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Do pupil-based binocular video eye trackers reliably measure vergence?

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ABSTRACT

A binocular eye tracker needs to be accurate to enable the determination of vergence, distance to the binocular fixation point and fixation disparity. These measures are useful in e.g. the research fields of visual perception, binocular control in reading and attention in 3D. Are binocular pupil-based video eye trackers accurate enough to produce meaningful binocular measures? Recent research revealed potentially large idiosyncratic systematic errors due to pupil-size changes. With a top of the line eye tracker (SR Research EyeLink 1000 plus), we investigated whether the pupil-size artefact in the separate eyes may cause the eye tracker to report apparent vergence when the eyeballs do not rotate. Participants were asked to fixate a target at a distance of 77 cm for 160 s. We evoked pupil-size changes by varying the light intensity. With increasing pupil size, horizontal vergence reported by the eye tracker decreased in most subjects, up to two degrees. However, this was not due to a rotation of the eyeballs, as identified from the absence of systematic movement in the corneal reflection (CR) signals. From this, we conclude that binocular pupil-CR or pupil-only video eye trackers using the dark pupil technique are not accurate enough to be used to determine vergence, distance to the binocular fixation point and fixation disparity.

1. Introduction

Humans have two frontally placed eyes which has a number of advantages compared to having only one eye (Ciuffreda & Engber, 2002). These include that:

1. the horizontal field of view of two eyes is bigger than that of one eye.
2. because the total sensor area is twice as large with two eyes, the signal-to-noise ratio in the dark is a factor $\sqrt{2}$ better.
3. in case of a risky lifestyle, having a spare eye increases survival chances.
4. having a binocular visual field enables stereopsis.

The two eyes are directed at objects in the world from different points. Therefore, the two retinal images may differ from each other. These differences (disparities) can be used by the visual system as a depth-cue in addition to monocular depth-cues. To prevent double vision, oculomotor activity (e.g vergence and/or cyclovergence) plays an important role in binocular vision. The orientations of the two eyes have to be coordinated so that binocular fusion is facilitated (Panum's area – Mitchell, 1966). Binocular coordination is not perfect in every person and the amount of people with a binocular vision anomaly is estimated to be 5% (Stidwill, 1997). This includes strabismus, the inadequate alignment of the eyes which can lead to double vision and is also one of the causes of the development of amblyopia in children.

An important question in eye movement research is: "What is the location of a fixation?". In most studies this is not seen as a difficult problem and the question is simply solved by intersecting the line of sight from one of the two eyes with the closest object in front of the observer that occludes the background. For example in the field of reading, researchers approach the question of where the fixation is located in the 3-D world (namely a fixation on a 2D screen with text) by assuming that the two eyes look on the same point on the screen[1] (Nuthmann, Beveridge, & Shillcock, 2014). Therefore, reading researchers often use eye tracking data from only one eye (the right eye) during binocular viewing (e.g. Rayner, Castelhano, & Yang, 2009; Reichle, Reineberg, & Schooler, 2010). However, Collewijn, Erkelens, and Steinman (1997) write about fixating with two eyes: "the two lines of sight will intersect in a single point in 3-D space, which is the unique,

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[1] In our opinion, this is a reasonable assumption when conducting screen-based research. We have approached visual search on a screen in a similar way (Burggraaf, van der Geest, Frens, & Hooge, 2018; Hessels, Hooge, & Kemner, 2016; Hooge et al., 1996).

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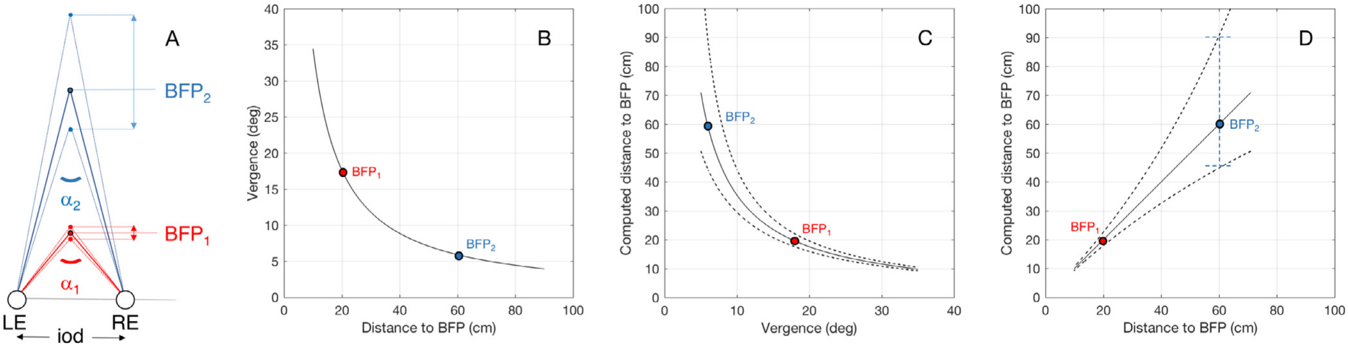

Fig. 1. Vergence, measurement error and computed distance to the binocular fixation point (BFP). Panel A shows binocular fixation of a far and a near target. LE – Left eye; RE – Right eye; Alpha – vergence; iod – interocular distance. Panel B shows the vergence angle as function of distance to the BFP (iod = 6.2 cm). Panel C shows the distance to the BFP computed from the vergence angle. The solid line shows the relation for an ideal eye tracker, the dashed lines represent cases with measurement errors of 2° (1° per eye). Panel D shows the distance to the BFP computed from the empirical vergence angle for a range of distances of the BFP. (error = 1° per eye). When an observer fixates at 60 cm, the computed distance to the BFP may range from 45 to 90 cm.

