.2°) placed on a grey background. The dot jumped between two positions every 1.5 s. The horizontal distances between the dot positions were 5° , 10° , 22.5° and 30° (O1) or 35° (O2, O3 and O4). The centre of gravity of the two positions coincided with the centre of the screen. Observers were asked to make saccades to the newly appearing dots accurately and to pay attention not to anticipate. They were also asked to sit very still. Observer O1 performed 640 trials (160 trials per distance, each including 80 saccades from left to right and 80 saccades from right to left), the other observers performed 320 trials (80 trials per distance, each including 40 saccades from left to right and 40 saccades from right to left).

Table 1
Sensitivity and RMS noise of pupil, CR and p-CR signals.

Observer	Sensitivity (cam. pixels/ $^\circ$)			RMS noise (cam. pixels)		
	Pupil	CR	Pupil – CR	Pupil	CR	Pupil – CR
O1	1.8558	0.9655	0.8807	0.0299	0.0134	0.0321
O4	1.6772	0.9942	0.6830	0.0241	0.0123	0.0263

Table 2
Absolute RMS noise (in degrees of eye rotation) of the pupil, CR, P-CR and gaze signal. Note that the gaze signal contains less noise than the P-CR signal.

Observer	Absolute RMS noise ($^\circ$)			
	Pupil	CR	Pupil – CR	Gaze
O1	0.016	0.014	0.036	0.011
O4	0.014	0.012	0.039	0.012

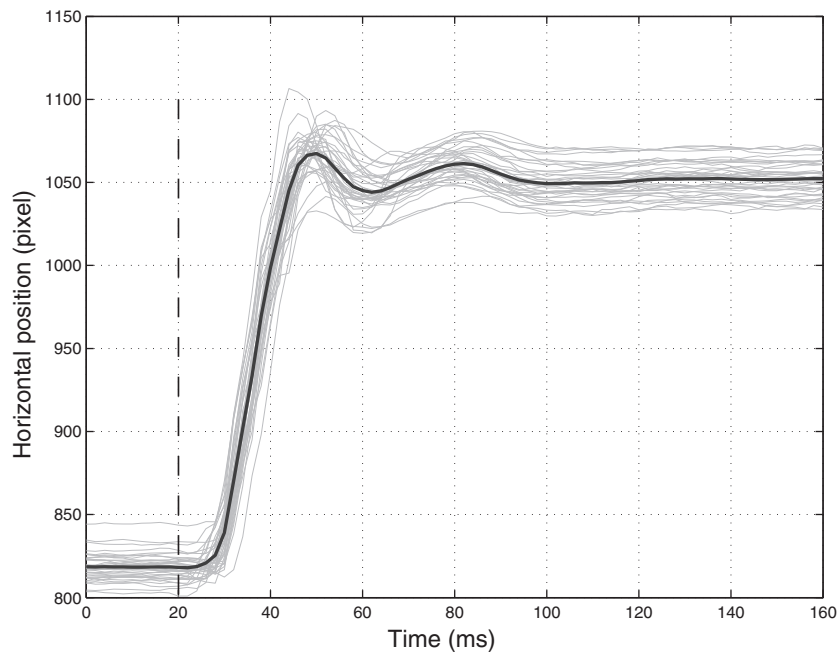


Fig. 3. Grey lines show 40 right eye saccades (size 5°) of observer O4; the black line denotes the average saccade. The *pixel* in the vertical axis refers to *screen pixels*. The vertical dashed line denotes the saccade start. The signal to noise ratio of the average saccade (black) is about 6 times (square root of 40) higher than the SNR of an individual saccade (grey).

4.1.4. Data selection and signal processing

We used the saccade averaging method (Hooge et al., 2015; Nyström et al., 2013) to enhance the signal to noise ratio in the already good signals from the SMI Hi-Speed eye-tracker. In order to do so, we determined saccade start in the gaze-signal with the adaptive velocity threshold method of Hooge and Camps (2013). Time stamps of the onsets of the gaze-saccades were also used to select saccade episodes in the pupil and CR signals. We selected saccades with latencies longer than 40 ms and shorter than 500 ms. Latency is defined as the time between the appearance of a new dot and the start of a saccade (extracted from the gaze signal). Fig. 3 shows 40 aligned saccades from the gaze signal (thin grey lines) and the averaged saccade (thick black line). We refer to gaze-saccade if the saccade is extracted from the gaze signal, the other two signals are referred to as CR-saccade and pupil-saccade.

To be able to compare shape and timing of the pupil-, CR- and gaze-saccades, we had to transform these signals to make them comparable to each other. The latter is necessary 1) because the pupil travels about twice the distance of the CR for a similarly sized saccade (see results experiment 1) and 2) the CR and pupil saccades are measured in camera pixels while the gaze saccade is measured in pixels on the screen. Firstly, we synchronised the signals by using the time stamp of saccade start of the gaze saccade. This enables us to look at timing differences between the different signals. Secondly, we scaled the pupil and CR saccades to become equal in size to the gaze saccade. We determined eye position 20 ms before the saccade start and after the endpoint (160 ms later) of the saccades in all signals. Then we computed horizontal displacement by subtracting eye position before start from eye position after saccade end. Subtracting the start eye position from the whole eye tracker signal produced displacement signals. To match the CR and pupil signals to the gaze signal we divided the pupil and CR signals by their displacements and multiplied them by the displacement of the gaze-signal. The previous resembles calibrating the CR and pupil signals to screen coordinates, which is transforming them into gaze signals. We can do this because experiment 1 showed that displacements in the pupil signal (in camera pixels), the CR signal (in camera pixels) and Gaze (in screen

pixels) are scaled versions of each other for the SMI Hi-Speed eye tracker. As a by-product, here we show that an SMI Hi-Speed tower can be used as a CR eye-tracker, pupil-only eye-tracker and p-CR eye-tracker. Of course CR and pupil eye tracking delivers good signals only if the participant is sitting very still.

