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# The art of braking: Post saccadic oscillations in the eye tracker signal decrease with increasing saccade size

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ABSTRACT

Recent research has shown that the pupil signal from video-based eye trackers contains post saccadic oscillations (PSOs). These reflect pupil motion relative to the limbus (Nyström, Hooge, & Holmqvist, 2013). More knowledge about video-based eye tracker signals is essential to allow comparison between the findings obtained from modern systems, and those of older eye tracking technologies (e.g. coils and measurement of the Dual Purkinje Image—DPI). We investigated PSOs in horizontal and vertical saccades of different sizes with two high quality video eye trackers. PSOs were very similar within observers, but not between observers. PSO amplitude decreased with increasing saccade size, and this effect was even stronger in vertical saccades; PSOs were almost absent in large vertical saccades. Based on this observation we conclude that the occurrence of PSOs is related to deceleration at the end of a saccade. That PSOs are saccade size dependent and idiosyncratic is a problem for algorithmic determination of saccade endings. Careful description of the eye tracker, its signal, and the procedure used to extract saccades is required to enable researchers to compare data from different eye trackers.



## 1. Introduction

With the proliferation of modern, user-friendly, video-based eye trackers, measuring eye movements is relatively straightforward for researchers nowadays. These modern systems are non-invasive, and they are easy to operate. They do not require extensive technical knowledge, because eye tracker manufacturers equip their devices with software enabling even novice users to calibrate and measure eye movements. However, a substantial body of previous knowledge about the oculo-motor system was built up with the use of scleral coils (Collewijn, van der Mark, & Jansen, 1975; Robinson, 1963), and the Dual Purkinje eye tracker (Cornsweet & Crane, 1973). To be able to compare findings obtained from modern video-based eye trackers with findings provided by older methods, it is essential to know the nature of the differences between measurement techniques. Eye movements may appear differently in the eye tracker signal depending on the eye tracker used. Nyström, Hansen, Andersson, and Hooge (in press), for example, found micro-saccades to appear larger when measured with a pupil based eye tracker compared to methods that track movements of the whole eyeball, such as coils. Another reason to investigate and carefully describe the video eye tracker signal is that many data analysis methods were not developed for the video signal and it is not sure whether these methods may be applied without adaptation (e.g. saccade detection, Nyström and Holmqvist, 2010).

### 1.1. The terminology

To discuss eye trackers, we must first define a number of concepts. Primarily, what kind of signal is being used to extract for example saccades and fixations? The eye tracker signals (if digital) may differ in temporal and spatial resolution depending on the device. Eye tracker signals may also differ qualitatively, depending on the way they are obtained, and the structure of the eye they are obtained from. What is considered as an eye movement depends on at least:

(1) The *structure* from which the eye movement is measured (e.g. inside of the iris (pupil), limbus, lens, muscle etc.).
(2) The *eye tracker*, its extraction method, internal filters and eye model, or transformation used. The scleral coil extracts globe rotation of the eyeball; the EyeLink 1000 uses ellipse fitting to determine pupil position in the eye image. An example of filtering is the heuristic filter (Stampe, 1993) of the EyeLink. Different systems build up an eye model in different (often hidden) ways, and sometimes a kind of transformation is also applied.

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(3) The *method and criteria* to extract events (saccades, fixations, blinks, smooth pursuit episodes, etc.) from the eye tracker signal. Saccade detectors and detection criteria define saccades. A nice example of how to determine v-saccades during pursuit eye movements is found in Larsson, Nyström, and Stridh (2013).
(4) The methods to compute measures from the extracted eye movements. How are saccade size, fixation duration Nyström & Holmqvist (2010), and saccadic curvature (Ludwig & Gilchrist, 2002) calculated?

Most of these signals have to be calibrated and transformed before they represent gaze direction, gaze location, or eyeball rotation. In modern video eye trackers, calibration and transformation of the signal is implemented in software, and may involve fitting or an eye model or a combination of the two techniques.

We do not know how internal eye tracker filters affect dynamic properties of eye movement recording, which, especially during and after saccades, may differ a lot depending on the visco-elastic structure of the eye measured. Because saccades and post saccadic episodes may appear differently in different eye tracker signals, we refer to saccades in relation to the eye tracker from which they were obtained. We will refer to c – (coil), d – (DPI) and v – (video) saccades in the present paper (though we measure only with pupil based video eye trackers here). V-saccades are saccades extracted from the eye tracker signal from head-mounted systems such as the EyeLink 2, tower-mounts (SMI Hi-Speed, EyeLink 1000) and from remote systems, like the Tobii TX-300. We will refer to whole eyeball rotation or eye movement without prefix, only when we talk about hypothetical eye movements; that is, un-altered by any measurement method. Of course, we do not know the exact characteristics of this hypothetical 'ideal' eye movement.

Before describing the video eye tracker signal, the introduction of some additional terminology will be helpful, when considering the movements observed at the end of saccades. We use *drift* for slow asymptotic movements, and *oscillation* for faster ringing movements in the eye tracker signal. Drift resembles the signals from critical and over-damped systems; oscillations are the typical output of an under-damped system, and can be characterized by one or more zero passages. Drift may occur after dynamic under- and overshoots (Bahill, Clark, & Stark, 1975; Kapoula, Robinson, & Hain, 1986). Depending on the eye tracker signal and condition, saccades may be followed by drift or oscillations or both simultaneously, resulting in complicated waveforms (Fig. 1 panels A and B). We are aware that *drift* is a member of the family of *oscillations*; however, we like to use the term *drift* because (i) it is very common in the literature, and (ii) for many readers *drift* is qualitatively different from *oscillation*. Instead of *post saccadic oscillation* we will write PSO.