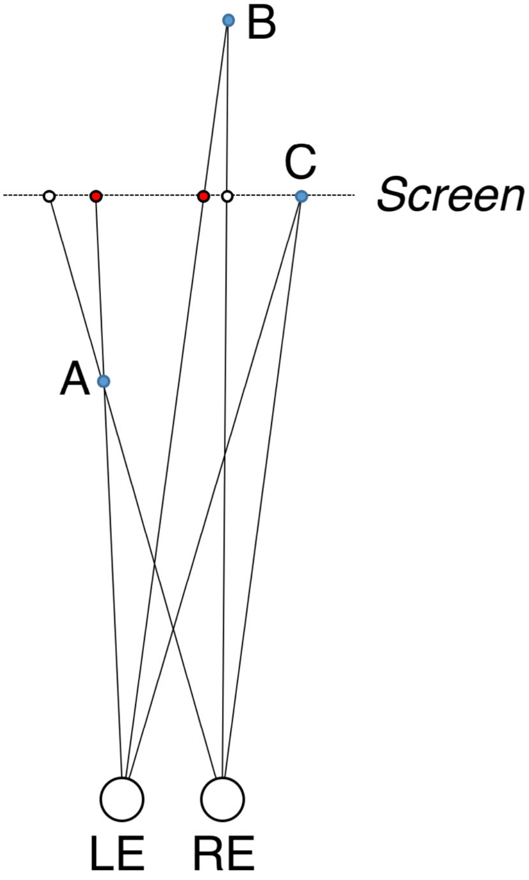

Fig. 2. Fixation disparities. Horizontal fixation disparity is the horizontal component of the distance between projections of the lines or sight on the stimulus plane (here the screen). During binocular fixation of point A (fixating in front of the screen) fixation disparity is positive and is referred to as crossed. During binocular fixation of point B (fixating behind the screen) fixation disparity is negative and uncrossed. During binocular fixation of point C (fixating at the screen) fixation disparity is zero and referred to as aligned.

binocular point of fixation" (p. 1049). The main question in this article is whether binocular eye tracking data from a pupil-based video eye tracker can be used to calculate the location of the binocular point of fixation. When we refer to a pupil-based eye tracker, we mean the most common type of pupil-based eye trackers at this moment, the single camera pupil-CR and pupil-only video eye trackers that use the dark-pupil technique (see Morimoto, Koons, Amir, & Flickner, 2000, for details on the dark and bright pupil technique).

To be able to fixate near and far points in different directions in space, humans make binocular eye movements (Erkelens, Steinman, & Collewijn, 1989; Zee, Fitzgibbon, & Optican, 1992). Binocular eye movements can be described with a conjugate (version) and a disconjugate (vergence) component. The version component is computed by averaging the left and the right eye signals; The vergence component is computed by subtracting the right eye from the left eye signal and represents the angle between the two lines of sight (Fig. 1A). In order to compute vergence and location of the binocular fixation point, gaze-position signals from an eye tracker capable of measuring binocular eye movements are required. As perfectly accurate eye trackers do not exist, vergence and the location of the binocular fixation point computed from the eye tracking signals are subject to measurement errors. To understand how errors in the signal recorded from each eye affect vergence angle and the apparent distance to the binocular fixation point, we have conducted a simulation. Fig. 1B shows the vergence angle as a function of fixation distance for a person with an interocular distance of 6.2 cm. The vergence angle is large for binocular fixation points close to the observer (Fig. 1A), becomes increasingly smaller for fixation points further away and approaches 0° for points at infinity. Imagine that one wants to use a binocular eye tracker to determine the location of the binocular fixation point. Fig. 1C shows the computed distance to the binocular fixation point given the empirical vergence angle (the vergence angle computed from the left and the right eye tracker signals). The solid line shows the relation for an ideal eye tracker, the dashed lines represent cases with measurement errors of 2° (1° per eye). From this figure it is clear that for the smaller vergence angles, the computed distances to the binocular fixation are most affected by measurement errors. Fig. 1D shows an alternative version of Fig. 1C. On the horizontal axis there is the distance to the binocular fixation point (under the assumption that an observer fixates exactly a point in 3-D with two eyes). The vertical axis shows the distance to the binocular fixation point computed from the empirical vergence angle. What can we learn from this simulation? Firstly, a small error in the gaze direction of an individual eye (here 1°), has major consequences for the estimated distance to the binocular fixation point. Secondly, the error in the estimated distance to the binocular fixation point based on the vergence angle increases more than proportionally for larger fixation distances (Fig. 1D). For a clear illustration of another simulation of this problem see Fig. 2 of Wang, Lindlbauer, Lessig, and Alexa (2015).

In the research field of binocular control of reading, fixation disparity is often reported instead of vergence (Fig. 2). Horizontal fixation disparity is the horizontal component of the distance between projections of the lines of sight on the stimulus plane (often a computer screen at approximately 60 cm from the observer). A positive value for fixation disparity occurs when the screen fixation of the left eye is located to the