5. Results

5.1. Pupil and CR timing and velocity

Fig. 4 shows calibrated pupil and CR and gaze saccades. From the left panels of this figure it is immediately clear that for this specific saccade the pupil starts later than the CR. For the post saccadic oscillations it is the opposite, the pupil starts to oscillate earlier than the CR. The right panels show velocity as function of time. The pupil saccade has a narrower velocity profile than the CR-saccade. The peak velocity of the pupil saccade is higher than the peak velocity of the CR-saccade and the peak velocity of the pupil saccade occurs earlier in time than peak velocity of the CR-saccade. To investigate the relative timing of the two signals, we plotted time of reaching peak velocity (marked as peak velocity in the upper right panel of Fig. 4) for pupil versus CR (Fig. 5). We marked the velocity peaks with a Matlab script by pointing with a cursor in high-resolution zoomed-in figures. Individual left panels of Fig. 5 show four clusters of 4 data points. Each observer has made saccades in 4 amplitude conditions. Each condition consists of 4 averaged saccades (from the left and the right eye and made to the left and to the right, $4 \times 2 \times 2 = 16$ data points). Fig. 5 also shows the unity line and if the dots are located under the unity line, the pupil peak velocity is reached earlier than the CR peak velocity, if they are above the line the opposite is true. Most points are located under the unity line. The right panel of Fig. 5 shows the mean timing difference of the pupil and CR signals. For O3 we do not see a systematic bias, in the other observers, the pupil reaches peak velocity earlier than the CR for the smaller saccades (5° and 10°). Fig. 6 shows timing of the first overshoot of the PSO for pupil and CR-saccades in the velocity signal (marked as *first velocity-PSO*

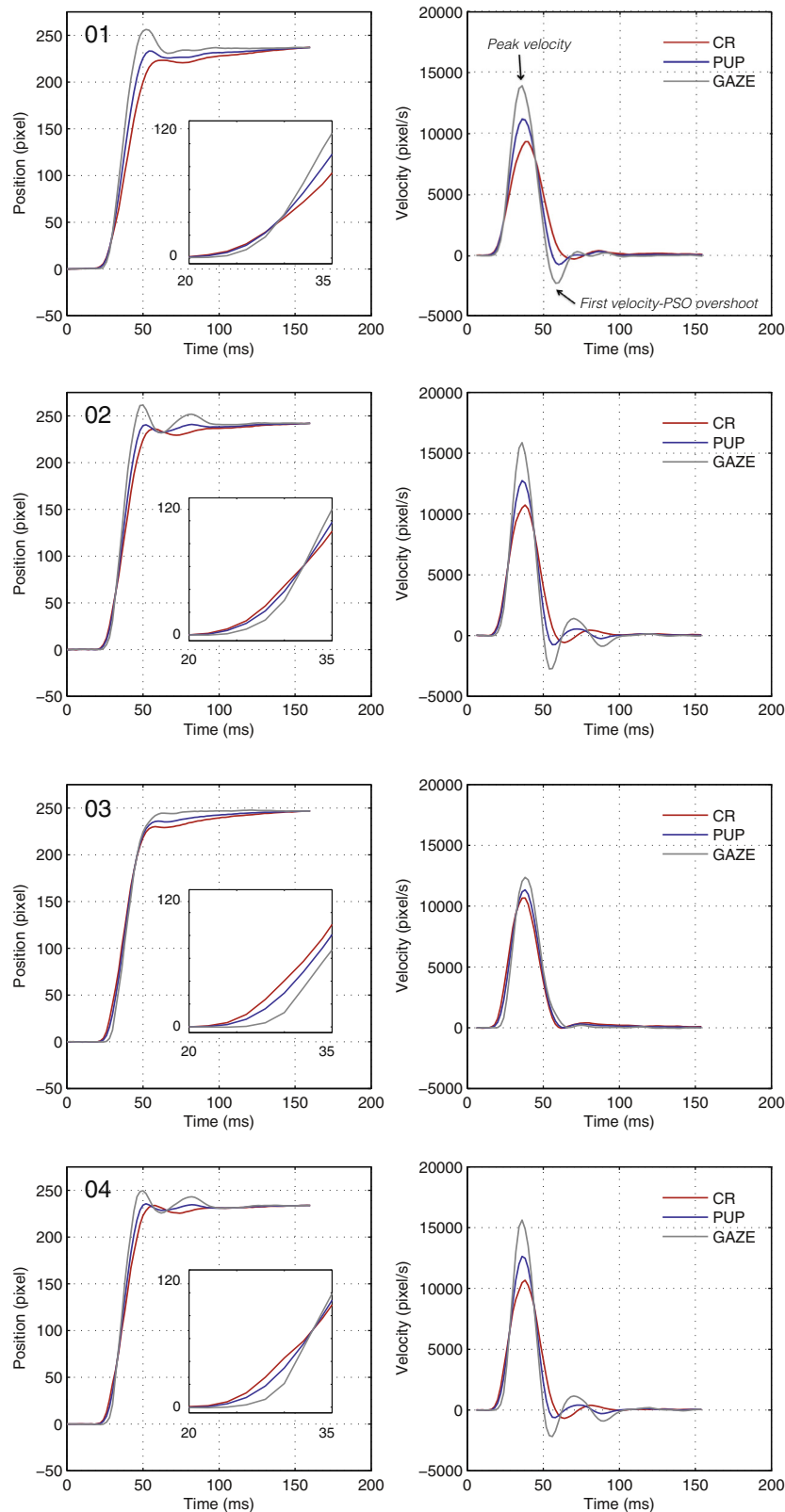


Fig. 4. Position and velocity profiles for pupil and CR and gaze saccades. The Pupil signal is blue; the CR signal is red; the gaze signal is grey. The *pixel* in the vertical axis refers to screen pixels. This figure shows the averaged saccade from the 5° target separation condition. This averaged saccade was measured in the right eye and was made in the rightward direction. We used the gaze-saccade onset to synchronise the signals. The onset of the gaze saccades occurs at $t = 20$ ms. The inset in the left panel shows that the CR (red) starts earlier than the pupil. Here it is clear that the gaze signal overestimates PSO and saccade peak velocity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