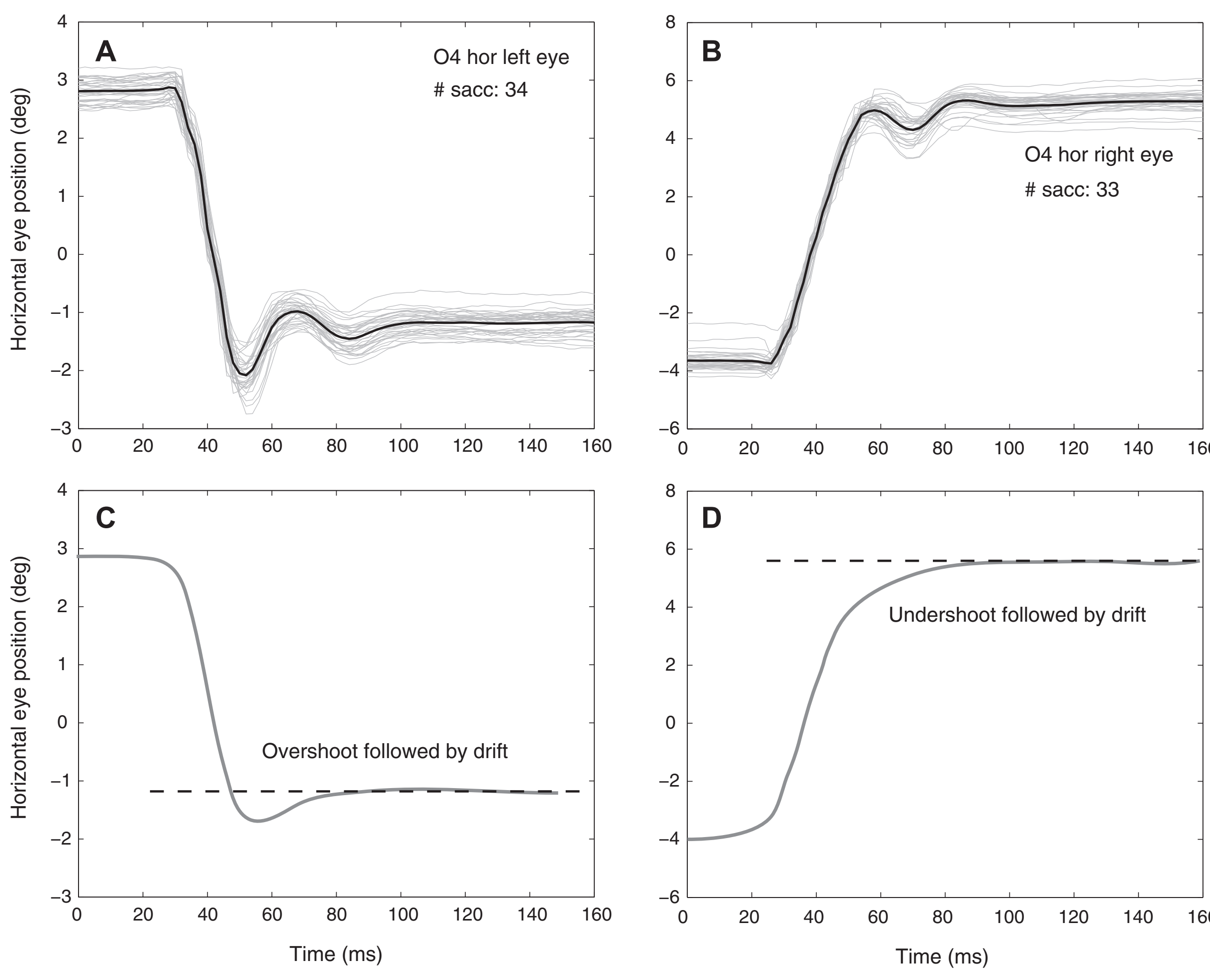


**Fig. 1.** Saccades of observer O4. Grey lines in A and B denote individual saccades, the thick black lines denote the mean of 34 saccades in A and 33 saccades in B (note the different *y*-axes). (C) Depicts a hypothetical saccade without PSO modeled after the saccades of A. Panel D depict hypothetical saccade without PSO modeled after the saccades of B. In contrast, the saccade in panel C shows dynamic overshoot followed by drift; the saccade of panel D shows dynamic undershoot followed by drift.

### 1.2. The video eye tracker signal

What are the characteristics of the v-eye tracker signal? To investigate the video signals from an EyeLink system, Van der Geest and Frens (2002) simultaneously measured with an EyeLink 2 and a coil system. Eye positions during fixation do not differ much between coils and the EyeLink. However, the saccadic profile of v-saccades and c-saccades does differ—the latter being less skewed in both velocity and position. Van der Geest and Frens (2002) write: "...the observation that saccadic peak velocity was slightly higher in the video system than in the coil system might be related to the visco-elastic coupling between the annulus and the cornea. This would suggest that the coil motion is a filtered version of the actual eye movement, thereby underestimating true peak velocity of saccades." Here it seems that van der Geest and Frens consider the EyeLink to represent the "real" movement of the eye. To find evidence in favor of the hypothesis that coils alter the eye movements, in another paper, Frens and Van der Geest (2002) describe v-saccades measured with an EyeLink 2. In a clever experiment they compared v-saccades performed with and without a coil in the eye. They show that v-saccades with and without a coil in the eye differ. Fig. 2 of their article shows that v-saccades with coil decelerate more slowly. Careful inspection of the left panel of their Fig. 2 shows a PSO at the end of the v-saccade without coil. The "lower deceleration effect" is especially present in larger saccades (>20°). For smaller saccades the differences between v and c- saccades are not that large.