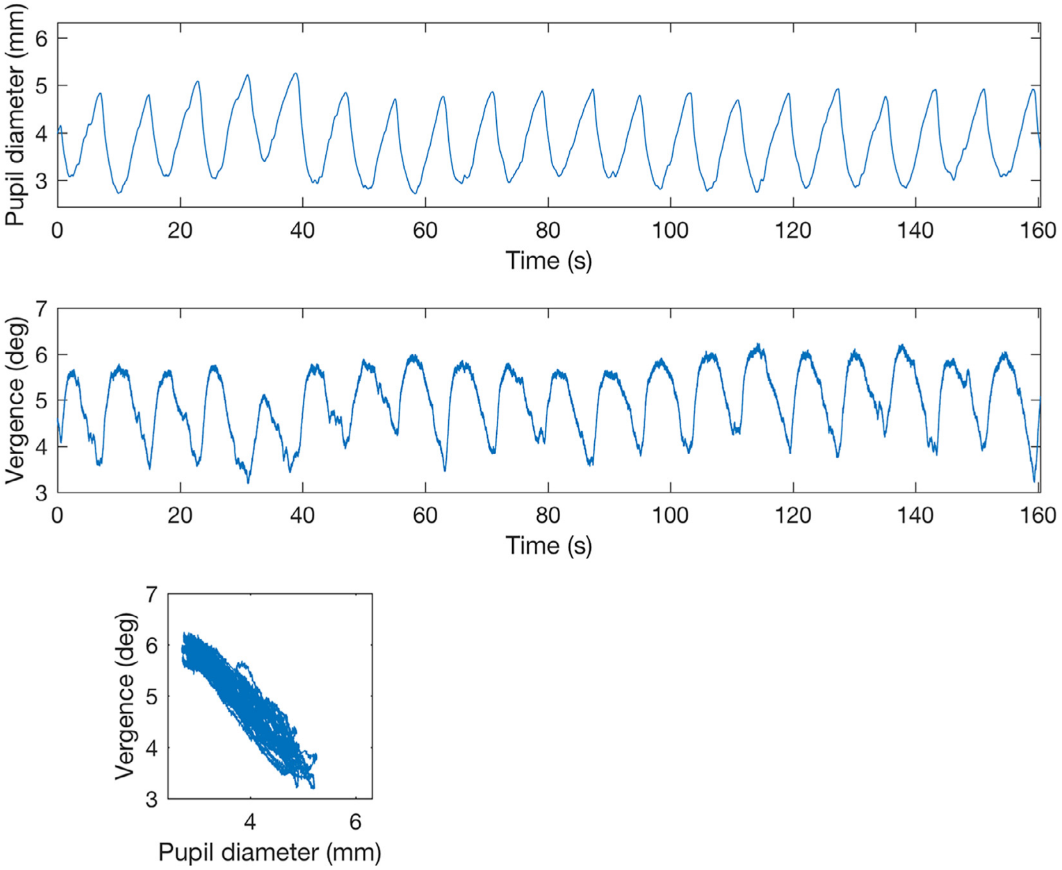

Fig. 3. Pupil size and horizontal vergence for one participant. The top panel shows pupil size as a function of time. In this example the pupil grows and shrinks, the panel consists of 160 s (20 cycles of 8 s) of data. The intermediate panel shows the horizontal vergence angle in degrees. The bottom panel shows the vergence angle as a function of pupil size.

right of the screen fixation of the right eye. This situation is referred to as crossed fixation disparity and is interpreted as a binocular fixation point that is located between the subject and the display (Fig. 2, point A). A negative value for fixation disparity is referred to as uncrossed fixation disparity and is interpreted as a binocular fixation point that is located behind the screen (Fig. 2, point B). Fig. 1C shows that interpreting crossed and uncrossed fixation disparity in terms of the location of the binocular fixation point (in front of the screen or behind the screen) is impossible due to the systematic errors of the eye tracking data, because the error in the estimated distance to the binocular fixation point around a fixation distance of 60 cm ranges from −15 cm to +30 cm.

The majority of research on binocular eye movements done before the year 2000 was conducted in humans with scleral coils (Collewijn, van der Mark, & Jansen, 1975; Robinson, 1963), the Dual Purkinje Image (DPI) eye tracker (Cornsweet & Crane, 1973) and the Limbus tracker (Russo, 1975) and in monkeys with implants (Robinson & Fuchs, 1969). Since the year 2000, many researchers investigating binocular eye movements switched to pupil-based video eye tracking systems such as the SMI EyeLink, SR Research EyeLink II, SR Research EyeLink 1000 and SMI iView X Hi-Speed towers. Measuring eye movements has become much easier with these non-invasive and easy-to-calibrate eye trackers. The question, however, is: do the signals from the pupil-based-video eye trackers contain the same information in terms of how the eyes are oriented and how they move in relation to each other as the signals of classic eye trackers? They are based on different principles, coils are attached to the sclera and the coil voltage is directly related to the orientation of the coil in space; pupil-based video eye trackers film the eye and the gaze direction is estimated indirectly from a two dimensional image (Merchant, Morrissette, & Porterfield, 1974). Whereas video eye trackers rely on the pupil, coils do not, and the measurement will therefore be unaffected by any change in pupil size. Therefore the question arises whether the measurements from the different systems can be directly compared. Some phenomena appear different in the different eye tracker signals. For example, micro saccades measured with a pupil-based video eye tracker have larger amplitudes than micro saccades measured with coils (McCamy et al., 2015; Nyström, Hansen, Andersson, & Hooge, 2016), saccade peak velocity measured with a coil system is lower than measured with a pupil-based video eye tracker (Frens & Van der Geest, 2002) and post saccadic oscillations in video eye tracking data are much larger than in coil data (Kimmel, Mammo, & Newsome, 2012).

In the context of binocular measurements, we want to know how the data quality of the pupil-based video eye-tracker compares to the data quality of the classic eye trackers. The variable error (precision) of the pupil-based video eye tracker signal is much larger than that of coils (van der Geest & Frens, 2002). This is not necessarily problematic. If the measurement frequency of the eye trackers is high enough, the averaged position signal can be used to determine the precise location of the binocular fixation point. As the earlier simulations show, the systematic error (inaccuracy) is particularly problematic. As long as the pupil does not change size, the systematic error is similar to that of coils (Imai et al., 2005). However, when the pupil becomes larger or smaller due to changing light conditions (De Groot & Gebhard, 1952), arousal (Hess & Polt, 1960), cognitive demands (Hess & Polt, 1964) or attention (Mathôt & Van der Stigchel, 2015), there may be an offset (up to 2.5°) in the monocular gaze direction reported by the eye tracker (Choe, Blake, & Lee, 2016; Drewes, Zhu, Hu, & Hu, 2014; Wildenmann & Schaeffel, 2013; Wyatt, 2010). Wyatt (1995) showed that if the pupil size changes, the shape of the pupil may change too. Changes of shape are idiosyncratic or may not occur (Wildenmann & Schaeffel, 2013). If the shape of the pupil changes, depending on the new shape, the location of the center of gravity of the pupil may shift (Wyatt, 1995). In this case, the eye tracker will report a changing gaze direction while the observer keeps the eye still (Choe et al., 2016; Drewes et al., 2014; Wildenmann & Schaeffel, 2013; Wyatt, 2010). The error in the gaze direction induced by the changed pupil size may reach values up to a few degrees (Choe et al., 2016; Drewes et al., 2014; Wyatt, 2010). In principle, the pupil size induced gaze-shift can be corrected for, but that requires a correction method (Choe et al., 2016; Drewes, Masson, & Montagnini, 2012; Drewes et al., 2014). As it is not commercially available, such a method would have to be implemented by the researcher (Drewes et al., 2014). The study of Drewes et al. (2014) was designed and executed binocularly and highlights the fact that the apparent gaze shifts resulting from pupil size changes are symmetric to the nasal plane (see their Fig. 3). They speculate about the consequences of these gaze shifts: “Binocular vergence measurements may serve as an example, as they are particularly sensitive to symmetric measurement drifts; pupil-size-based artefacts might be mistaken for vergence movements” (p.5). The occurrence of unpredictable and potentially large idiosyncratic systematic errors is problematic, especially for the vergence signal, because it is a differential signal, and the magnitude of the systematic error is large in relation to the magnitude of the vergence signal. This is certainly true in the range where most pupil-based video eye trackers operate (0.5 m and up). It is also problematic because the magnitude of the vergence angle varies little as a function of distance at larger fixation distances (0.5 m and up, see Fig. 1, panel A). In other words, a small offset in one of the two eye signals leads to a significant change in the apparent distance to the binocular fixation point.

