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Pupil size influences the eye-tracker signal during saccades

Marcus Nyström [a,*], Ignace Hooge [b], Richard Andersson [c]

[a] Lund University Humanities Laboratory, Lund, Sweden
[b] Experimental Psychology, Helmholtz Institute, Utrecht University, Utrecht, The Netherlands
[c] Department of Philosophy & Cognitive Science, Lund University, Sweden

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A B S T R A C T

While it is known that scleral search coils—measuring the rotation of the eye globe—and modern, video based eye trackers—tracking the center of the pupil and the corneal reflection (CR)—produce signals with different properties, the mechanisms behind the differences are less investigated. We measure how the size of the pupil affects the eye-tracker signal recorded during saccades with a common pupil-CR eye-tracker. Eye movements were collected from four healthy participants and one person with an aphakic eye while performing self-paced, horizontal saccades at different levels of screen luminance and hence pupil size. Results show that pupil-, and gaze-signals, but not the CR-signal, are affected by the size of the pupil; changes in saccade peak velocities in the gaze signal of more than 30% were found. It is important to be aware of this pupil size dependent change when comparing fine grained oculomotor behavior across participants and conditions.

1. Introduction

Eye tracking has become a standard tool to study visual attention and cognition, diagnose neurological disorders, and interact with computers. The majority of modern eye trackers are video based and use information about the center of the pupil and the center of one or many corneal reflections (CRs) in the eye image to estimate movements of the eye. The most advanced eye trackers can measure the position of the eye every millisecond, and resolve tiny movements of the eye that researchers base their conclusions on. It is therefore crucial to understand the relationship between a physical eye movement and the digitized eye-tracker signal representing it Hooge, Nyström, Cornelissen, and Holmqvist (2015). The aim of this paper is to investigate how the size of the pupil affects the eye-tracker signal during saccadic eye movements.

1.1. How does pupil-CR tracking work?

An eye tracker typically output several different signals acquired at a particular rate. The most common is the gaze signal, which represents the estimated direction of gaze. Additional signals may include the size of the pupil and the positions of the pupil and CR centers in the eye image. Each sample in a signal is associated with a timestamp representing the time it was acquired.

The gaze direction is estimated through a calibration process, where participants are asked to look at a number of targets with known locations. The positions of the pupil center and the CR(s) are associated with each target location. Intermediate locations can then be calculated through a mapping function whose parameters are derived from the calibration (Hansen & Ji, 2009).

A prerequisite for accurate gaze estimation is that the center of the pupil is accurately computed from the eye image, a problem associated with several challenges. For instance, the eye image is a two dimensional representation of a three dimensional object, which, in conjunction with camera optics may distort the size and shape of objects (Hayes & Petrov, 2015). There are also different methods to compute the pupil center, e.g., as the center of gravity of pixels associated with the pupil or as the center of an ellipse fitted to the pupil. In addition, problems can originate from the participant's physiology such as droopy eyelids that occlude parts of the pupil.

The reflections in the eye are generated by illuminating the eye with a near-infrared light source, which reflects off the cornea and the crystalline lens (henceforth lens), as seen in Fig. 1. The brightest of these reflections comes from the front of the cornea, i.e., the CR, also referred to as the first Purkinje image (P_1). Since the light reflects off the corneal bulge, which lies anterior to the center of ocular rotation, the corneal reflection moves in the same direction as the eye, and this technique has been used extensively in the past to measure eye movements (Young & Sheena, 1975).

* Corresponding author.
E-mail addresses: marcus.nystrom@humlab.lu.se (M. Nyström), i.hooge@uu.nl (I. Hooge), richard.andersson@humlab.lu.se (R. Andersson).

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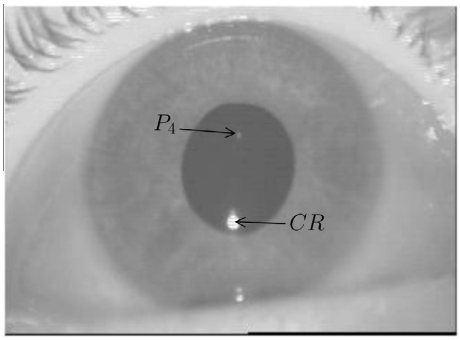

Fig. 1. Eye image where the first (CR) and fourth (P_4) Purkinje reflections are marked with arrows.

The rationale behind combining the pupil and the CRs is that—while their positions in the eye image change with even small head movement—their positions *relative* to each other are robust to small changes in head position. Together with its non-invasive nature, this has made pupil-CR eye tracking the dominating principle over the past decades. The advantage in robustness to head movements provided by pupil-CR tracking comes at the cost of a noisier gaze signal compared to pupil-only tracking, since the center of the CR typically cannot be measured with the same precision as the center of the relatively larger pupil (Kolakowski & Pelz, 2006). For a comprehensive introduction to pupil-CR eye-tracking, see e.g., Hammoud (2008), Duchowski (2007), and Holmqvist et al. (2011).

1.2. Non-rigid pupil during fixation

Despite their popularity, a fundamental limitation of pupil-based eye trackers is that changes in pupil size introduce deviations in the estimated direction of gaze (Choe, Blake, & Lee, 2016; Drewes, Zhu, Hu, & Hu, 2014; Merchant, Morrissette, & Porterfield, 1974; Wyatt, 1995; Wyatt, 2010; Wildenmann & Schaeffel, 2013). The reason is that the pupil center does not remain fixed relative to the fibrous tunic and therefore introduces displacements of the pupil center even in the absence of an eyeball rotation. The size of these deviations can be up to several degrees (Drewes et al., 2014), and have been investigated both with exogenous and endogenous manipulations of pupil size (Choe et al., 2016).

While changes in the accuracy of the eye tracker signal in response to such pupil size change have been carefully investigated in the fixated eye, it is less clear whether the pupil size influences the eye tracker signal during saccade—periods so brief that light manipulations and cognitive control of the pupil size typically are negligible (Bergamin, Schoetzau, Sugimoto, & Zulauf, 1998).

1.3. Properties of signals from pupil-CR eye trackers during saccades

The eyeball is exposed to relatively large forces during saccades due to the high accelerations induced by the eye muscles to initiate and stop the rotation of the eye globe. Since the eye is an elastic body comprised of structures with different material properties, the eyeball does not rotate rigidly during a saccade, i.e., it does not conform to what we call the *rigid eye assumption*. The distinction between the rotation of the eyeball and its internal structures was described already in the 1737, where Porterfield (as quoted in Wade & Tatler, 2005) writes that.