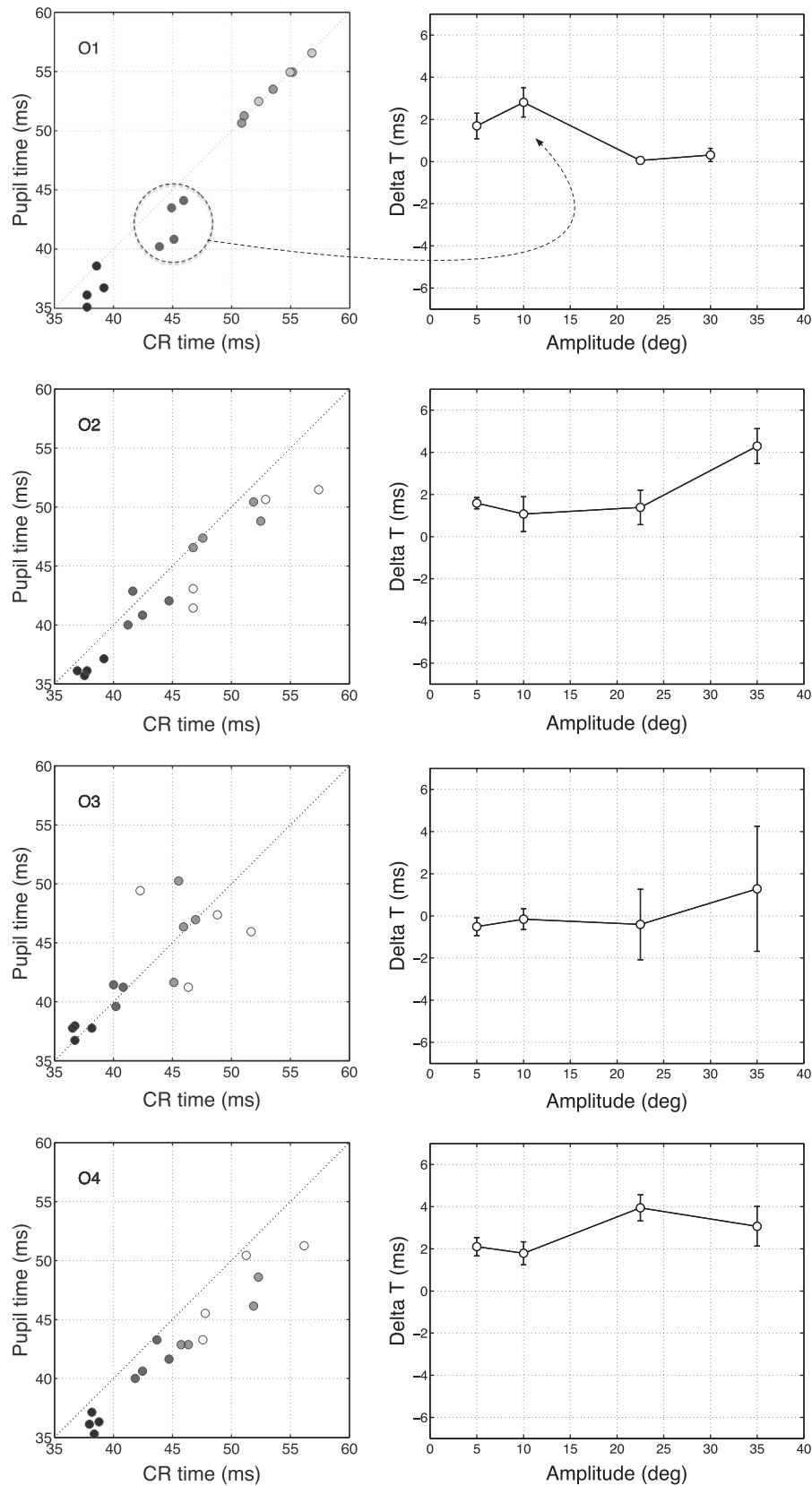


Fig. 5. Peak velocity timing for CR and pupil signals. Left panels: horizontal axis denotes time of reaching peak velocity for the CR signal, vertical axis denotes time of reaching peak velocity for the pupil signal. If data points are located above the unity line, the CR reaches peak velocity earlier than the pupil. If data points are located beneath the unity line, the pupil reached peak velocity earlier than the CR. Darker data points belong to conditions with smaller saccade amplitude. Each individual panel of this figure shows four clusters of 4 data points. Each observer has made saccades in 4 amplitude conditions. Each condition consists of 4 averaged saccades (from the left and the right eye and made to the left and to the right, $4 \times 2 \times 2 = 16$ data points). Right panels: Mean timing difference between pupil and CR signal (Delta T). A positive Delta T indicates a quicker pupil, negative indicates a quicker CR. Error bars denote standard error of the mean. Except for O3, for the smaller saccades (5° and 10°) the pupil reaches peak velocity earlier than the CR.