The vergence angle and the distance to the binocular fixation point are used to investigate depth perception and binocular coordination in vision science (Enright et al., 1987a, 1987b; Wagner, Ehrenstein, & Papathomas, 2009; Wismeijer, van Ee, & Erkelens, 2008; Wismeijer & Erkelens, 2009) and binocular coordination in reading (Kirkby, Blythe, Benson, & Liversedge, 2010; Köpsel & Huckauf, 2017; Huckauf, 2018; Liversedge, White, Findlay, & Rayner, 2006; Nuthmann & Kliegl, 2009). There is a debate about fixation disparity in the literature on binocular control in reading. Most studies conducted with a pupil-based video eye tracker (Jainta, Hoormann, Kloke, & Jaschinski, 2010; Nuthmann & Kliegl, 2009; Vernet & Kapoula, 2009) report crossed disparities when fixation locations of the two eyes are unaligned. This is interpreted as apparent looking in front of the screen. The unaligned fixations obtained with the DPI (Blythe et al., 2006; Juhasz, Liversedge, White, & Rayner, 2006; Liversedge et al., 2006) have uncrossed fixation disparity (fixating behind the screen). There have been many attempts to solve this problem by finding the cause of the discrepancy between the results of Nuthmann and Kliegl (2009) and Liversedge et al. (2006). In one attempt to investigate whether the type of eye tracker plays a role, Kirkby, Blythe, Drieghe, Benson, and Liversedge (2013) performed the same experiment with both a DPI and an EyeLink1000 (a pupil-based video eye tracker). Surprisingly the main outcome of this study was that both systems (DPI and EyeLink1000) showed non-aligned fixation locations of the two eyes with uncrossed fixation disparity. Kirkby et al. (2013) conclude that: “Thus, the conflicting results within the literature concerning the direction of disparity cannot be attributed to the different eye-tracking systems or the software used in the different laboratories” (p. 674). Although Kirkby et al. (2013) reported similar fixation disparities measured with two systems, we are not convinced that their statement about the eye trackers is correct. Our simulation (Fig. 1) shows clearly that for binocular fixation of the screen, the reported fixation disparities obtained by pupil-based video eye trackers may be crossed or uncrossed. The stimuli in Kirkby’s lab (white on a black backgound) differed from the stimuli (black on a white background) used in the labs that reported the unaligned crossed fixations with a pupil-based video eye tracker (Jainta et al., 2010; Nuthmann & Kliegl, 2009), Vernet and Kapoula (2009) did not provide this information. Köpsel and Huckauf (2017) used dark and light backgrounds and were able to replicate the results of both Nuthmann and Kliegl (2009) and Liversedge et al. (2006) with a pupil-based video eye tracker (SMI iView X hi-speed 1250). Huckauf (2018) added combinations of calibrations with dark and light backgrounds with dark and light stimuli and report that when the calibration background matches the one during reading, fixation disparity was close to zero deg. Huckauf (2018) concludes that vergence shifts occur as an effect of brightness changes, but cannot rule out that “the effects measured here are only artifacts (or side-effects) of the pupil-size changes reported earlier, nor can it be ruled out that the changes in pupil size are only artifacts (or side- effects) caused by vergence shifts”. According to Drewes et al. (2014), different lighting conditions affect pupil size and may consequently affect the apparent vergence state in an idiosyncratic way. Simply said, we hypothesise that in most cases vergence measures from a pupil-based video eye tracker cannot be trusted to reflect vergence and that one should not compute the location of the binocular fixation point from these vergence angles (Fig. 1).

The question in this study is whether a pupil-based video eye tracker is suitable for studying vergence, fixation disparity or the distance to the binocular fixation point. We conducted our experiment at a fixation distance of about 77 cm. This distance is in the range of operational screen distances of most pupil-based video remote and tower eye trackers (> 0.5 m). We will not measure at a smaller binocular viewing distance. A recent study (Jaschinski, 2016) has measured in this range and shows that for smaller fixation distances, due to the accommodation-convergence reflex, the pupil size also depends on the vergence angle.

In the current study we asked subjects to fixate a dot while the lighting conditions were slowly varied to evoke the pupil to change size (and shape). We measured the gaze directions of both eyes with the SR Research EyeLink 1000 plus, a top of the line pupil-minus-CR eye tracker. Drewes et al. (2014) predict that due to the shifting pupil centre the eye tracker should report changing vergence. The question here is whether or not there is a real vergence change when the eye tracker reports a vergence change. To answer this question we analysed the standard calibrated pupil-minus-CR (corneal reflection) signal, and we expect this signal to contain changing vergence. In addition, we also analysed the underlying raw pupil and CR signals as in Nyström, Andersson, Niehorster, and Hooge (2017), because both the pupil and the CR signals reflect eye orientation (for an explanation see the section *Data analysis and signals*). When there is a real vergence change, we expect a vergence change to be present in both the pupil and the CR signal. When there is only the pupil-size artefact, we expect a vergence change only to be present in the raw pupil signal and to be absent in the CR signal. Because the pupil-size artefact is idiosyncratic we will test 24 participants. To verify that the effect reported is not an artefact of one specific eye tracker, we repeated the measurements with the SMI iView X hi-speed for a number of participants.

2. Method

2.1. *Observers*

24 participants (6 females) between the ages of 22 and 52 (mean age 31.3 years) took part in the experiment. Participants were students and staff members from Lund University and Utrecht University. Written informed consent was provided by the participants, and the experiment was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Eye tracking data of 2 participants were excluded from the analysis, since manual inspection revealed that both participants had probably moved their heads in such way that the raw pupil and CR data became unusable for this study.

2.2. Set up

We ran this experiment on two EyeLink 1000 plus set ups (one at Utrecht University and the other at Lund University) and an SMI iView X hi-speed 1250 (at Lund University).