> Motion of the Eye are either external or internal. I call *external*, those Motions performed by its four straight and two oblique Muscles, whereby the whole Globe of the Eye changes its Situation or Direction. And by its *internal* Motions which only happen to some of its internal Parts, such as the Crystalline and Iris, or to the whole Eye, when it changes in spherical Figure, and becomes oblong or flat (Porterfield, 1737, p. 160, original italics).

According to Porterfield, an eye movement can therefore refer to many different movements within the eye, and the type of intraocular structure an eye tracker uses determines the properties of the eye-tracker signal. For instance, it is well known that the signal acquired with scleral search coils—measuring the rotation of the eyeball—does not share the exact same dynamic properties as signals recorded with other recording techniques such as the Dual Purkinje eye tracker (DPI) measuring lens movements (Deubel & Bridgeman, 1995; He, Donnelly, Stevenson, & Glasser, 2010) or modern video-based eye trackers, which use the pupil center to estimate where someone looks (Kimmel, Mammo, & Newsome, 2012; Nyström, Hooge, & Holmqvist, 2013). In the case of the DPI, the deviations originate from the fact that the lens is elastically attached to the eyeball by zonular fibers, which delay and increase the maximum velocity of the movement of the lens in response to an abrupt rotation of the eyeball. Consequently, at the stop of a saccade, the DPI-signal exhibits a characteristic oscillation known as dynamic overshoot or post-saccadic oscillations (PSOs). Compared to coil-data, pupil-based eye trackers share many of the dynamic features of the DPI-signal; a delayed saccade onset, an increase in saccade peak velocity, and larger PSOs. However, these features are less pronounced when using the pupil center instead of the lens to measure eye movements.

PSOs in signals recorded with pupil-based eye trackers reflect a combination of dynamic overshoot of the eyeball and motion of the pupil center relative the eyeball (Nyström et al., 2013, Nyström, Andersson, Magnusson, Pansell, & Hooge, 2015). Such relative motion occurs in association with saccades since the iris is elastic and allows its inner border—the pupil—to move when exposed to the forces exerted on the iris due to fluid motion in the anterior chamber of the eye.

The quivering of the iris in association with eye movements is known as iridodonesis, and is particularly marked in people with aphakia - where the lens is completely removed - or in people where the lens or its suspension are displaced or damaged, e.g., due to trauma or disorder of the eye. The normal, phakic eye has a lens suspended in the ciliary bodies of the eye, making the anterior part of the eye more rigid and less prone to iris deformations in association with saccades. The forces exerted on the eye during periods of saccadic acceleration are however large enough to produce internal ocular deformation, which, although visually indiscernible, are picked up by modern eye trackers. In an aphakic eye, the stabilizing barrier between the vitreous humor and the posterior chamber is weakened, making the iris and the fluid in the anterior chamber more exposed to viscous forces (Jacobi & Jagger, 1981). Consequently, aphakic participants typically exhibit a large degree of iridodonesis in conjunction with saccades that is visible even through direct observation.

The overall goal of this paper is to investigate whether the gaze signal recorded from a common, high-end, pupil-CR eye tracker is influenced by the size of the pupil, given that the underlying eye movement of the eyeball is the same. Unlike fixational eye movements, when the accuracy of eye-tracking signals can be estimated as a function of pupil size and deformation by comparing the position of the recorded data with the position of a target participants are asked to fixate, there is no straight-forward measure of the accuracy of saccadic profiles. We approach this problem by comparing the gaze signal against the movement of the CR, which is invariant to changes in pupil size. Any deviation from the CR-signal would therefore indicate an interocular deformation. A completely rigid eyeball would generate similar gaze- and CR signals, given that the eye tracker does not introduce any additional biases. Since the gaze signal is composed of a combination of the CR and the pupil, we also present results from the pupil signal, which corresponds to the center of the pupil measured in camera pixels.

Using screen brightness to manipulate pupil size, we present data from an aphakic eye along with four normal eyes. Aphakic eyes offer a unique opportunity to study an exaggerated form of iridodonesis that is impossible to induce through manipulations of healthy eyes. As such, the aphakic eye represents an extreme model that is used to reveal the weakness of pupil-CR based eye-tracking.

2. Methods

2.1. Participants

Five participants were recorded. One of the participants, a female in her forties, was aphakic and had both her lenses removed at an early age. Sufficient vision to perform everyday activities such as driving was possible by wearing a contact lens in the left eye. While the contact lens improved vision, it distorted the view of the pupil from the eye camera and made it difficult to track the eye with our video based system. An image of the participant's eye as captured with the eye trackers is shown in Fig. 2.

The remaining four participants were male (26–49 years old) with normal or corrected-to-normal vision and otherwise healthy eyes. Written informed consent was provided by the participants, and the experiments were conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2. Stimuli and apparatus

Eye movements from the right eye were recorded with the Hi-speed 1250 system at 500 Hz, using iView X (v. 2.8.26). The particular sampling frequency is more than sufficient to capture the movements of interest. The system has a camera that films the eyes via an infrared reflecting mirror, through which the participant sees the stimulus screen. System output consists of gaze position in screen coordinates, the position of the pupil and CR centers as well as the horizontal and vertical pupil diameters, all in the coordinate system of the camera. Exactly how this output is generated is however proprietary and not publicly available. Binocular eye movements were recorded from the aphakic participant using the same setup adjusted to binocular recordings, but only data from the right eye were analyzed.

Stimuli consisted of two red, 0.2 degree large dots presented on an ASUS VG248QE monitor with resolution 1920×1080 pixels (530×300 mm) and a refresh rate of 144 Hz. The dots were separated horizontally by 5 or 20 degrees and their center of gravity was aligned with the center of the screen. Following (Drewes et al., 2014), the dots were presented on a background with one of seven different brightness levels ranging from black (-1) to white (1): {−1, −0.75, −0.5, −0.25, 0, 0.5,1}, where 0 denotes gray. These values map linearly to screen pixel intensities from 0 (black) to 255 (white). PsychoPy (v. 1.79.01) was used for stimulus presentation (Peirce, 2007; Peirce, 2008).