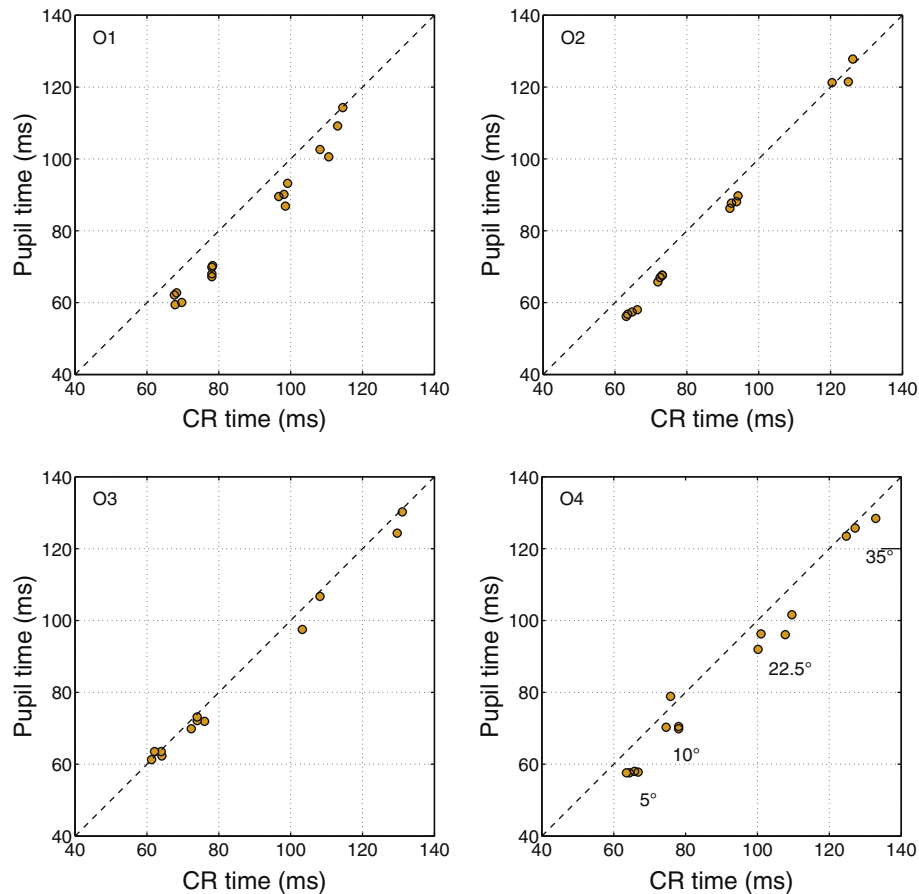


Fig. 6. Timing of the first PSO peak in the velocity signal of the pupil signal versus CR signal. Data points below the unity line point to the pupil be earlier in oscillation than the CR. Individual panels of this figure show four clusters of 4 data points. Each observer has made saccades in 4 amplitude conditions. Each condition consists of 4 averaged saccades (from the left and the right eye and made to the left and to the right, $4 \times 2 \times 2 = 16$ data points). However, some panels have less data points because some larger saccades lack PSO (see also Hooge et al., 2015). Some data points are invisible due to overlap (panel of observer O4).

overshoot in the upper right panel of Fig. 4). The same reasoning from Fig. 5 hold for Fig. 6. Most data points lie under the unity line, indicating that the pupil-PSO starts earlier than the CR-PSO. Due to overlap some panels seem to show less than 4 dots. In summary, the CR starts to move before the pupil does, and then the pupil is catapulted and catches up with the CR, to stay ahead of the CR until the end of the saccade.

5.2. Gaze timing and velocity

Both timing and shape of the pupil and the CR-saccades differ. The gaze signal is composed of those signals and the dynamic differences may have unwanted effects for the timing and shape of the gaze signal. Fig. 4 shows CR, pupil and gaze saccades. The grey line represents the gaze signal as produced by the SMI Hi-Speed. In the position signal (left panel, inset) it is clear that the gaze saccade starts later than both CR and Pupil signal, the overshoot in the gaze signal is much larger than in CR and the pupil signal. Here the gaze signal appears an excessive version of the pupil signal. The previous also holds for the PSO, gaze-PSO starts earlier and has larger amplitude. The right panels show the velocity signals; Gaze velocity is up to 50% higher than the CR velocity.

Fig. 7 shows peak velocity of the gaze signal versus the peak velocity of the CR-saccade. The majority of the data points lie above the unity line indicating that gaze saccade peak velocity is higher than the CR peak velocity. To get insight how peak velocities of the gaze signal and pupil signals are related to the size of a saccade we plotted relative peak saccade velocity versus saccade

amplitude. Relative gaze peak velocity is absolute gaze peak velocity divided by absolute CR peak velocity. Relative pupil peak velocity is calculated in a similar way. Fig. 8 contains 4 panels (one for each observer) and each panel contains 2 lines with data points (relative gaze and pupil peak velocity). Black dots denote relative gaze peak velocity; white dots denote relative pupil peak velocity. Each individual dot represents the average relative peak velocity of averaged saccades from the left and right eyes made from left to right and vice versa. From Fig. 8 it is clear that for small saccades both the gaze and the pupil signals overestimate saccade peak velocity relative to the CR saccade peak velocity, for the larger saccades gaze, pupil and CR saccade peak velocity are more similar.