Recently, new phenomena of the v-signal have been described. Kimmel, Mammo, and Newsome (2012) show that macaque v-saccades (EyeLink 1000) differ from c-saccades (sclera embedded search coils) in the same monkey. The v-saccades show post saccadic oscillations (PSO) and elevated saccade peak velocities compared to c-saccades. Drewes, Montagnini, and Masson (2011) describe similar phenomena when they used scleral coils and an EyeLink 1000 simultaneously in a human study. As in Van der Geest and Frens (2002), peak velocities of the v-saccades were elevated compared to c-saccades, and peak velocities occurred at a later point during the saccade (skewed velocity curves). They also report post saccadic oscillations (PSO) in the v-signal. Kimmel, Mammo, and Newsome (2012) suggest that PSOs in their v-signal do not represent whole eyeball rotation. Following an earlier suggestion Inhoff and Radach (1998), Kimmel, Mammo, and Newsome (2012) hypothesize that the pupil may move with respect to the whole eyeball. Pupil-tracking video eye trackers may then misinterpret pupil motion for eyeball rotation. Nyström, Hooge, and Holmqvist (2013) showed that this is indeed the case in video eye tracker signals. They used SMI Hi-Speed eye trackers, having the option to save the eye images at high temporal resolution (240 and 500 Hz). Nyström, Hooge, and Holmqvist (2013) analyzed the raw eye images and determined positions of the pupil center and iris center. At the end of a saccade the pupil center was moving with respect to the iris center. The pupil center signal also had a high correlation with the v-signal of the eye tracker (ranging from $r = 0.84$ to $r = 0.89$). Nyström, Hooge, and Holmqvist (2013) suggest that v-saccades are not the perfect model for eyeball rotation, since the v-signal yields aspects of relative pupil motion. They also show that the iris center signal also yields PSOs. However, amplitudes are much smaller than those of the pupil center PSO. Iris center PSOs resemble very much PSOs in the c-signal, measured by Kimmel, Mammo, and Newsome (2012). This makes sense, since they used sclera implanted coils.

Are these findings related to PSOs and video-based eye trackers problematic for conducting research involving eye movements? We think the answer is yes for many applications. PSOs distort the saccadic profile as a function of time. This is a serious problem for event detection. Determining the end of a saccade (both its timing and location) is a problem, since PSOs mask when a saccade actually terminates. This is magnified when one tries to detect v-saccades during v-pursuit (Larsson, Nyström, and Stridh, 2013). A short non-exhaustive list of applications that may suffer from inaccurate measurement of saccade end point includes: (1) determining saccade size, (2) determining fixation time, (3) determining *any* latency from fixation onset, (4) comparison of binocular saccades, (5) determining the main sequence of saccades (especially amplitude as function of duration), (6) gaze-contingent displays (PSO may have durations up to 50 ms and amplitudes of 2°, giving a noticeable mismatch between volitional eye movements and movement of the 'moving window'), (7) clinical applications where PSOs are mistakenly seen as part of the rotation of the whole eyeball.

Since the majority of the eye trackers today are pupil-tracking video systems, we believe it is useful to investigate and describe the video eye-tracker signal carefully. Many researchers have obtained v-PSOs (Nyström & Holmqvist, 2010; Drewes, Montagini, & Masson, 2011; Hutton, 2013; Kimmel, Mammo, & Newsome, 2012; Nyström, Hooge, & Holmqvist, 2013), but v-PSOs have not been studied systematically in humans. Since it is clear that v-PSOs are related to visco-elastic properties of the inner border of the iris (pupil), we want to know whether v-PSO amplitude depends on saccade size and saccade direction. This is because velocity profiles of these types of saccades may differ substantially (Collewijn, Erkelens, & Steinman, 1988a,b). Further, it is important to know whether v-PSOs are similar between and within individuals. In experiment 1 we study large and small, horizontal and vertical binocular v-saccades to answer these questions. One of the counterintuitive results of experiment 1 is that v-PSO amplitude seems to decrease with increasing saccade amplitude. One of the possible explanations is that larger saccades evoke less oscillations of the inner border of the iris (pupil) because they have longer deceleration periods, with lower deceleration near the end of the saccade. We refer to this as "the gentle braking" hypothesis. In experiment 2 we measured much larger horizontal (up to 50°) and vertical saccades (up to 30°) to test this hypothesis.

## 2. Experiment 1

### 2.1. Observers

Five observers took part in the experiment (one female (O2) and 4 male [including the first, second and the last author]). Age ranged from 30 (O1) to 47 (O4) years. Two of the subjects (O4 and O5) wore glasses during the experiment. The work was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

### 2.2. Set up

Both the left eye and the right eye were recorded with an SMI Hi-Speed 1250 eye tracker operating at 500 Hz. Visual stimuli were presented on a Samsung SyncMaster 245T 24′ monitor (refresh rate 60 Hz) at a distance of 82 cm from the eye. The resolution of the monitor was set to 1680 pixels by 1050 pixels (16:10 ratio). We used a standard 13-point SMI calibration (IView X Version: 2.7.13) that was carried out binocularly.

### 2.3. Stimulus and task

The stimulus consisted of two white circular dots (diameter 0.86°) with a one pixel black border and a center black dot (diameter 0.10°) placed on a gray background. The horizontal distance between the centers of the circles were 4.04°, 6.58°, 9.08°,