To contrast the worst case scenario with large differences in pupil size, we also constructed stimuli where all items were isoluminant following the procedure outlined in Guo, Abrams, Moscovitch, and Pratt (2010). In brief, two rectangles with different colors in the RGB-space were alternated at 15 Hz to induce flicker. The isoluminant level was found by adjusting the green component, g_2, in one of the rectangles until the flicker was perceived to be at its minimum. This procedure led to the colors $c_1 : (r_1, g_1, b_1) = (170, 0, 255)$ representing the background and $c_2 : (r_2, g_2, b_2) = (0, 124, 255)$ representing the dots. The lighting in the room was adjusted such that the combined illumination from the isoluminant presentation and the overhead lamps corresponded to 79 LUX at the position of the participants' eyes. This value was obtained by positioning a photometer (Standard ST-1300) at the eye position, and directing its head toward the stimulus screen. This also corresponded to the illumination at eye position using the brightest condition above, i.e., the one with a white background.

2.3. Procedure

The participants were placed 50 cm in front of the screen and their heads were stabilized relative to the eye tracker with a chin-, and forehead rest. Following the standard 13 point calibration in iView X using red targets on a gray background, the participants were asked to saccade between the dots at a pace of two saccades per second. Since there were two saccade amplitudes and seven levels of background brightness, 14 trials were performed by each participant. Each trials lasted for 40 s, and therefore included about 80 saccades. One of the participants (S2) conducted two additional trials with the isoluminant stimuli.

Due to expected fatigue, the aphakic participant performed a shorter version of the same experiment, including only the smallest saccade amplitude and the black and white backgrounds, i.e., four trials in total.

2.4. Data analysis

Only saccade in the rightward direction (abducting) were analyzed, but the results for saccades in the other direction were similar. Besides gaze direction, the horizontal pupil diameter as well as the positions of the pupil and theCR in the eye image were extracted from the data files generated by the eye tracker. Saccades were detected as 'outliers' in the velocity space using the algorithm by Engbert and Kliegl (2003). A saccade was detected from the gaze signal when at least 6 consecutive samples (12 ms) exceeded a velocity threshold $\eta_{x,y} = \lambda\sigma_{x,y}, \lambda = 3$, where $\sigma_{x,y}$ is an estimate of the noise in the velocity signal computed separately in the horizontal and vertical direction.

Only saccades with amplitudes, A_s, similar to that of the target amplitude, A_t, were included, $(0.7A_t \leqslant A_s \leqslant 1.3A_t)$. Since saccades are highly repeatable within participants, we can increase

Fig. 2. Image of the aphakic eye taken with the eye-tracker camera. A contact lens can be seen in the participants's left eye. Data from the right eye was used in the paper.

the signal-to-noise ratio by using average saccade waveforms in the analyzes (Nyström et al., 2013).

To be able to directly compare the average saccade position signals, their starting positions were aligned, and each signal was normalized such that the area under the signal equals one (see Fig. 7). Since small offsets between the position signals do not affect the appearance of the velocity signals, they were averaged and plotted directly. Velocity was computed as the first derivative of the position signal using a third order Savitzky-Golay filter (Savitzky & Golay, 1964) in windows of seven samples.

To calculate the precision of the eye tracking signals during fixation, a sliding window of length 30 ms (15 samples) was applied to the gaze signal. The precision of the pupil and CR-signals was computed from samples inside the window with the lowest root mean square (RMS) of intersample distances.

3. Results

3.1. Signal quality

Previous work has shown that the precision of the pupil signal generally is higher than the precision of the CR-signal (Kolakowski & Pelz, 2006). In Fig. 3, the RMS of intersample distances computed directly from the CR-, and pupil signals are provided. While the precision of these signals are similar in units of camera pixels, the signal-to-noise ratio is higher in the pupil signal compared to the CR signal. This is since the pupil is displaced a longer distance in the video image compared to the CR for an equal sized saccade. This is confirmed when both signals are mapped to degrees of visual angle, as shown in Fig. 4. Across all participants, the CR-signal corresponded to 1.28 ($SD = 0.18$) deg/pixels [camera] and the pupil-signal to 0.67 ($SD = 0.05$) deg/pixels [camera].

3.2. Influence of pupil size on the eye-tracker signals

Fig. 5 shows eye images taken from one participant when the brightness is minimized or maximized. To verify that the brightness manipulation generated the desired changes in pupil size, Fig. 6 shows the median horizontal pupil diameter as a function of screen brightness for each participant. Overall, the pupil diameter increases by more than a factor two when the brightness changes from white to black.

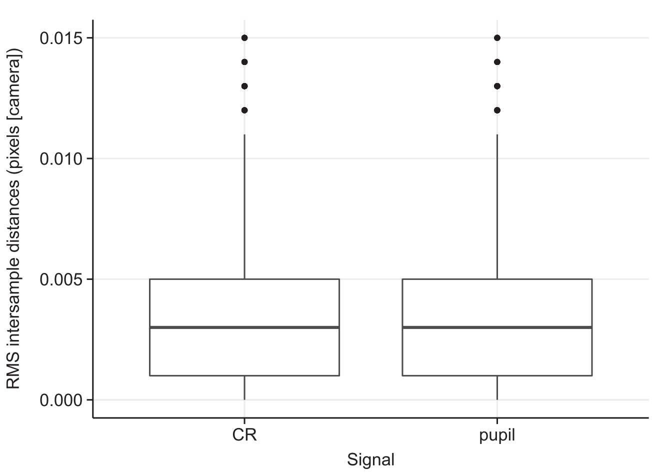

Fig. 3. Precision of the CR-, and pupil signals measured as the root mean square (RMS) of intersample distances in camera pixels. The boxes correspond to the first (lower hinge) and third (upper hinge) quartiles, and the whiskers extend 1.5 times the inter-quartile range, or the largest (upper hinge) or smallest (lower hinge) value within this range. Outliers are plotted as points. The center of the box represents the median value.

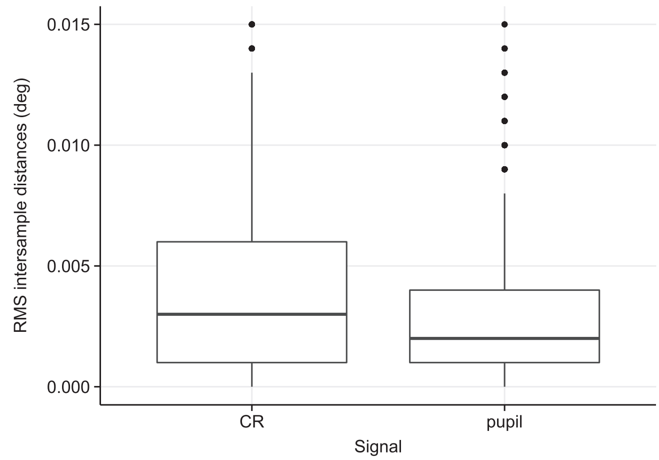

Fig. 4. Precision of the CR-, pupil-, and gaze signals measured as the root mean square (RMS) of intersample distances in degrees of visual angle.