6. General discussion

6.1. Summary of results

P-CR eye trackers form the majority of eye trackers nowadays and we question whether the p-CR technique is adequate to investigate saccade dynamics. In the p-CR technique the difference vector between pupil and corneal reflection signals is used to calculate the gaze direction. The p-CR method aims at diminishing the disruptive effects of movements between the head and the eye-tracking camera. To get a better understanding of the gaze signal of a p-CR eye tracker during saccades we performed two experiments with a standard high quality eye tracker that reports pupil,

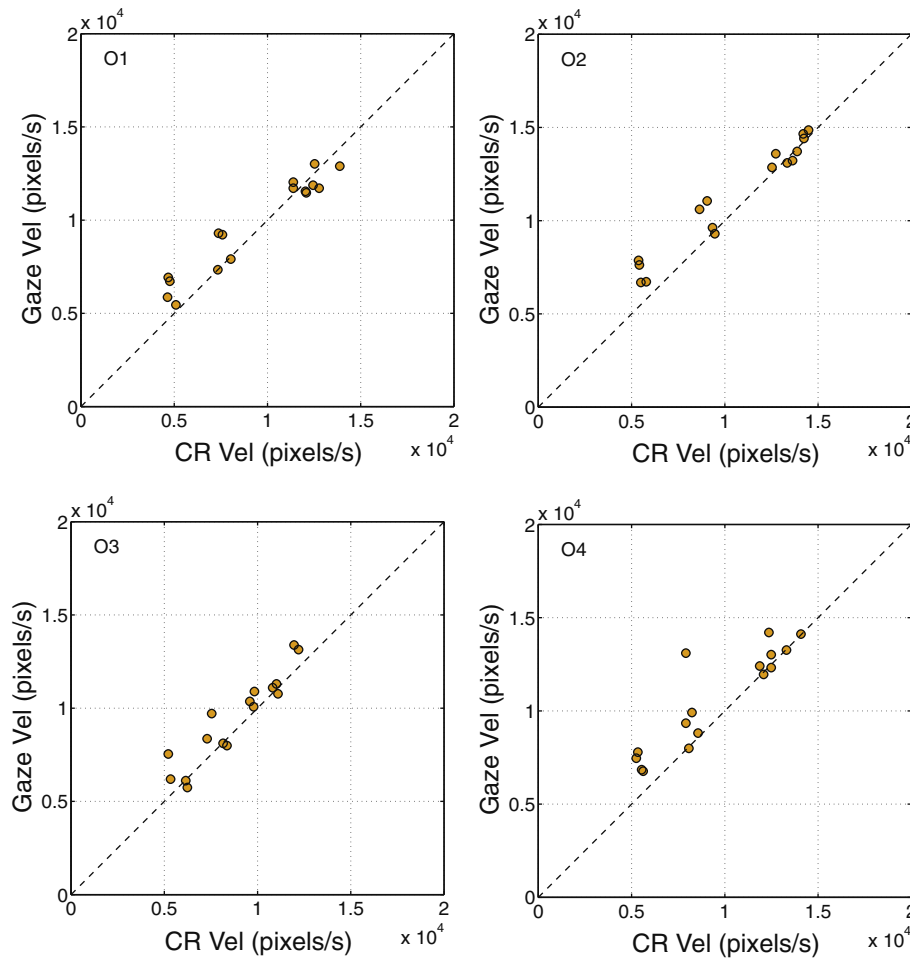


Fig. 7. Absolute saccade peak velocities (in pixels/s) of the gaze signal versus the absolute saccade peak velocities of the calibrated CR signal. The *pixel* in the vertical axis refers to *screen pixels*. Data points above the unity line indicate that the gaze velocity is higher than CR velocity. Individual panels of this figure show four clusters of 4 data points. Each observer has made saccades in 4 amplitude conditions. Each condition consists of 4 averaged saccades (from the left and the right eye and made to the left and to the right, $4 \times 2 \times 2 = 16$ data points).

CR, and gaze data in its output file. The first experiment was conducted to reveal the p-CR to gaze transformation of this specific eye tracker. Experiment 1 clearly showed how effective the p-CR method is in case of relative movements between the eye and the camera (Fig. 2, observer 1, panels B and C). Secondly, it also showed that the SMI Hi-Speed eye tracker contains a relatively simple mapping function. We described adequately the transformation between the p-CR signal and the gaze signal by a scale factor followed by a shift.

In the second experiment four observers were asked to perform horizontal saccades of different sizes. The second experiment revealed that:

1. The timing of the pupil and CR signals differs. The CR starts moving before the pupil does. During the saccade, the pupil catches up and peak velocity is reached earlier than the CR reaches peak velocity. Time differences may have durations up to 5–10 ms, but are of the order of milliseconds for most saccades. The pupil stays ahead of the CR and PSOs start earlier for the pupil signal than for the CR signal.
2. The shape of the pupil and CR signals differs. This becomes clearly visible in the velocity signal. To be able to compare the signals, we transformed the pupil and CR signal to gaze coordinates by scaling them. Calibrated pupil peak velocities were higher than CR velocities. This effect was mainly present for the smaller saccades (5° and 10° ; see Fig. 8).

3. The gaze signal of the eye tracker consists of a scaled and shifted version of the pupil-CR vector. This is a potentially erroneous method to use in episodes where the pupil and CR signals change quickly and are shifted in time (severe violation of the rigid eye assumption). The gaze peak velocity is too high for the smaller saccades (up to 1.5 times, Fig. 4) and gaze-PSOs are much larger than PSOs in the CR and pupil signals (Fig. 4). The gaze signal looks like an excessive version of the pupil signal. From the comparison between gaze, pupil and CR signals we conclude that the gaze signal represents aspects that are not present in the more directly measured CR and pupil signals. The gaze signal is not veridical during and after saccades. The p-CR artefact seems to be more severe for the smaller eye saccades (Fig. 8).