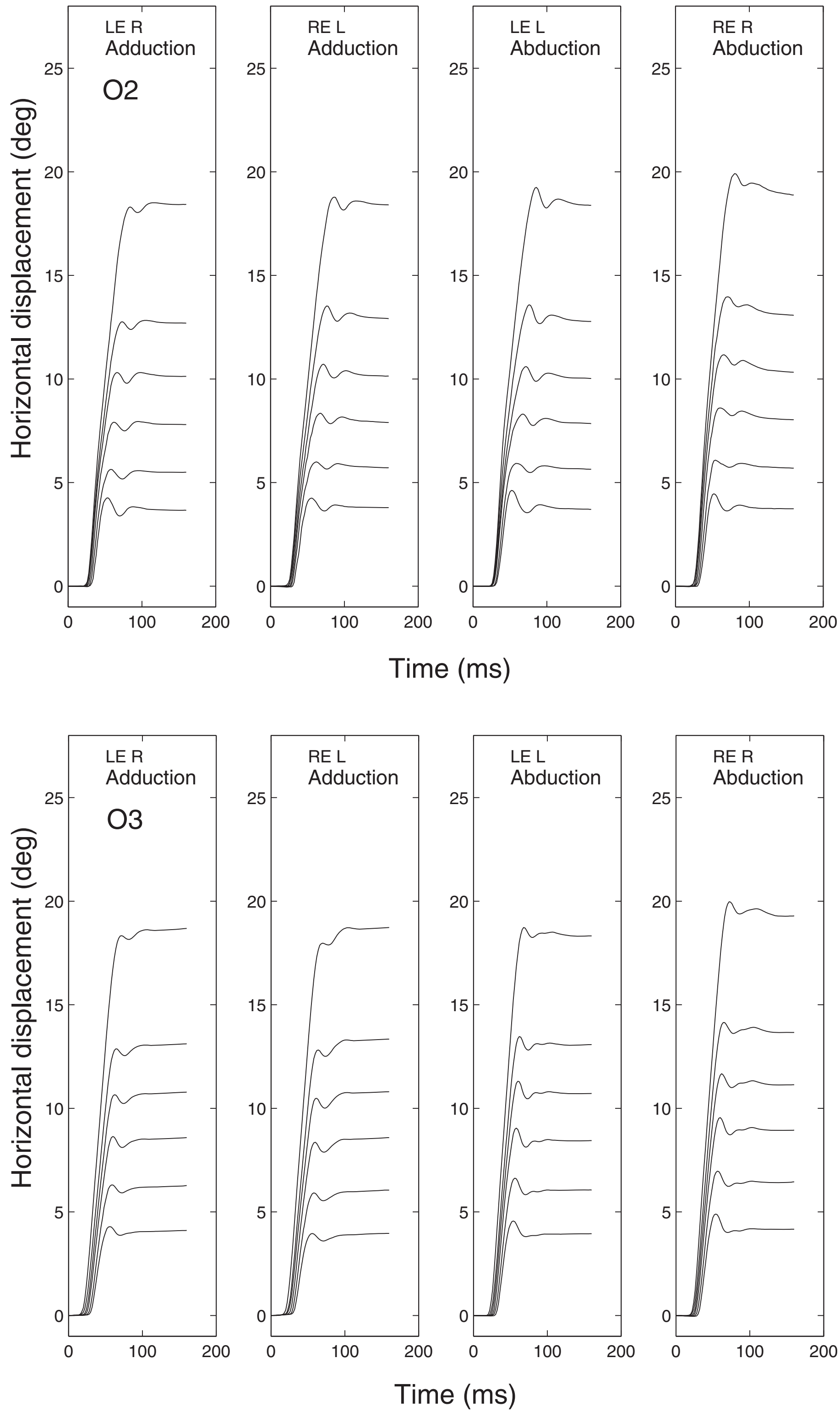


**Fig. 2.** Horizontal saccades. This figure contains averaged horizontal saccades of two observers. To enable comparison of the saccades, all saccade start points were aligned at 0° and we show displacement on the *y*-axis. Saccades are labelled by eye (left or right), saccade direction (left or right) and direction relative to the nose (adduction [to the nose] or abduction [from the nose]). We did this to facilitate comparison of saccade shape between adduction and abduction saccades from the left and the right eye (that resemble each other remarkably).

11.46°, 14.08° and 20.16°. The center of the (invisible) horizontal line connecting the dots coincided with the center of the screen. Observers were asked to make saccades between the two dots accurately but quickly in a self-paced manner for the period of one minute.

### 2.4. Data analysis

To enhance signal to noise ratio in our eye tracker signal we used a method inspired by ERP averaging (Nyström, Hooge, & Holmqvist, 2013). In the analysis we determined onsets of saccades by determining the end of a fixation using the adaptive velocity-threshold-fixation-detection algorithm described in Hooge and Camps (2013). Only saccade onsets (fixation ends) were used to select and subsequently align episodes of 160 ms of the eye tracker signal containing a saccade. We then checked each saccade for starting position; all saccades starting inside a circular AOI (radius 1.65°) surrounding the stimulus dot were included in the analysis. Then we averaged the eye tracker signal to obtain the average saccade. We excluded episodes that contained blinks. This resulted in averaged saccades based on 14–68 saccades (mean = 38.4, sd = 10.6).

## 3. Results

Before describing the saccade shapes as function of direction, amplitude or eye of origin we would like to give two examples of averaged saccades. Fig. 1 panel A contains 34 saccades and the average saccade (thick line) performed between two targets separated by 4.04° of O4. The saccades are performed with the left eye from right to left. This panel clearly shows that the PSOs are very reproducible; the shape of the average saccade is similar to the shapes of the thin gray lines (representing individual saccades). Panel B shows larger saccades (target distance 9.08°). When comparing saccades from panels A and B, we see clear differences but also similarities. Both signals of subject O4 contain small pre-saccadic back shoots and similar but longer periods of PSO which lasts between 40 and 60 ms, depending on where one defines the start of the PSO. Onset determination is a potential problem; when does the PSO start? This problem is not solved in this article but we will come back to this topic in the general discussion. PSO amplitudes are of the same size (top-top amplitude is about 1°), but they are not easy to estimate. Panel A yields a saccade with an overshoot, followed by post-saccadic drift with super-positioned post saccadic oscillation. Panel B contains a saccade that undershoots with post saccadic drift in the direction of the saccade combined with PSO. Since we believe that the post-saccadic movement may consist of drift and oscillation superimposed, panels C and D of Fig. 1 contain sketches of our ‘ideally measured’ or hypothesized ‘real’ eye movement (i.e. without the v-PSO, and thus showing the underlying over/undershoot followed by drift). These figures are not based on calculations and are drawn by hand.

Just like the saccades from Fig. 1, the horizontal saccades from Fig. 2 also contain several forms of dynamic overshoot (Collewijn, Erkelens, & Steinman, 1988a; Kapoula, Robinson, & Hain, 1986). It is difficult to see or estimate the magnitude of the different drifting and oscillating contributions independently, because the eye tracker signal contains at least two signals superimposed (see Fig. 1c and d). All averaged horizontal saccades in the figure contain PSOs, and the majority also contain some form of over-/under-shoot, and subsequent post-saccadic drift. The eye may drift in two directions: against or with the direction of the preceding saccade. We obtain consistent overshoot (Fig. 2, O2, right panel right eye, abduction saccades) and systematic undershoot (Fig. 2, O3 left panel, left eye, adduction saccades). Overshoot and undershoot are followed by drift. The magnitude of the over- and undershoot seems to increase with saccade size. Two (O3 and O4) of our five subjects show undershoot in adduction saccades (to the nose), and overshoot in abduction saccades. In the other subjects we see other combinations. O1 and O2 show overshoot (followed by drift in the opposite direction) in all saccades. O5 always undershoots and drifts in the direction of the saccade.