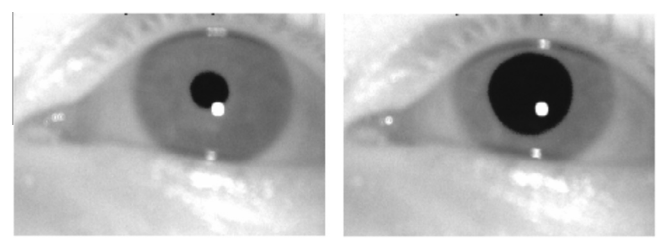

Fig. 5. The smallest (left) and largest (right) pupil sizes for participant S1.

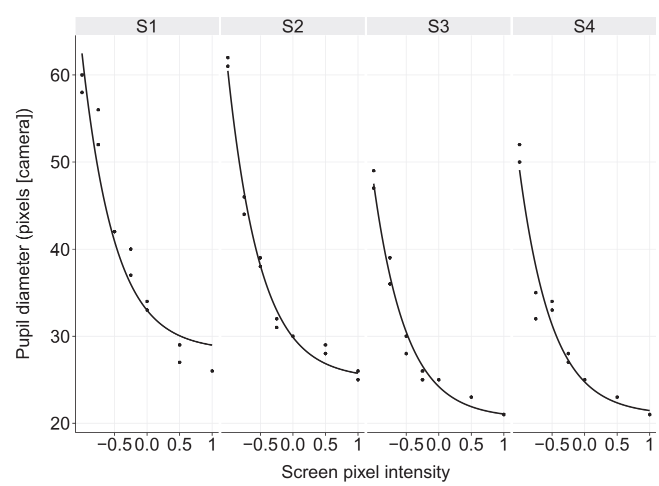

Fig. 6. Screen pixel intensity (−1: black, 1: white) vs pupil size for each participant (S1 → S4). Each dot represents the median horizontal pupil diameter for a particular level of screen background brightness and saccade amplitude. Each line represents an exponential fit to the data.

Fig. 7 illustrates average saccades for each background luminance, where warmer colors denote larger pupil sizes. Fig. 7(A) shows the CR position signals, Fig. 7(C) the pupil signals, and Fig. 7(B) the gaze position signals, all of which have been normalized to facilitate the comparison of shape (see Data Analysis-section). A few things are evident from the figures directly upon visual inspection. First, and perhaps the most obvious, is the difference in variance between the CR and the gaze-signals across the different pupil sizes. Importantly, the CR-signal seems largely unaffected by the pupil size, confirming that participants' eye movements are similar across the different levels of brightness.

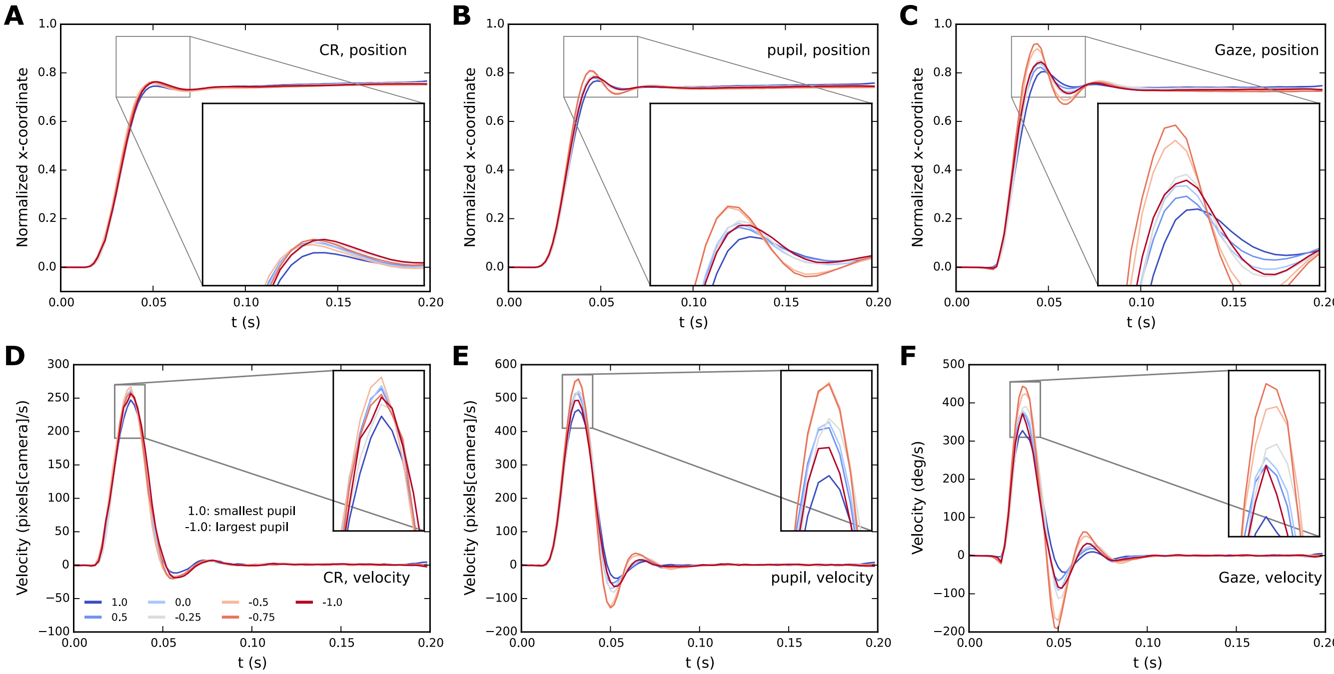

Fig. 7. Average saccade waveforms for position (A, B, C) and velocity (D, E, F) signals for seven different levels of screen brightness, each represented by a different line color (−1: black screen, 1: white screen). The columns represent CR (A, D), pupil (B, E), and gaze (C, F) signals. Parts of the plots are zoomed into highlight differences between the signals. Warmer colors represent darker screens (and hence larger pupil sizes). While the CR-signals are largely unaffected, the shapes of the pupil signals, and in particular the gaze signals vary substantially as a function of pupil size. The smallest pupil size (dark blue line) provides the lowest saccade peak velocity in the gaze signal. The highest peak velocity in this signal is produced for the second largest pupil size. For the largest pupil size (dark red line), the peak velocity is again lower. All signals have been aligned to facilitate comparison. The position signals have in addition been normalized (*cf.* the 2.4 section for details). Data from participant S1 performing five degree saccades. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

Interestingly, the waveform of the gaze signal changes with the size of the pupil; the smallest pupil size indicated by the dark blue line seems to most closely resemble the shape of the CR-signals. As the pupil size increases, the signal deviates increasingly more away from the waveform of the CR signal. The exception is the largest pupil size, which more closely resemble the CR-signal than the second largest pupils size. Second, the difference between the signals in the gaze signal appears to be the largest at the end of the saccade, where the signals exhibit relatively large oscillations. Finally, the slopes of the signals are steeper in the gaze signal compared to the CR-signal, indicating that the velocity of the gaze signal is higher. This is shown explicitly in Fig. 7(D, E, F), which also depicts how the saccade peak velocity changes as a function of pupil size. The pupil signals in Fig. 7(B, E) follow the same pattern as the gaze signals, but the effect is smaller.