6.2. Implications for eye tracking research

6.2.1. Studying saccade dynamics

The p-CR eye tracker is not the only non-invasive eye tracker which tracks eye features that move relative to each other during fast eye movements. Another one is the dpi eye tracker (Cornsweet & Crane, 1973), which can be best described as the p_4 -CR tracker. The p_4 reflection originates from the rear surface of the lens and it has been shown that the lens moves with respect to the eye during and after saccades (Deubel & Bridgeman, 1995). They write: “The Purkinje signal follows the onset of the saccade

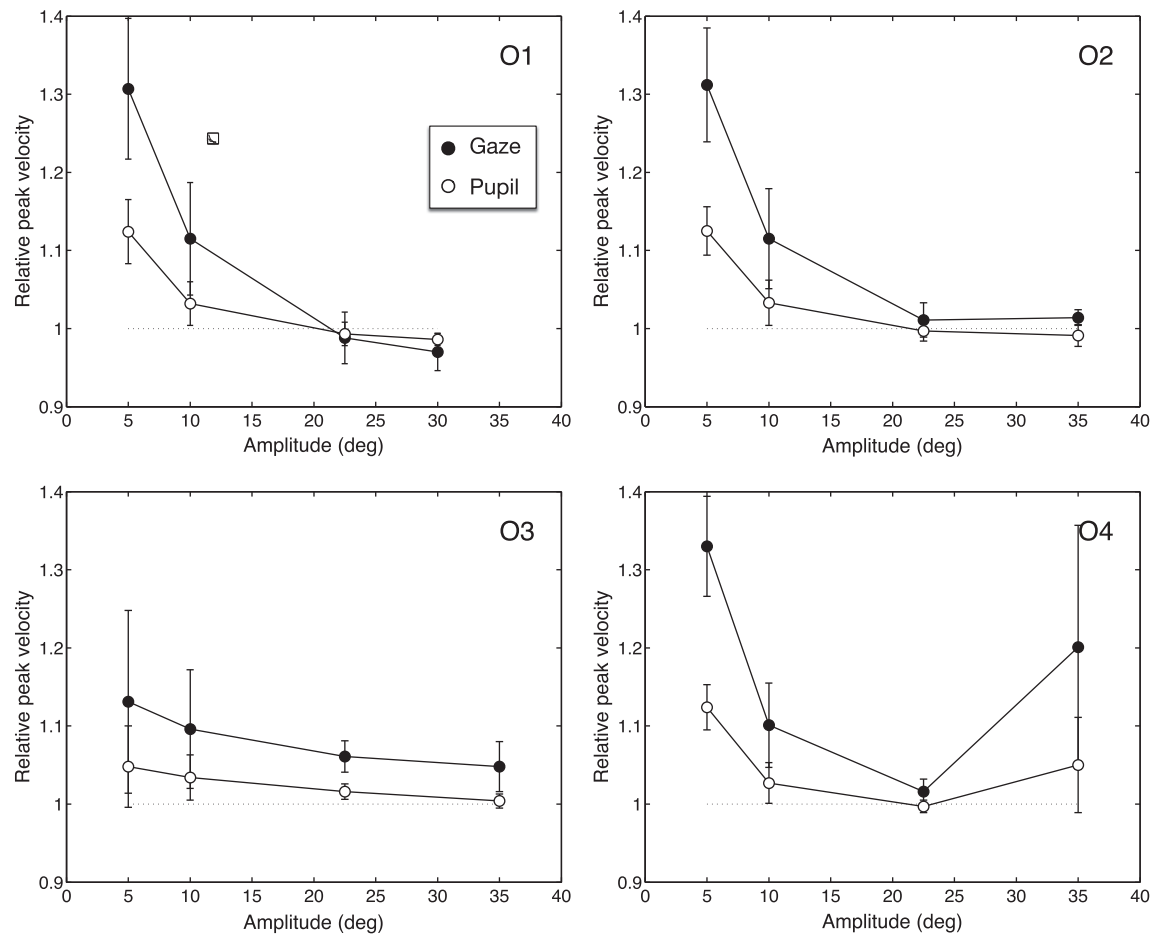


Fig. 8. Relative saccade peak velocities of the gaze (black symbols) and the calibrated pupil signal (open symbols) versus saccade amplitude. Error bars denote standard error of the mean. Relative peak velocity is determined by dividing the peak velocity of the Gaze and pupils signals by the peak velocity of the CR signal.

only after a considerable delay, then overtakes the eye movement reaching velocities almost twice as high as the true eye rotation, finally ending in a prominent overshoot.” Based on these observations Deubel and Bridgeman conclude: “However, our study demonstrates that, due to the biological properties of the eye, the system is not suitable for the analysis of saccade dynamics (main sequence) and of post-saccadic events such as saccadic dynamic overshoots and post-saccadic drift.” In the present study we observe similar but smaller effects in the p-CR signal of a high quality eye tracker and following the rationale of Deubel and Bridgeman (1995) we conclude that the p-CR eye tracker is not suitable for studying saccade dynamics.

6.2.2. About backshoots before saccade start

The dpi signal is known for showing small backshoots in the beginning of a saccade (Deubel & Bridgeman, 1995). These backshoots do not reflect physical eyeball rotations. The explanation is that the P_4 reflection (which stems from the back of the lens signal) starts to move later in time than the P_1 reflection because the lens lags behind in the beginning of the saccade. In the DPI eye tracker signal the position of the already moving P_1 is subtracted from the position of the static or slower moving P_4 reflection and this results in a signal opposite to the actual eye movement. We predict a similar effect in the eye tracker signal of a p-CR eye tracker because the pupil starts to move later than the CR, which is subtracted from the pupil signal. In the dpi eye tracker signal backshoots are small, they are probably not visible in the p-CR eye tracker signal because p-CR eye trackers are less precise. How-

ever, in the study of Hooge et al. (2015) Figs. 1A, B and 3B contain small backshoots in the eye tracker signal of Observer 4. We checked the eye tracking signals of the current study carefully and we observed small backshoots in the signals of 3 out of 4 observers (Fig. 9). Based on our observations we also conclude that backshoots preceding saccades are an artefact of the p-CR technique as they are an artefact of the DPI.