### 3.1. PSO waveform, period and amplitude

Just like in d-PSOs, v-PSOs have aspects of a damped oscillation, and in some observers damping is stronger than others. As an illustration, O4 shows many oscillations (Fig. 3B), O3 and O5 show less (Fig. 3A, C and D). The waveform of the abduction saccades of O3 is more complicated (Fig. 2); it does not resemble a singular damped sinusoid. Although it may be suspected that this is due to erroneous saccade alignment, inspection of individual saccades (examples shown in Fig. 3C and D) shows that they all yield many small oscillations. We will come back to this, but for now note that v-PSOs are probably more complicated oscillations than singular damped sinusoids.

If there were only PSOs (only oscillations, no dynamic under or overshoot, followed by drift) in the eye tracker signal, determining PSO amplitude would be much easier than with the current signal, consisting of both drift and PSOs. Whether PSO amplitude decreases with increasing saccade size is hard to see (Fig. 2). We do not have an exact method to measure PSO amplitude. To estimate PSO amplitude and PSO period from a signal containing PSO and drift, we used a simple trick (Fig. 4). We first marked by hand the first three extreme values in the signal ($p_1$ occurring at $t_1$, $p_2$ and $p_3$ occurring at $t_2$ and $t_3$, respectively). To estimate the PSO-period we took the time difference between $t_3$ and $t_1$. To estimate PSO-amplitude we determined the displacement between $p_2$ and $p_4$. This was done by fitting a line through ($p_1$,$t_1$) and ($p_3$,$t_3$). Filling in $t_2$ in this line equation delivered $p_4$. The saccade size was determined by comparing eye orientation at saccade onset and the orientation 130 ms after saccade onset. We used the method of Fig. 4 instead of the method used by Hutton (2013) and Nyström, Hooge, and Holmqvist (2013). The previous authors estimated PSO amplitude by comparing $p_1$ and $p_2$ and estimated PSO period by comparing $t_1$ and $t_2$. We used our method because it compensates better for the drift present in our eye tracker signal. Post saccadic drift occurs with larger saccades and causes the local maxima and minima to shift both spatially and temporally compared to the maxima and minima in signals without dynamic overshoot and drift. We cannot exclude that post saccadic drift affected the quality of our period estimations. Another way to estimate PSO amplitude and period is fitting the signal with a function that contains a drift and an oscillation component. However, we did not choose to apply the fitting approach because it comes at the price of some assumptions we do not want to make. One of these assumptions is the point in time at which the saccade ends (that is the point where fitting starts). We do not want to make assumptions about this point because the very reason for our interest in v-PSOs is precisely because they mask the end of the saccade.

Fig. 5 shows PSO amplitude as a function of v-saccade size. A few things stand out immediately. The smallest PSO amplitudes are about 0° (meaning no PSO) and occur with the largest v-saccades. The PSO-amplitudes differ a lot between observers, however within one observer the relationship between saccade size and PSO amplitude does not vary much. Nor is there much within-observer variation between the left and the right eyes, or between adducting and abducting v-saccades. The largest amplitudes were seen in data from O1 (up to 1.3°), while the smallest were found for observer O5. Each data point of Fig. 5 is based on three points from an averaged saccade (Fig. 4). In most cases the data points of Fig. 5 are based on ±40 saccades. The disadvantage of this method is that it does not deliver error estimation. To estimate the error, we determined PSO values for all individual saccades underlying one data point of Fig. 5 separately, and computed standard error of the mean (SEM) based on the