To quantify the effect of pupil size change on the gaze-signal, we compute and compare the saccade peak velocity, which is one of the most common parameters to quantify saccades. Fig. 8 shows how the saccade peak velocity changes as a function of pupil size for the CR-, pupil-, and gaze signals for (A) 5 and (B) 20 degree saccades. Overall, the data show the same trend as in Fig. 7, where no or very small changes are observed in the CR-signal due to pupil size changes. Moreover, the saccade peak velocity in the gaze signal changes considerably as a function of pupil size; the largest effect is observed in participant S2 for five degree saccades, where the saccade peak velocity increases from 341 to 450 deg/s—an increase of more than 30%. Participant S4 had the smallest increase, 13%, for five degree saccades (S1: 24%, S3: 26%). For 20 deg saccades, the peak velocity increased between 12–22% (S1: 12%, S2: 13%, S3: 22%, S4: 12%) from the pupil size that produced the lowest saccade peak velocity compared to the pupil size that generated the highest saccade peak velocity.

As a best case scenario, Fig. 9 shows the average saccade-form of the gaze and CR signals when two trials are conducted with the same isoluminant stimuli. As expected, only small differences can be observed across the trials. However, even though measures have been taken to minimize fluctuations in pupil size, there are still clearly discernible differences between the gaze and CR signals.

3.3. Pupil deformation during saccades

One possible explanation to the observed results is that, like during pupil dilation, the shape of the pupil is deformed in such as way that its center is displaced relative to the fibrous tunic, which would temporarily distort the gaze signal. To probe such mechanisms, we use the change in pupil diameter across a saccade as a crude measure on how the pupil deforms. Fig. 10(A, B) shows how the pupil diameter changes over the course of a saccade for different levels of screen brightness (participant S1), allowing a number of observations. First, it can seen that the eye tracker reports changes in the horizontal pupil diameter during saccades for both saccade amplitudes and all levels of screen brightness. Second, there are two distinct peaks of the deformation, reflecting periods of saccadic acceleration and deceleration; the deformations have the same shape as the absolute values of the gaze acceleration signals, but with a slight time lag. Third, the lower levels of background brightness producing large pupils have larger absolute deformations compared to the smaller pupil sizes. Finally, 20 degree saccades are associated with larger absolute deviations and accelerations compared to five degree saccades.

To summarize the pupil deformation across participants, Fig. 11 shows the maximum deviation of the pupil diameter during the first 50 ms after saccade onset. It can be seen that all participants have a larger absolute deviation when the pupil size becomes larger. The deformations seem to be about a factor two larger for 20 degree saccades compared to 5 degree saccades.

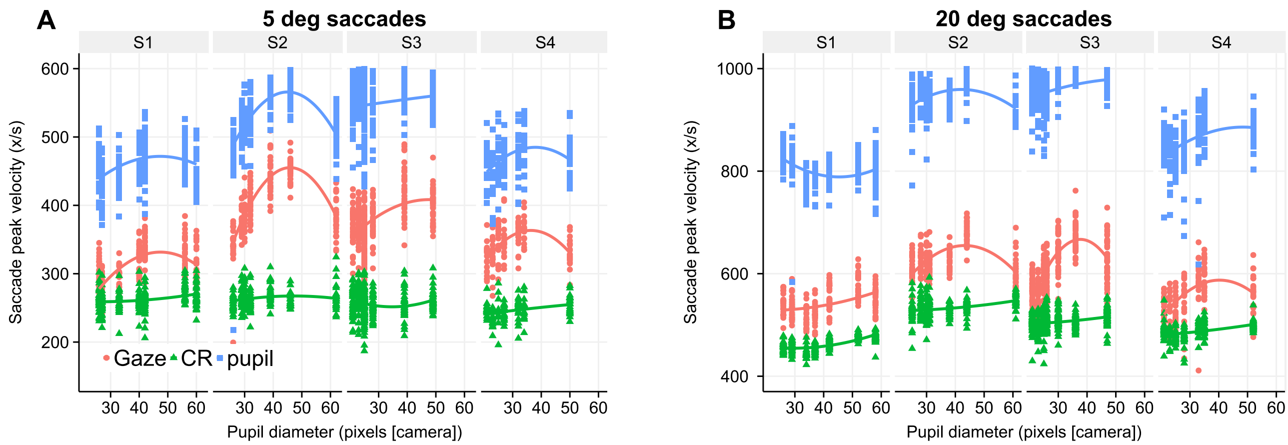

Fig. 8. Saccade peak velocity for CR- (green), pupil- (blue), and gaze-signals (red) plotted as a function of pupil diameter across four participants (S1–S4) and two saccade amplitudes: (A) 5 and (B) 20 deg. The lines are the results of fitting second degree polynomials to the data. The value *x* on the *y*-axis is deg/s for the gaze signal and pixels [camera]/s for the CR-, and pupil-signals. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

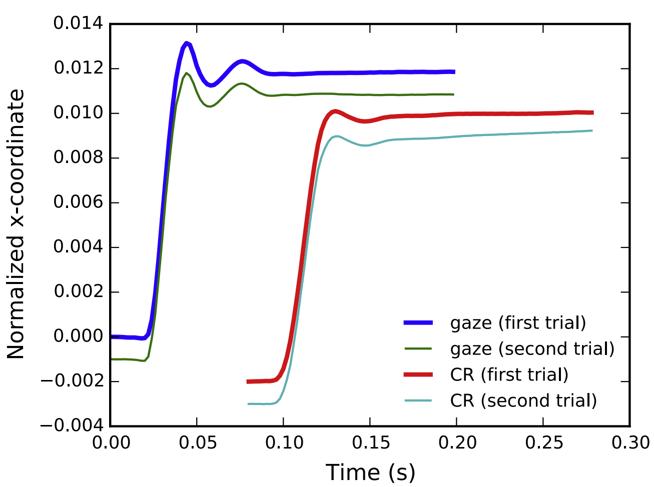

Fig. 9. Average waveforms of the gaze-, and CR-signals during two trials with similar isoluminant stimuli. Offsets have been introduced for display purpose. Data from participant S2.