2.2.1. EyeLink 1000 plus

In Lund, binocular eye movements were recorded with an SR Research EyeLink 1000 plus (host software v. 5.12) at 1000 Hz (pupil area mode heuristic filters turned off). The visual stimulus was presented on a 24 inch ASUS VG248QE (53 × 30 cm; refresh rate: 240 Hz) placed at a distance of 77 cm from the eye. Pupil Detection Model was centroid. The resolution of the monitor was set to 1920 pixels by 1080 pixels (16:9 ratio). The walls were painted white and the floor of the experimental room was light blue. The operator was author MN.

In Utrecht, binocular eye movements were recorded with an SR Research EyeLink 1000 plus at 500 Hz (pupil area mode heuristic filters turned off). The visual stimulus was presented on a 24 inch Samsung 2433BW (51.7 × 32.5 cm; refresh rate: 60 Hz) placed at a distance of 77 cm from the eye. Pupil Detection Models was centroid. The resolution of the monitor was set to 1920 pixels by 1200 pixels (16:10 ratio). Both the walls and the floor of the experimental room were black. The operator was author RH.

In both labs, the light in the experimental room was turned off. Pupil detection method was set to centre of mass. We used the default binocular 9-point EyeLink calibration with 9 point validation. We could have used monocular calibration. In their study about the effect of the calibration method on systematic errors Svede, Treija, Jaschinski, and Krumina (2015) wrote: “the objective fixation disparity differs depending on whether the calibration is performed monocular or binocular, and this difference depends on the individual’s fixation disparity” (p. 13). The explanation is the following. If the participant shows a nonzero fixation disparity when fixating the markers during the binocular calibration, this fixation disparity is not present anymore in the binocularly calibrated eye tracking data. Monocular calibration does not have this disadvantage. Therefore, if the goal of the study is to determine objective vergence angles, the calibration method of preference is monocular instead of binocular. However, in this study we choose to calibrate binocularly (the standard option of our eye tracker) since it suffices to investigate the influence of pupil size on vergence angle. Stimulus presentation was done with PsychoPy v.1.83.01 (Peirce, 2007, 2008) and the EyeLink Dev Kit (v.1.11.571) was used to communicate with the EyeLink Host computer. Head movements of the participants were minimised by using the standard EyeLink 1000 plus chin and forehead rest.

2.2.2. SMI iView X hi-speed 1250

Binocular eye movements were recorded with an SMI iView X hi-speed 1250 at 500 Hz. Pupil detection method was centre of mass. Visual stimuli were presented on a EIZO FlexScan EV2451 24 inch monitor (refresh rate 60 Hz) at a distance of 63 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 Version: 2.7.13) that was carried out binocularly. Stimulus presentation was done with PsychoPy v.1.83.01 (Peirce, 2007, 2008). Head movements of the participants were minimised by using the SMI iView X hi-speed chin and forehead rest. The operator was author MN.

2.3. Stimulus and task

The stimulus consisted of one fixation marker (blue disk diameter 0.6° with a red center dot diameter 0.1°) placed on a background that slowly changed from black to white and back with a frequency of 0.125 Hz following a sinusoidal profile. Presentation time was 160 s (20 cycles of 8 s). The participants were asked to continuously fixate the marker without blinking during stimulus presentation. Blinks were removed by deleting all samples having a velocity value that was 2 standard deviations above the average value. The velocity filter is described in Hooge et al. (2013). In case of a blink, we interpolated the data off-line with a first order interpolation method.

2.4. Data analysis and signals

In this article we use four types of signals. We use the eye tracker signal from the EyeLink 1000 plus. We refer to this signal as the gaze signal and it represents the calibrated pupil-minus-CR signal and is expressed in degrees. As in our earlier studies (Hooge, Holmqvist, & Nyström, 2016; Nyström, Hooge, & Andersson, 2016; Nyström et al., 2017), we also use the raw pupil and CR signals, which are expressed in pixels of the eye camera image. For readers who are not familiar with the pupil-minus-CR technique, if the eye rotates, both the positions of the pupil centre and CR centre translate in the eye camera image (see Figs. 1 and 2 from Hooge et al. (2016)). A rule of thumb is that the pupil moves approximately twice the distance of the CR when the eye rotates. Because both pupil and CR signals are related to the orientation of the eye, these signals can be used to conduct eye tracking. An example of pupil eye tracking is the SR Research EyeLink 2 in pupil-only mode. Examples of CR eye tracking are found in Eizenman, Frecker, and Hallett (1984) and Salapatek and Kessen (1966). A known problem of both pupil-only eye tracking and CR-only eye tracking is that the accuracy of the signal is extremely sensitive for head movements relative to the camera. To conduct CR-only and pupil-only eye tracking with an EyeLink 1000 plus requires the participants to sit extremely still (Nyström et al., 2016). In the present study this problem is smaller because we investigated the vergence signal. The vergence signal is a differential signal and it is therefore less sensitive for relative head-camera movements since these movements affect the left and the right eye signal similarly. The fourth signal is pupil size (diameter) and is expressed in mm. The original pupil signal of the EyeLink 1000 plus was expressed in arbitrary units (SRResearch, 2009), we converted the pupil signal to millimeters by an off-line calibration. Raw pupil and CR signals were detrended with a standard Matlab zeroth and first order method (window length was the total number of samples of the trial).

3. Results

3.1. The gaze signal

Is it possible to evoke apparent vergence eye movements by manipulating the lighting condition and therefore altering the pupil size of an observer? Drewes et al. (2014) have predicted this scenario based on the monocular pupil-size-based artefacts. Fig. 3 shows pupil size and gaze data from a representative participant. The top panel shows the repetitive pupil-size changes of 20 periods of 8 s. The pupil size represents the mean of the left eye and right eye pupil sizes. The center panel shows the vergence angle, this signal is computed by taking the difference signal between the horizontal components of the left and right eye. The top-top amplitude of this signal is about 2°. To achieve the previous we only changed the screen luminance from 0.21 to 175 cd/m^2 (EyeLink Utrecht), 0.5 to 384 cd/m^2 (EyeLink Lund) and 0.2 to 163 cd/m^2 (SMI Lund). The bottom panel shows how the horizontal vergence angle depends on the pupil size. Although this is a representative example, there is a great deal of variation between the data of the different participants in terms of pupil size, but also in the relationship between fixation disparity and pupil size.