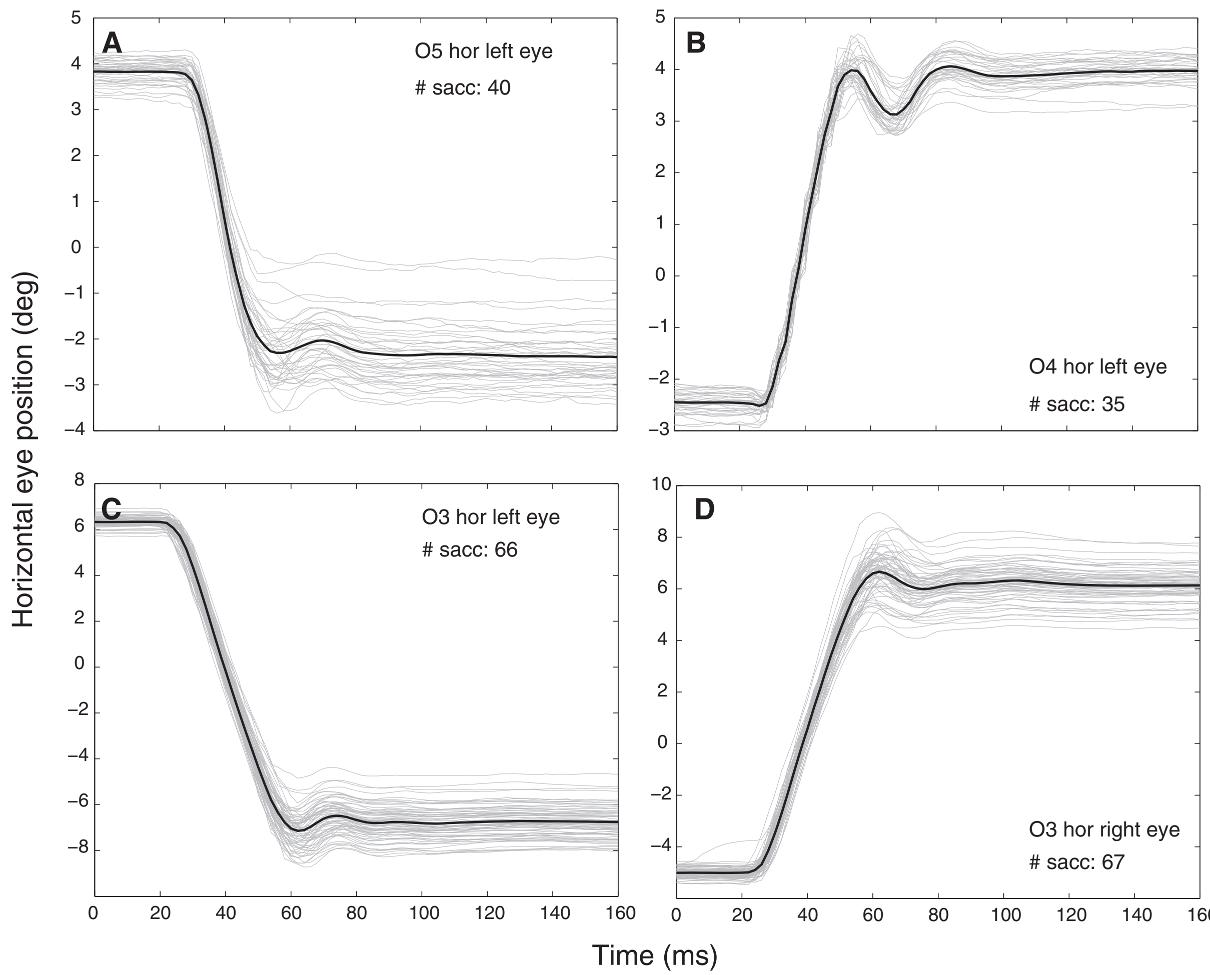


**Fig. 3.** Panel A saccades of observer O5. Grey lines denote individual saccades, the fat black lines denote the mean many saccades (note the different *y*-axes). Panel B saccades of observer O4. Panels C and D show saccades of observer O3.

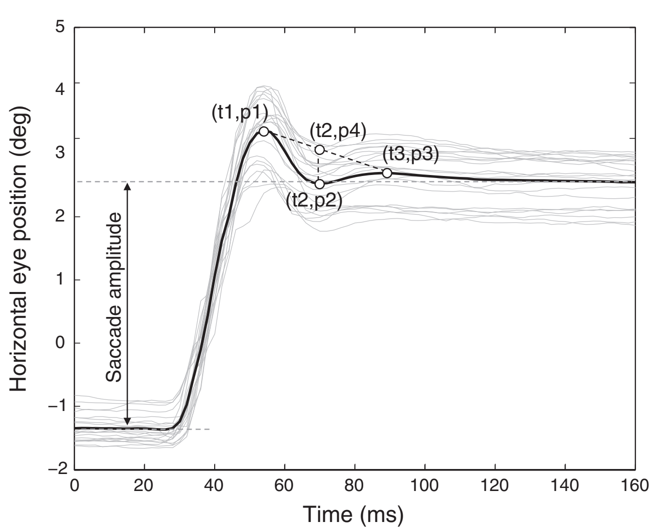


**Fig. 4.** Estimation of saccade size, PSO amplitude and PSO period. PSO-amplitude is estimated by the vertical distance between $p_2$ and $p_4$. The PSO period is estimated by the time between $t_1$ and $t_3$. Saccade size is estimated by taking the difference of eye orientation at saccade onset and 160 ms after saccade onset.

estimated PSO values. The previous was repeated for three different data point of Fig. 5. We obtained SEMs of 0.038° (37 saccades of O5), 0.066° (35 saccades of O1) and 0.022° (67 saccades of O3). PSO amplitude seems to decrease with saccade size for saccades larger 8°. Fig. 6 contains PSO period as function of saccade size. In general, the period decreases with saccade size. For the smaller saccades the period varies between 30 and 35 ms (±30 Hz) and decreases to ±25 ms (±40 Hz) for the larger saccades.

### 3.2. Vertical saccades

Vertical c-saccades differ from horizontal c-saccades, they are less accurate. Moreover, upward c-saccades differ from downward c-saccades. For a detailed and careful description of horizontal and vertical binocular c-saccades see Collewijn, Erkelens, and Steinman (1988a,b). Fig. 7 shows examples of vertical v-saccades. Here it can be seen that the shape of vertical v-saccades is different from the shape of horizontal v-saccades (panels 7c and d). At the end of the saccade, vertical v-saccades decelerate more slowly than horizontal v-saccades of the same size. Note that the *y*-axis range differs a lot between the top and bottom panels of Fig. 7. It is also clear if one compares panel A and B (smaller saccades) with C and D (larger saccades) that the larger saccades have a much longer duration and a more skewed profile than the smaller ones. As with c-saccades, upward v-saccades are smaller than downward v-saccades (Fig. 8). Individual variation between vertical v-saccades is larger than in individual horizontal v-saccades.

In vertical v-saccades we also obtain PSOs. PSOs are present with the smaller saccades (Figs. 8 and 9). Large vertical