3.4. Aphakic participant

Aphakic people are known to produce iridodonesis, i.e., quivering of the iris, in association with saccades. Therefore one could hypothesize that the deviation between CR- and gaze signals found in normal eyes would be even more exaggerated in aphakic eyes. In agreement with the four normal eyes, Fig. 12 shows that the CR-signal does not change notably across the dark and bright background conditions (A, D). However, there is a large difference between the gaze signals which is based on information from a combination of the pupil and the CR-signal (C, F). Again, the pupil signals show similar but smaller differences compared to the gaze signal. As expected, the pupil deformation is large compared to the normal eyes for both levels of background brightness (Fig. 12).

4. Discussion

To test the influence of pupil size on the gaze signal during saccades, participants performed repetitive, horizontal saccades while the screen brightness was manipulated. Analyzes of the CR-signal confirmed that motion of the corneal bulge is similar across different brightness levels. In contrast, the waveforms of both the pupil signal and the gaze signal changed with the size of the pupil. The most dramatic effect was found in the gaze signal where the peak saccade velocity changed between 12–32% across the tested participants. Interestingly, there seems to be a local maximum in saccade peak velocity that coincides with a pupil size in the 'typical' experimental range, where the pupil is neither very small nor very large.

Possible mechanisms behind the differences in the gaze signal due to pupil size changes were probed. We found that the horizontal pupil diameter—a crude estimate of pupil shape deformation—changed over the course of a saccade, and that the degree of change was associated with the size of the pupil; a larger pupil size leads to larger changes in measured pupil diameter. Importantly, the pupil deformation increased monotonically with the pupil size, which was not true for the peak velocity. Therefore, it is unlikely that the pupil deformation fully explains the effects we observe in the gaze signals.

The results from the aphakic participant showed similar but larger effects; both the pupil deformation and the difference between the gaze signals recorded with a large and small pupil were larger then for the normal participants we tested. As an extreme model of a non-rigid eyeball, the aphakic eye does indeed highlight the limitations of pupil-based eye tracking, irrespective of the pupil size. (see Fig. 13).

Given previous research showing that the pupil center moves relative to the iris center (Nyström et al., 2013), it is likely that the degree of relative motion is related to the pupil size and therefore the state of the iris. Fig. 14 show the circular, sphincter muscle used to contract the pupil and the radial muscle used to dilate the pupil. These muscles work in pairs, and when the pupil is maximally constricted, the sphincter muscle constricts whereas the radial muscle relaxes, and vice versa.

It is tempting to interpret the findings on the relationship between the pupil size and the saccade peak velocity with respect to the activation of the two iris muscles. When either of muscles is maximally tensed, the region of the iris controlled by this muscle has very limited room to move relative to the eyeball. However, when neither of the muscles is particularly tensed, i.e., for medium pupil sizes, there is more room in either direction of the intersection between the two different muscles. Conceptually, one can consider the muscles as two springs attached radially to each other through a mass element and the inner (sphincter) and outer (radial) border of the iris. Clearly, a radial impulse applied to the mass element will make the system oscillate with a higher amplitude when the system is at its natural equilibrium compared to when the equilibrium has been displaced by a force prior to the application of the impulse. However, it is likely that the mechanisms behind the results we observed are more complicated,