Fig. 4 contains data from 22 participants in the EyeLink set up. Each coloured line represents the relation between pupil diameter and the horizontal vergence angle for one participant. It is clear that for some participants the luminance change evokes a larger pupil-size effect and some participants have larger pupils than others. When looking at the vergence angles, we can clearly distinguish three patterns, vergence decreases with pupil size, vergence does not change as a function of

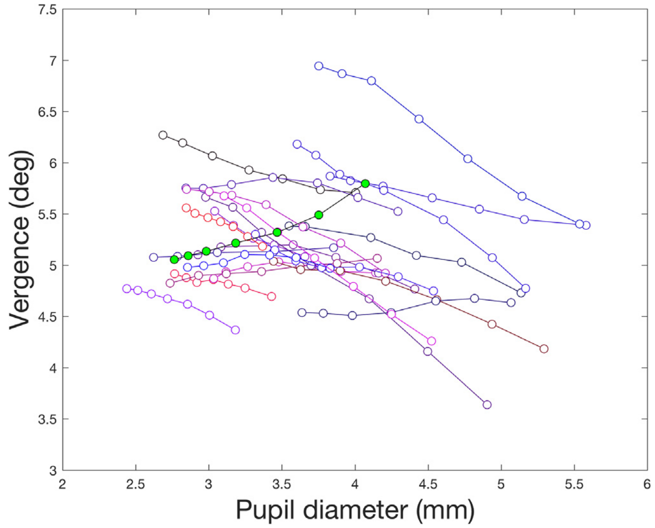

Fig. 4. Horizontal vergence angle and pupil size. This figure shows data for 22 participants. For each participant there is a coloured line depicting horizontal vergence angle versus pupil size. Each line consists of a maximum of 7 points, x-values representing the second until the eighth decile of pupil size with steps of one tenth, y-values represent the mean of the corresponding vergence values. This figure shows clearly that for each participant the relation between vergence angle and pupil size may be different. For some participants the pupil-size range is large and the vergence angle does not change at all, for others, pupil-size range is large and the vergence angle varies over a range up to −1.5°. For a one participant the effect is in the opposite direction (green dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

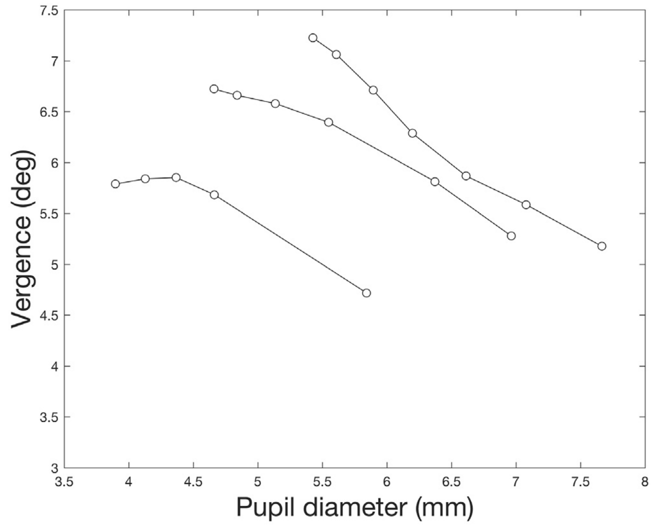

Fig. 5. Horizontal vergence and pupil size. This figure depicts data for 3 participants measured with the SMI iView X hi-speed 1250. For each participant there is a line depicting horizontal vergence angle versus pupil size. This figure clearly shows that the vergence pupil-size relation is also present in data from another dark pupil video eye tracker.

pupil size and vergence increases with pupil size (one participant). Another measure to estimate the magnitude of the pupil-size artifact is the slope of the individual lines of Fig. 4. The slope denotes the vergence change in degrees per mm increase in pupil diameter. The average slope is −0.36°/mm ± 0.09°/mm (SEM). If we do not take into account the line with positive slope (the green line), the average slope measures −0.40°/mm ± 0.08°/mm (SEM). Fig. 5 contains data from 3 participants in the SMI set up. Here, the vergence angle clearly decreases with pupil size. The average slope is −0.72°/mm ± 0.11°/mm (SEM).

3.2. The pupil and the CR signals

Fig. 6 reveals whether our participants rotated their eyes in relation to the changing luminance. The left panel of Fig. 6, shows ΔX. ΔX is computed by subtracting the horizontal coordinate of the pupil center of the left eye from the horizontal coordinate of the pupil center of the right eye. Note that the coordinates of both the pupil and the CR are in pixels of the eye camera image. Here we see that ΔX changes systematically as a function of the pupil diameter. We also computed ΔX for the raw CR position signals. The right panel shows that there is no systematic ΔX change as a function of the pupil diameter in the CR signal. We conducted a Bayesian paired-samples T-test in JASP (version 0.8.5), with the hypothesis that the pupil slope was more negative than the CR slope. The data were in support of this hypothesis with a Bayes Factor of 3329 (pupil slope mean = −2.187, sd = 1.556, CR slope mean = −0.190, sd = 0.366). As stated, the pupil moves twice as much as the CR when the eye rotates (as a rule of thumb), so we conducted the same analysis with the CR slopes multiplied by 2. Still, the data support the hypothesis that the pupil slope was more negative than the CR slope * 2, with a Bayes Factor of 386. We see this as strong evidence that the eyeballs did not rotate systematically due to the slowly changing light conditions.

4. Discussion

Is a pupil-based video eye tracker suitable for providing binocular eye movement signals such as the vergence angle, fixation disparity or distance to the binocular fixation point? This is an important question because in recent years, there is growing interest in measuring fixation in 3D space in addition to screen eye tracking (fixation on a 2D plane in 3D). Measurement equipment becomes better and cheaper every year and many modern eye trackers have the ability to measure binocularly and deliver binocular (i.e. separate left eye and right eye) eye-tracker signals. This renewed interest for binocular eye tracking does not only comes from the fields of visual perception and binocular motor control. Our expectation is that with the introduction of affordable high quality wearable eye trackers (whether or not in combination with virtual or augmented reality), the use of binocular measurements will increase.