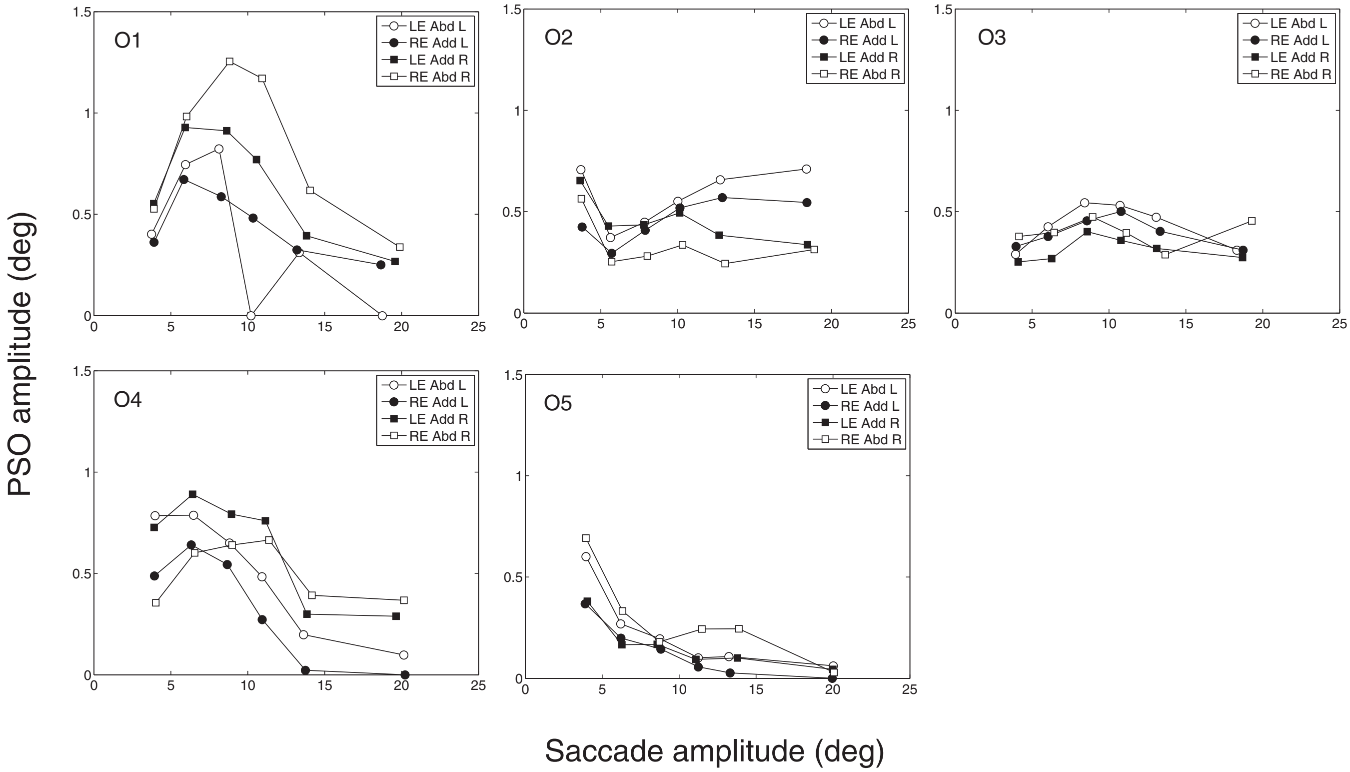


**Fig. 5.** PSO-amplitude versus saccade-amplitude. Black symbols denote adduction (to the nose) eye movements. White symbols denote abduction (from the nose) eye movements. RE – right eye, LE – left eye, Abd – abduction, Add – adduction, R – to the right, L – to the left. Thus RE Abd R indicates saccades to the right performed by the right eye.

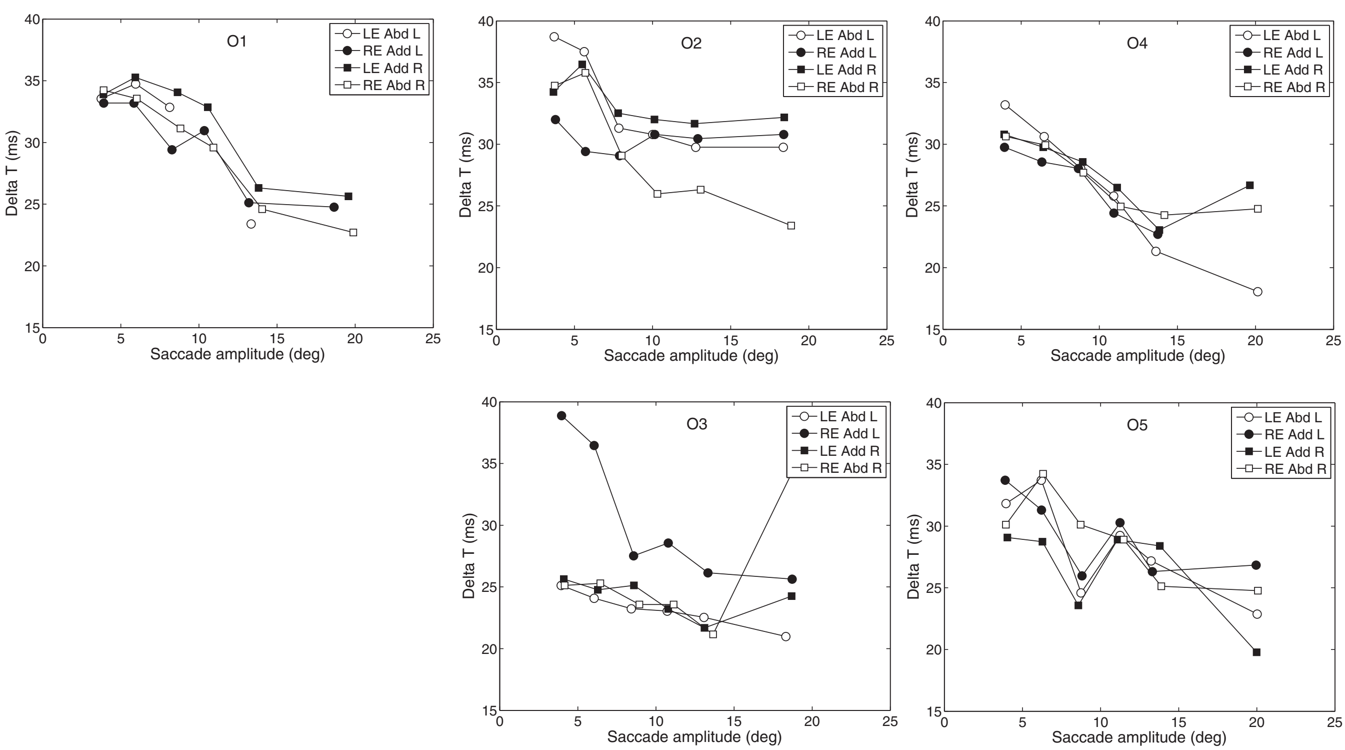


**Fig. 6.** PSO period versus saccade size. Black symbols denote adduction (to the nose) eye movements. White symbols denote abduction (from the nose) eye movements. RE – right eye, LE – left eye, Abd – abduction, Add – adduction, R – to the right, L – to the left. Thus LE Abd L indicates saccades to the left performed by the left eye.