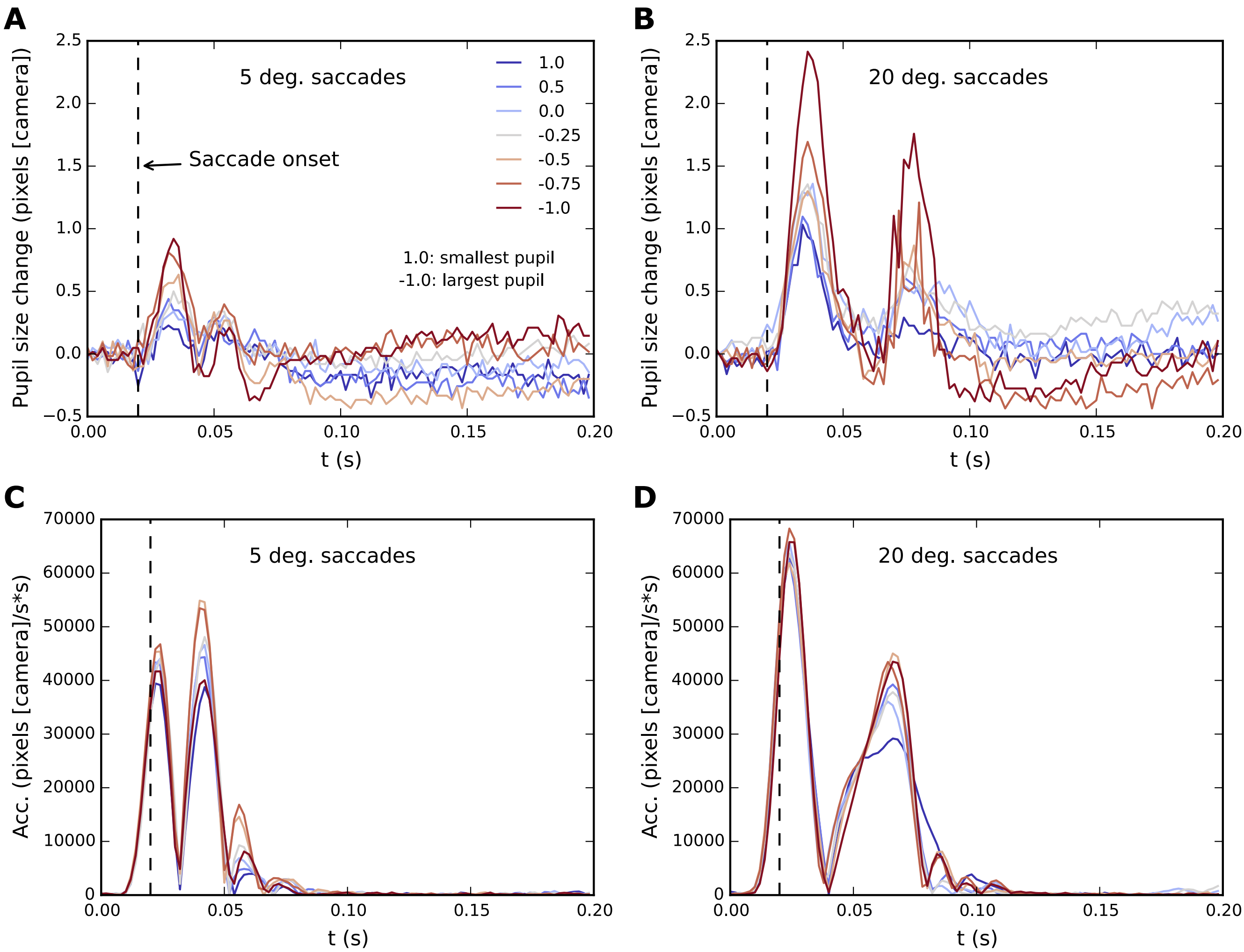

Fig. 10. Deviation in pupil diameter over the course of a saccade for (A) 5 degree saccades and (B) 20 degree saccades. Absolute values for the corresponding acceleration signals for each amplitude are provided below (C, D). Each signal represents a certain background brightness; the warmer the color, the darker the background (−1: black, 1: white). The deformation follows the saccadic acceleration phases, and is higher when the pupil size is large. The vertical, dashed line represents the saccade onset. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

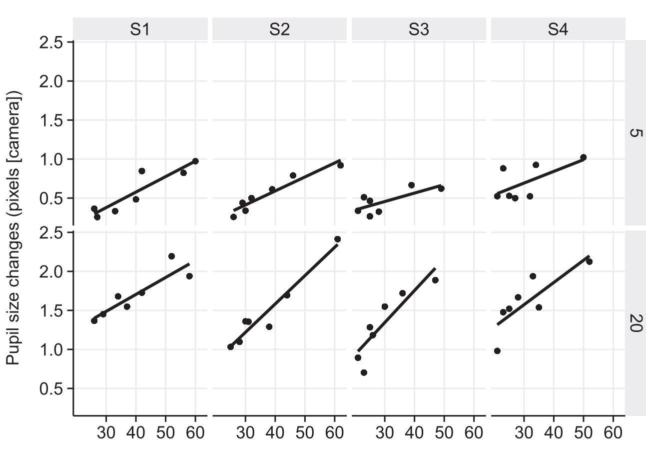

Fig. 11. Maximum deviation of the pupil diameter (largest minus smallest) during saccades as a function of pupil size. The plots show that a larger pupil size gives a larger maximum deviation, for all tested participants (S1 → S4) and saccade amplitudes (5 and 20 degrees). The lines represent least square fits of the data.

and related to other factors such as viscous forces due to interocular fluid motion, or an interaction between these and the pupil size.

The findings presented in this paper have several implications. Perhaps the most urgent issue is to review previous literature on the relationship between processes that have been reported to affect both the pupil size and the saccade peak velocity. In a recent review, several studies that report a correlation between different measures of arousal and saccade peak velocity are cited, and the authors propose that “peak velocity is a good index of arousal, with potentially important applications in ergonomics and in the clinic” (Di Stasi, Catena, Canas, Macknik, & Martinez-Conde, 2013). However, the word ‘pupil’ is mentioned twice, and then only to report that one of the cited studies used pupil diameter and pupil constriction as dependent variables. At the same time, is it well known that arousal can modulate the pupil size (Bradshaw, 1967). The large effect sizes we find in this paper strongly warrant that future investigators should take pupil size into account when correlating parameter of saccades extracted from the gaze signal with factors also known to affect the pupil size.

It is important to note that the magnitude of the pupil size changes we induce (>100%) by manipulating the screen brightness

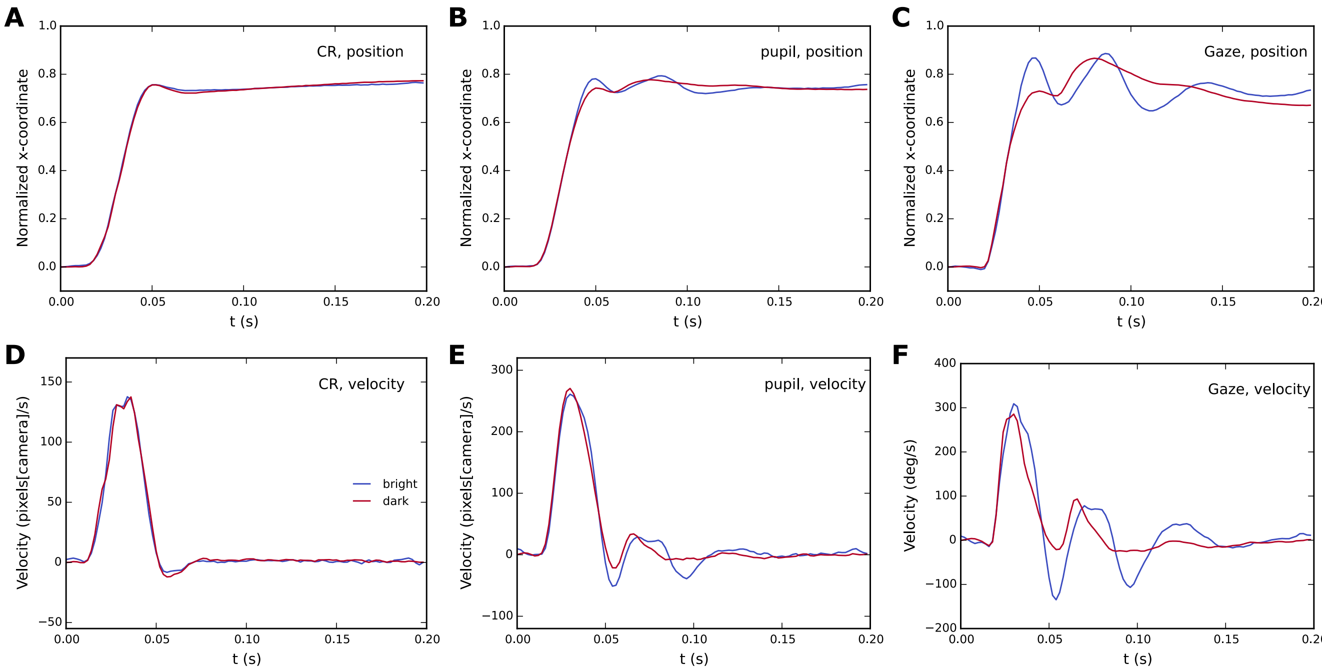

Fig. 12. Data from the aphakic participant who performed repetitive, five degree horizontal saccades with a dark (red) or a bright (blue) screen background. The overlapping CR-signals (A, D) indicate that the underlying eye movements were similar across the two conditions. The gaze signals (C, F) have different shapes from the CR-signals, and also differ substantially due to the change in screen brightness and therefore pupil size. The pupil signals (B, E) show similar but smaller deviations from the CR-signal. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