6.2.3. Dependency on saccade amplitude

The overestimation of saccade velocity by the gaze signal seems to be relatively larger for smaller saccades (Fig. 8). We hypothesize that this is due to two effects. One factor is described in Hooge et al. (2015). Smaller saccades start to move more abruptly than larger saccades causing the pupil to start oscillating more already during the saccade causing the pupil peak velocity to be higher than the CR peak velocity. The second factor is the overestimation of velocity caused by the temporal shift between the pupil and the CR signals. The temporal difference of the time reaching peak velocity between the pupil and CR is especially present in the smaller saccades (Fig. 5). The combination of these two factors results in a velocity overestimation effect that is relatively larger for small saccades.

6.2.4. Gaze contingent displays

High speed (>500 Hz) p-CR eye trackers are popular tools in gaze contingent eye tracking (e.g. Aguilar & Castet, 2011; Nuthmann, 2013; Saunders & Woods, 2014). Are the current findings of overestimation of velocity and enlarged PSOs problematic

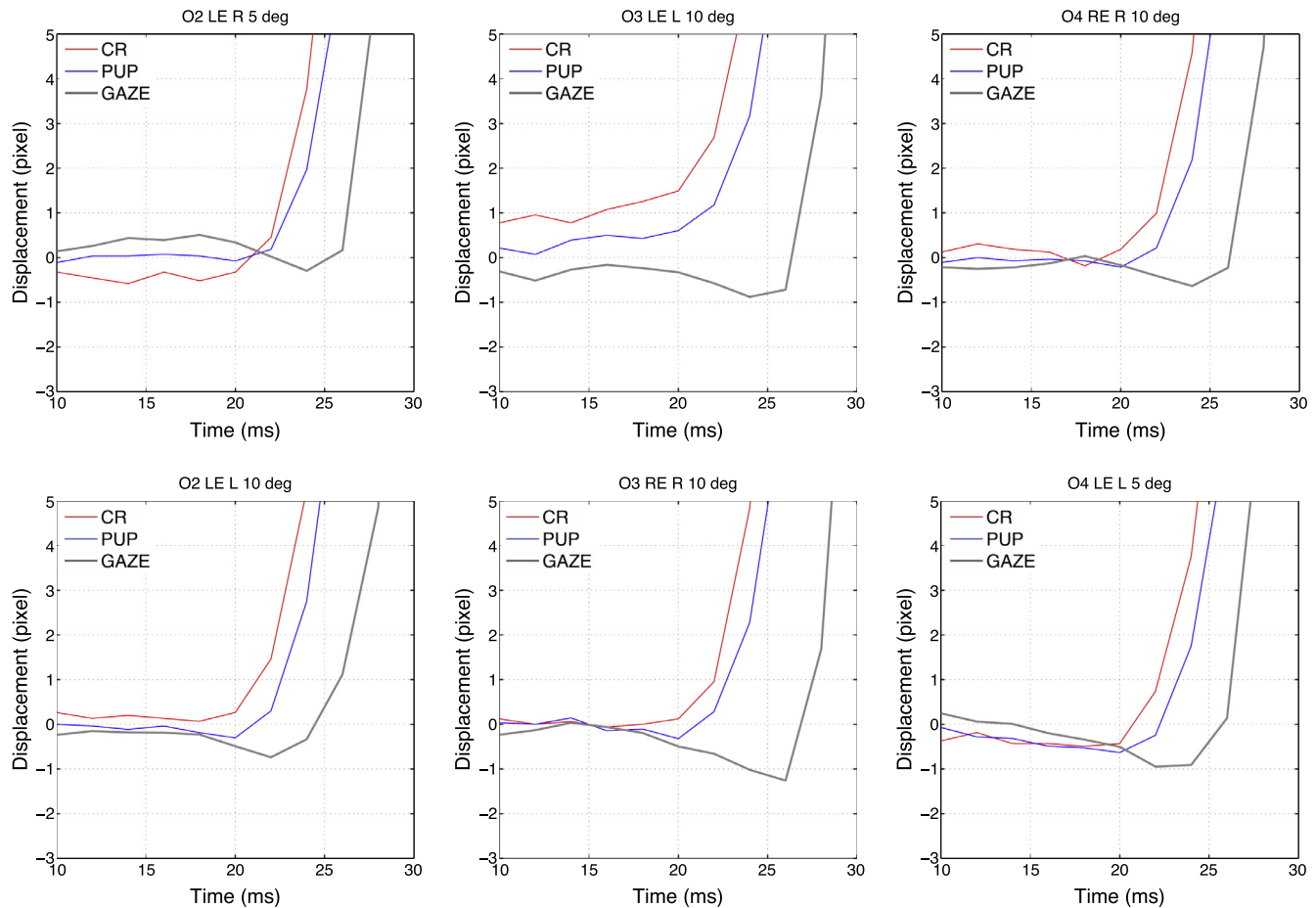


Fig. 9. Examples of backshoots in the Gaze-signal. The 6 panels show saccade starts of averaged saccades of O2, O3 and O4; the gaze signal of O1 did not show backshoots. LE and RE denote right eye and left eye; R and L denote leftward and rightward saccade directions. The size of the backshoot is of the order of one pixel ($= 0.02^\circ$). In these examples it is clear that both CR and pupil signal do not show any backshoot.