The expectations of novice users of the binocular eye tracking technique are often high. For example, they expect to be able to determine the locus of attention in 3D by estimating the location of the binocular fixation point. Our goal in this study is to determine what is possible with a top of the line binocular pupil-based video eye tracker. Based on very simple geometric models (Fig. 1) and the extrapolation of the findings of Drewes et al. (2014) to the vergence signal, we do not expect flawless 3D performance from a pupil-based video eye tracker. The main reasons are (1) that the binocular measures are susceptible to the systematic errors of the left and right eye eye-tracker signals and that (2) the eye-tracker signal of pupil-based video eye trackers may contain large errors due to changes in pupil size. To test whether the predictions of Drewes et al. (2014) are realistic, we manipulated pupil size in 22 participants by varying the luminance of the screen while the participant was asked to maintain fixation at the center of the screen. During this manipulation, we measured four signals, the gaze signal, the pupil-size signal and the raw pupil and CR signals. From the gaze signal, we have calculated the vergence angle. From the raw pupil position and the raw CR position signals we have calculated the horizontal component of difference (ΔX). What did we find?

4.1. Summary of results

1. The pupil diameter varies per participant.
2. The extent of the change in pupil diameter as a function of the luminance varies per participant.

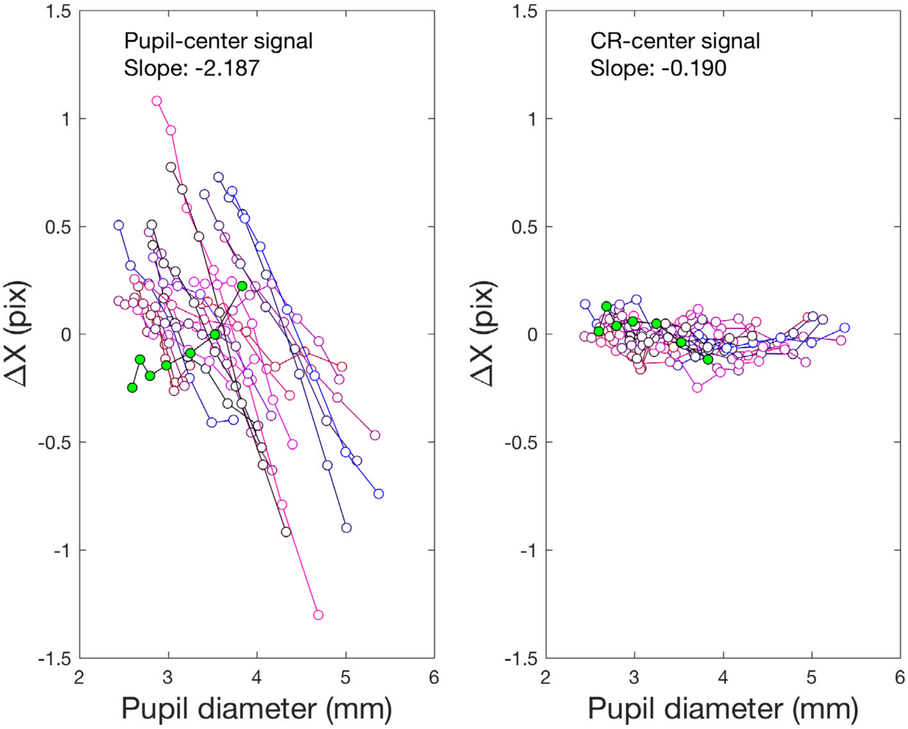

Fig. 6. Difference signals (ΔX) of the horizontal component of the left and right eye pupil-center and CR-center signals. The left panel shows ΔX (in pixels of the camera image) computed from the horizontal component of the pupil signals as a function of pupil size. Each line again consists of 7 points, x-values represent the second until the eighth decile of the pupil diameter with steps of one tenth, y-values represent the mean of the corresponding ΔX values of the specific bin. Despite that the current figure looks different than Fig. 4, it is again clear that for different participants (different coloured lines), the relation between ΔX and pupil diameter varies between participants. For a one participant the effect is in the opposite direction (green dots). The right panel shows ΔX computed from the horizontal component of the CR position signal. The absolute value for the mean slope is more than eleven times higher for the pupil signal compared to the CR signal. This figure clearly shows that ΔX for the CR positions does not change as a function of pupil diameter. We interpret this as strong evidence that the eyes did not systematically rotate due to the slowly changing light conditions during the experiment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Vergence angle determined from the calibrated P-CR eye tracker signals from the left and the right eye may vary greatly if the pupil size changes. For most participants, the vergence angle decreases with increasing pupil size, which occurred for both the SMI and EyeLink setups. This was to be expected based on the results of Drewes et al. (2014).
4. ΔX determined from the raw pupil signal may vary greatly when the pupil changes size. For most participants ΔX decreases with increasing pupil size.
5. ΔX determined from the raw CR signal does not change with changing pupil size.

Based on the previous we conclude that apparent vergence change during slowly varying lighting conditions is due to the pupil-size artefact, not to the actual change in vergence state.

4.2. Comparison with earlier studies

How do our results compare to other studies? Firstly, the pupil-size artifact (1.5°, 0.75° per eye) in our study is smaller than in Drewes et al. (2014) and in the range of the results of Wildenmann and Schaeffel (2013) and Wyatt (2010). Drewes et al. (2014) report 2.5° on average in a monocular signal and a maximal value of 5°. These higher values may be due to the ramp-like stimulation alternated with plateaus that allow for enough time for the pupil to reach the largest and smallest size. Our sinusoidal luminance stimulus may not have maxed out pupil size variability. Another difference is that we estimated the size of the effect by comparing data from the second until the eight decile, we did not use the whole range. Comparison is also hampered because we cannot compare the luminance conditions because Drewes et al. (2014) do not give luminance values. Another difference is that Drewes et al. (2014) do not report participants without the pupil-size artefact. However, there is one other study that reported participants without the pupil-size artefact (Wildenmann & Schaeffel, 2013). We also estimated the magnitude of the pupil-size artefact by the vergence change per unit pupil-size change. We report a value of $-0.40°/\text{mm}$ (EyeLink) and $-0.72°/\text{mm}$ (SMI). These values resemble the quantitative conclusion of several earlier studies summarized in Jaschinski (2016).

4.3. Is it realistic to assume the size of the pupil to vary substantially during experimentation?

What level of change in pupil size may be expected under normal experimental conditions? We do not have statistics of the nature of visual stimulation in eye tracking experiments, but we can elaborate about reasonable eye tracking experiments with spatially and temporally varying lighting conditions. We know at least two types of experiments where the full range of pupil sizes may be expected. The first type of experiments concerns outdoor eye tracking. Imagine driving a car on a sunny day while wearing an eye tracker. The lighting conditions may vary from dark when driving through a tunnel or in the shadow of a big building to very bright when driving into the direction of the sun. The second type of experiments is eye tracking while watching a movie or a television commercial. In this type of stimulus material, the stimulation may vary from a black screen to a completely white screen for a long enough period to cause the pupil to become very small or very big. We can also think of experiments where the stimulus material has local minima and maxima in luminance (e.g art, natural images and advertisements). Thus it is realistic to assume that the pupil may vary a lot during various types of experiments.