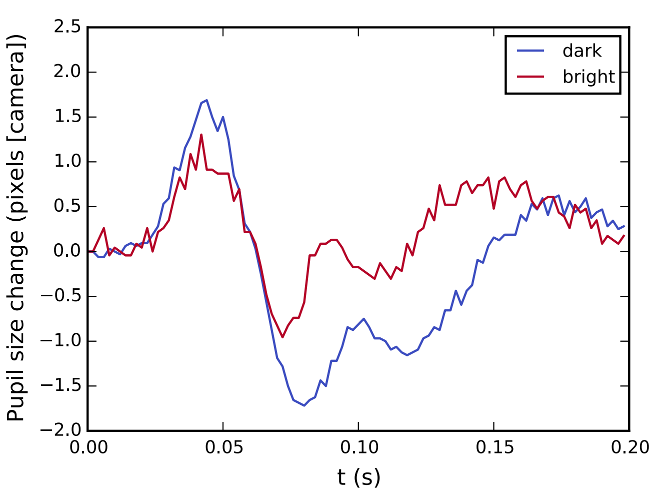

Fig. 13. Aphakic participant. Deviation in pupil diameter over the course of a five degree saccade for a small pupil (bright screen) and a large pupil (dark screen).

is uncommon in experiments using more controlled stimuli, and where the pupil changes solely in response to internal factors such as arousal and cognitive load (typically <10%, e.g., Johnson, Singley, Peckham, Johnson, & Bunge, 2014). To provide the reader with a best case scenario, i.e., when measures have been taken to minimize pupil size changes, data from two trials with identical isoluminant stimuli were compared. As expected, the difference between average gaze signals was small. Consequently, as long as saccades are recorded with stimuli controlled for brightness and cognitive influences remain stable, their waveforms can safely be compared across trials within the same participant. However, due to a non-rigid eyeball, the waveform still deviates from the CR-signal, which is invariant to changes in brightness and more accurately estimates rotation of the whole eyeball. In other words, using isoluminant stimuli improves only the precision of saccade signals, but not the accuracy.

Many of the previous studies investigating the effect of pupil size on the direction of gaze during fixation also proposed methods to correct for the offset caused by the changes in pupil size (Choe et al., 2016; Drewes et al., 2014). A prerequisite to correct an error is to know the true value of the measurement. During fixation, this

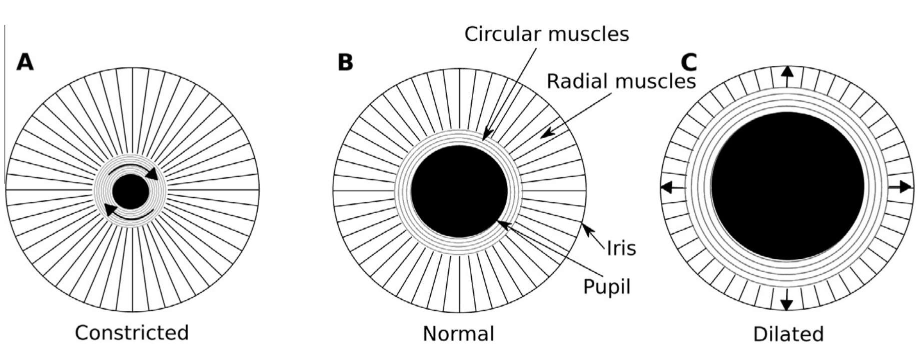

Fig. 14. State of the iris for a (A) constricted, (B) normal, and (C) dilated pupil. Inspired by Sjaastad et al. (2010).

is usually the position of the target that the participants are asked to fixate. Using the same logic to correct errors in the gaze signal during saccades is more challenging for a number of reasons. First, is it not clear what the 'true' trajectory looks like and how it can be estimated. However, one could argue that the CR-signal is a gold standard, since it more closely estimates rotation of the whole eyeball and does not seem to be affected by changes in pupil size. Second, even if there was an estimate of the true route of a saccade, finding a simple mapping function that captures the complex deformations of the eye that contribute to the gaze signal may be difficult. What remains is a look-up table similar to that described in Drewes et al. (2014). However, such a table would probably have to be very large since the gaze signal depends on, at least, the participant, the eye (left or right), as well as the amplitude and the direction (vertical/horizontal, up/down, abducting/adducting) of the saccade (Hooge et al., 2015). Moreover, not all commercial systems openly provide information about the CR-signal.

As a methodological note, we want to emphasize that it is important to maintain a fixed head position during a test similar to the one described here, and be very careful to maintain an even and systematic production of saccades over the different blocks, i.e., the different levels of background brightness. 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. Any small movement of the head relative to the camera affects the CR-signal, and makes the averaging procedure difficult. Moreover, slight changes in head position toward or away from the camera can change both the estimated pupil size and the gaze signal. Finally, it is important that all the blocks are recorded using the same calibration, since different calibrations may change the shape of the gaze signal during saccades.

The results in this paper are based on data recorded with the Hi-speed 1250 system from SMI using the center of gravity method to compute the pupil center. It is currently an open question whether other systems with different methods to estimate the center of the pupil and the CR may alleviate the problem we observe.

5. Conclusions

We found that during saccades, the pupil signal and in particular the gaze signal, but to a much lesser extent the CR-signal, change as a function of pupil size in a common pupil-CR based eye tracker. Specifically, the peak saccade velocity of the gaze signal reaches its maximum for pupil sizes in the 'typical' ranges, whereas smaller and larger pupils provide lower velocities for similar sized saccades. Overall, the smallest pupil sizes produced gaze signals that most closely resembled the CR-signal. The shape of the pupil deforms during saccades, and the absolute deformation is higher when the pupil size is large. This shape deformation affects the appearance of the gaze signal. When comparing saccade parameters across conditions and participants, it may be important to control for pupil size. When answering fine-grained questions about the oculomotor systems from saccade data, researchers should be aware of the fact that the gaze signal is different from the CR-signal and changes as a function of pupil size.

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