for gaze contingent paradigms? Overestimation of saccade velocity by the eye tracker is not problematic because during saccades the visual input is largely suppressed and therefore the observer is practically blind for position mismatch of the gaze contingent display. Whether the enlarged PSO is problematic depends on 1) the amplitude and duration of the PSO, 2) the refresh rate of the stimulus presentation system, 3) the delay between measurement of eye position and subsequent update of the screen of the and 4) the precision of the eye tracker. PSOs may have durations from 30 to 50 ms and amplitudes up to 2° (however most PSO amplitudes are much smaller and around 0.5°), probably giving a noticeable mismatch between the gaze position and the position of the gaze contingent display (Hooge et al., 2015). According to Nuthmann (2013), her system has a maximal delay of seven milliseconds and a screen refresh rate of 140 Hz. She does not report precision, but the EyeLink 1000 desktop used has a precision smaller than 0.01° . Nuthmann's system should be able to produce a considerable mismatch between the gaze position and the location of the gaze contingent area directly after a saccade due to PSOs. However, in her study she does not report that subjects perceived any mismatches. Here we did not take one factor into account and that is the perception onset time after saccades. It takes time after a saccade before perception is fully recovered. McConkie and Loschky (2002) report that the availability of monochromatic high spatial frequency information in a picture is not acquired sooner than 6 ms after saccade end and reaches its maximum at 32 ms

after the end of the saccade. Based on the previous we may assume that observers are probably blind for the position mismatch due to PSO because the largest mismatch occurs directly after the saccade end.

6.2.5. Future directions for studying dynamics of eye movements

We like to propose solutions and directions for eye trackers to study eye movement dynamics. Is the pupil-only modus measurement a solution to avoid p-CR artefacts (overestimation of PSO and saccade peak velocity)? We consider this one of the weaker solutions. As pointed out in Nyström et al. (2013), the pupil moves with respect to the iris and therefore we consider pupil motion not to be the best estimator eyeball rotation. If one has no objection against pupil-only eye tracking one should use the EyeLink 2 in pupil-only modus. This unique eye tracker is attached to the head and does not suffer too much from relative eye-camera movements. Another solution is going back to the classic method of CR-only eye tracking. It is a possibility that is not ideal for everybody and one needs an eye tracker that provides the CR signal in the output file. Nyström, Hansen, et al. (2016) and Nyström, Hooge, et al. (2016) write: "Even though all four participants were experienced eye movement researchers, we had to run several recording each to achieve data where the variance of the CR-signal was sufficiently low." Besides problems with head movements, Hartridge and Thomson (1948) state that the CR is probably not the ideal feature to measure eye rotation: "The corneal reflection has one disadvan-

tage, namely that the movement of the reflected image of the light source is not as great as the actual movement of the anterior surface of the cornea itself, but is about half the movement.” However, this resolution problem can be solved with better sensors, Eizenman, Frecker, and Hallett (1984) describe an analogue CR eye tracker that is as accurate as coil-systems and the dpi. The smaller movement of the CR is not a problem today; spatial resolution of digital high speed cameras still increase and the present study shows that the absolute unfiltered RMS noise of the CR signal of the SMI Hi-Speed 1250 is even slightly lower than that of the pupil signal. If one is only interested in saccade dynamics and not so much in absolute gaze direction, CR only eye tracking with the SMI Hi-Speed is a possibility. A better solution is probably CR eye tracking with an additional signal as reference to minimise the relative head-camera movement problem. Such systems do not exist yet and candidates for reference signals are facial features or (artificially applied) marks on the participants face like the target sticker of the EyeLink 1000 remote eye tracker (http://www.sr-research.com/camup_remote.html).

There are alternative eye features that are candidates to be tracked, one such feature is the iris. Iris eye tracking has been used to measure torsion (e.g. Groen, Bos, Nacken, & de Graaf, 1996; Onga & Haslwanter, 2010). The positions of small iris features may suffer from the same oscillations during and after saccades as the inner iris border (pupil). However iris centre tracking based on iris border detection should suffer less from these oscillations (Mingxin et al., 2015). Another technique is Limbus eye tracking (Schmitt, Muser, Lanz, Walz, & Schwarz, 2007). Gaze estimation by iris and limbus tracking has the disadvantage of being worse in measuring vertical eye movements, however, some limbus eye trackers advantages over video techniques; they are not expensive, small and some have the ability to measure a high frequencies (1000 Hz). Another advantage of tracking the limbus or iris is that these structures are larger than the pupil and suffer less from post saccadic oscillations (Hooge et al., 2015).

Is the recently developed and fascinating technique of high magnification retinal imaging a candidate to measure saccade dynamics (Sheehy et al., 2012; Stevenson, Sheehy, & Roorda, 2016)? We do not think this technique suitable to study saccade dynamics because current scanning eye tracking laser ophthalmoscopes have fields of view of 8° or smaller and are meant to study fixational eye movements (micro-saccades). Saccades measured with this technique also suffer from PSOs; Stevenson et al. (2016) report: “Saccades show a distinct, very brief overshoot that is likely due to motion of the eye’s crystalline lens at the end of the saccade. For these microsaccades, the amplitude of the lens wobble induced retinal motion is sometimes larger than the saccade itself.” It seems that the eye tracker signal from the laser ophthalmoscope suffers from the same problem as the DPI.

The last potential eye tracking solution is probably already present in prototypes and makes use of several cameras and arrays of CRs. Arrays of CRs and multiple cameras should enable an algorithm to compute a physical model of the eye. With a sophisticated physical 3D eye model the reliance on a simple reference point in a 2D camera image is probably not necessary anymore.

7. Conclusion

Despite the fact that the p-CR technique is useful to compensate for the consequences of some relative head-camera movements, the consequences for the dynamics of the eye tracker signal are severe, therefore we conclude that the Pupil-CR technique is not suitable for studying detailed dynamics of eye movements. This means that most current video based p-CR eye trackers are not suitable for studying dynamics of eye movements.

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