4.4. Solutions for the pupil-size artefact

To be able to measure reliable vergence angles, fixation disparity and distances to the binocular fixation point, one needs an accurate eye tracker. The pupil-size artefact is an idiosyncratic error that causes the measurement to become inaccurate. In our experiment we have shown that due to the pupil-size artefact binocular measures such as the vergence angle cannot be determined reliably. We have done our best to evoke a large effect of varying pupil size on vergence angle. Is it possible to minimise the effects of the pupil-size artefact on binocular measures? We see five possible solutions; The first two solutions are already described by Drewes et al. (2014).

1. The first solution consists of correcting for the pupil-size artefact. Drewes et al. (2012, 2014) suggest an extensive calibration at different light levels and a calibration model to compensate for the pupil-size artefact. This option is not offered by the eye tracker manufacturers and therefore this solution is not applicable for every researcher. Researchers have to implement this option themselves and this solution is probably the best available, but it is not perfect. Residual errors may be up to 0.5° per eye, which according to our Fig. 1C, may be too much to determine the location of the binocular fixation point. In the literature there are also other correction methods. Choe et al. (2016) offers a regression-based solution for errors caused by pupil-size changes over time that does not require additional calibration. Jaschinski (2016) is the first to offer a binocular regression-based correction method in order to directly correct the vergence angle for the pupil-size artefact.
2. Another solution is to run the eye tracking experiment at high light levels to evoke a small pupil; if there is enough light the pupil size hardly changes.
3. The participants could also be selected on the basis of the absence of the pupil-size artefact. We do not know whether this is realistic. When enough participants are available, it is a possibility. In this study we had 5 out of 22 subjects without or with a small pupil-size artefact.
4. Using equiluminant colour stimuli and equiluminant colour calibration screens. This is not a very realistic approach and only applicable in situations with artificial stimuli. However, equiluminant stimuli cannot prevent that the arousal state of the participants changes during the experiment. However, the effect of mental activity on pupil size is much smaller than the effect of light (De Groot & Gebhard (1952) reported the pupil diameter to increase up to 300% due to light; Hess & Polt (1960) reported effects of mental activity on pupil diameter varying from 4 to 30%).
5. The last solution is using an eye tracking technique that does not make use of the pupil. Alternatives are available (e.g coils, CR eye tracking, outer rim iris eye tracking and limbus tracking). We understand that invasive measurements like coils are not attractive for many researchers.

We would like to see eye tracker manufacturers improve their eye trackers. From the five suggested solutions presented above, two (solutions 1 and 5) could be applied in eye trackers. Manufacturers could implement correction methods as suggested by Choe et al. (2016), Drewes et al. (2012, 2014) and Jaschinski (2016). We are in favour of the other solution, however. Namely that manufacturers develop high-quality eye trackers that do not use the pupil as a feature to estimate the eyeball orientation. The reason is that the pupil-size artefact is not the only pupil-related problem in modern video eye tracking. For example, the pupil causes post-saccadic oscillations (Nyström, Hooge, & Holmqvist, 2013) and overestimation of saccade velocity (Hooge et al., 2016) in the eye tracker signal.

4.5. Vergence and attention

In the introduction we have cited a number of studies that may have drawn incorrect or incomplete conclusions about the actual binocular eye orientation as a result of the pupil-size artefact (e.g. Jainta et al., 2010; Kirkby et al., 2013; Nuthmann & Kliegl, 2009; Vernet & Kapoula, 2009). After a literature search for more candidates, we found a number of articles dealing with vergence measured with pupil-based video eye trackers (Esposito et al., 2018; Solé Puig, Puigcerver, Aznar-Casanova, and Supèr, 2013; Solé Puig et al., 2015; Solé Puig et al., 2016; Solé Puig, Romeo, Cañete, Crespillo, and Supèr, 2017; Varela Casal et al., 2018). Solé Puig, Pérez Zapata, Aznar-Casanova, and Supèr (2013) published a study that suggests a link between covert spatial attention and vergence. They used an EyeLink ll at 500 Hz (pupil-only mode). In their study they compared the vergence angle between a cue and a no-cue condition as a function of time. In the cue condition the vergence angle increased more than in the no-cue condition. They also report pupil size and in the cue condition the pupil size increased more than in the no-cue condition. This resembles the typical condition outlined by Drewes et al. (2014), namely, the pupil size increases, the pupil shape changes and this causes the reported angle of vergence to increase. Solé Puig et al. (2013), however, do something peculiar. On page 6, they conclude: “Finally, our findings indicate that the changes in pupil size does not cause the observed changes in AoEV (the angle of eye vergence) as the temporal modulation in pupil size did not correspond to the temporal modulation in AoEV”. This conclusion is based on the following observation: the point of significant difference was reached about 200 ms later for the pupil size than for the vergence angle. In another article, Solé Puig et al. (2016) use the same kind of reasoning. We have a problem with these conclusions and we believe that the order of events should not be determined in this way. Based on the literature about the pupil-size artefacts in gaze estimation (Choe et al., 2016; Drewes et al., 2012, 2014; Wyatt, 1995; Wyatt, 2010; Wildenmann & Schaeffel, 2013), we cannot exclude that the vergence-attention relation reported by Solé Puig et al. (2013) is influenced by the pupil-size artefact as described in this article.

5. Conclusions

We conclude that during binocular fixation under varying lighting conditions when the eyes are still, the pupil-based eye tracker reports vergence movements due to pupil-size changes. Based on the literature on pupil-size artefacts (Choe et al., 2016; Drewes et al., 2014; Wildenmann & Schaeffel, 2013; Wyatt, 2010), we conclude that these vergence changes are caused by the pupil-size artefact as predicted by Drewes et al. (2014). We questioned whether the eye tracking data from binocular pupil-based eye trackers using the dark pupil technique are suitable to determine vergence, distance to the binocular fixation point and fixation disparity. The answer is no because binocular pupil-based eye trackers are prone to idiosyncratic systematic errors and therefore they are not accurate enough.

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