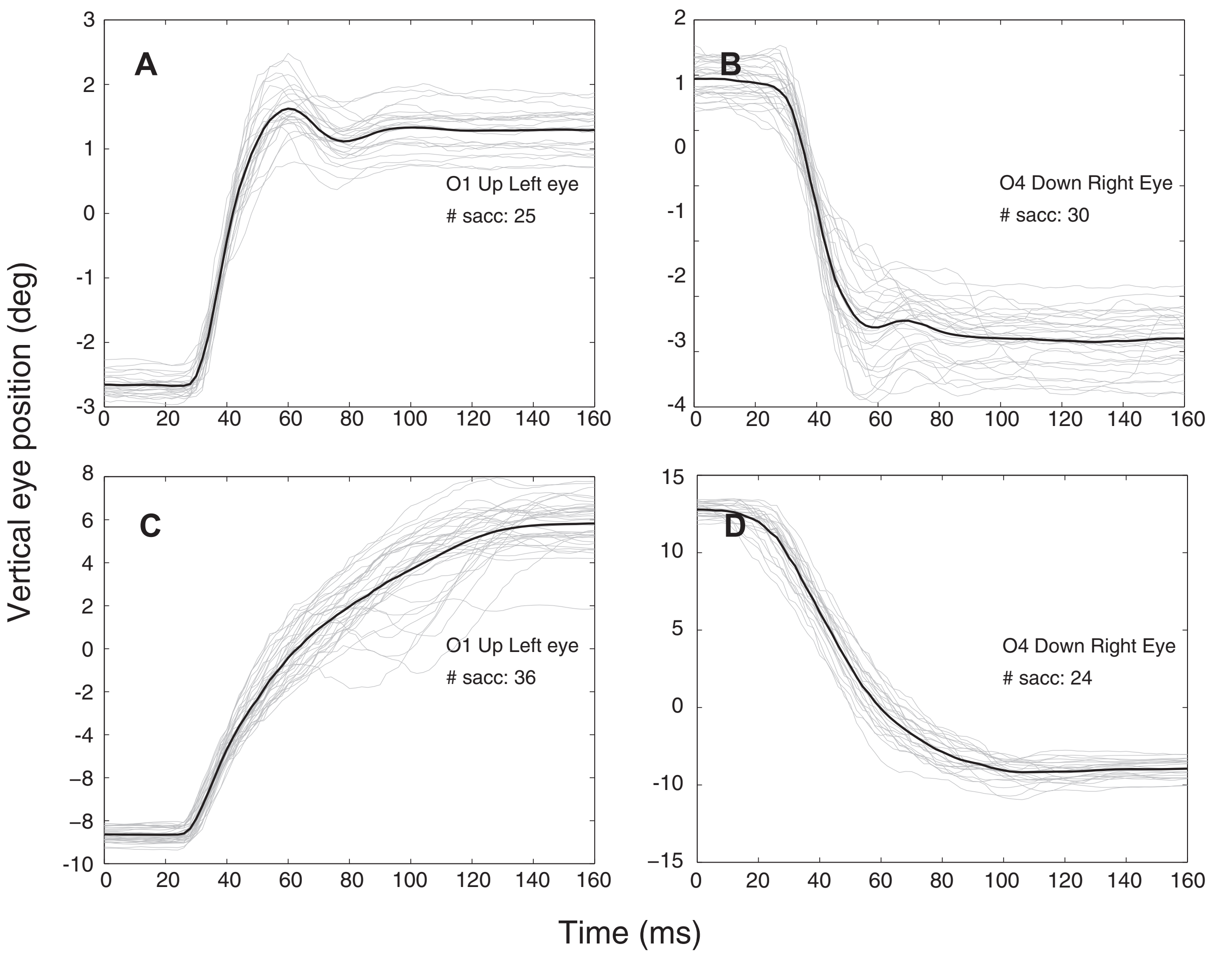


**Fig. 7.** Examples of vertical saccades. Panels A and B contain small vertical saccades. Small vertical v-saccades often contain PSOs. Panels C and D contain larger vertical saccades (note that vertical axes differ). In the larger vertical v-saccades PSOs are absent.

v-saccades may lack PSOs altogether (Figs. 7–9). Fig. 9 shows that PSO amplitude in vertical v-saccades is smaller and PSOs occur less frequently than in horizontal v-saccades (Fig. 9). As in horizontal saccades, PSO amplitude decreases with saccade size.

## 4. Discussion experiment 1

This is the first attempt to quantify PSOs in binocular horizontal and vertical v-saccades of various amplitudes in humans. Estimating PSO amplitude and frequency is not easy because saccades have complicated and subject-dependent waveforms. We used a pragmatic approach to estimate PSO amplitude and found that PSO amplitude in v-saccades decreases with increasing saccade size for saccades larger than 8°. Most PSO amplitudes range from 0° to 1.5°. PSO amplitudes in vertical saccades are smaller than in horizontal saccades. PSO amplitudes in downward saccades are smaller than in upward saccades, and in some of our observers PSOs are absent in downward vertical saccades (PSO amplitude of zero degrees). The effect of decreasing PSO amplitude with increasing saccade size is stronger in vertical saccades than in horizontal saccades. Our PSO amplitudes are of the order of values reported in the literature. However, direct comparison of values is not possible due to the different estimation methods used. Kimmel, Mammo, and Newsome (2012) reported values between 0° and 1.6° in two macaque monkeys. In contrast to our results, in macaque monkeys PSO amplitude increased with saccade size. Nyström, Hooge, and Holmqvist (2013) reports PSO amplitudes of about 0.25° for saccades of 13.4°. In the present study, PSO frequency is not constant for saccade size. Rough estimations of the values range from 25 to 50 Hz. We think that our estimation method overestimates PSO frequency, especially when the saccade is followed by drift.

Kimmel, Mammo, and Newsome (2012) suggest that PSO amplitude may be related to deceleration at the end of the saccades. They write: "In brief, we considered whether the optically tracked ringing resulted from the rapid deceleration of an elastic system (i.e. the iris suspended in the globe)". From Collewijn, Erkelens, and Steinman (1988a,b) we know at least that larger c-saccades have skewed velocity profiles with a longer deceleration episode and lower deceleration overall. Stated differently, shorter saccades brake more abruptly than larger saccades, causing the pupil to oscillate for a certain period after braking. Larger saccades brake more gently and do not cause PSOs or generate PSOs with smaller amplitudes. We refer to this idea as the "gentle braking" hypothesis. To test this hypothesis we performed a second experiment with a larger range of saccade sizes.

## 5. Experiment 2

Experiment 2 is meant to extend the findings of experiment 1 to a larger range of saccade sizes. This experiment serves two purposes.

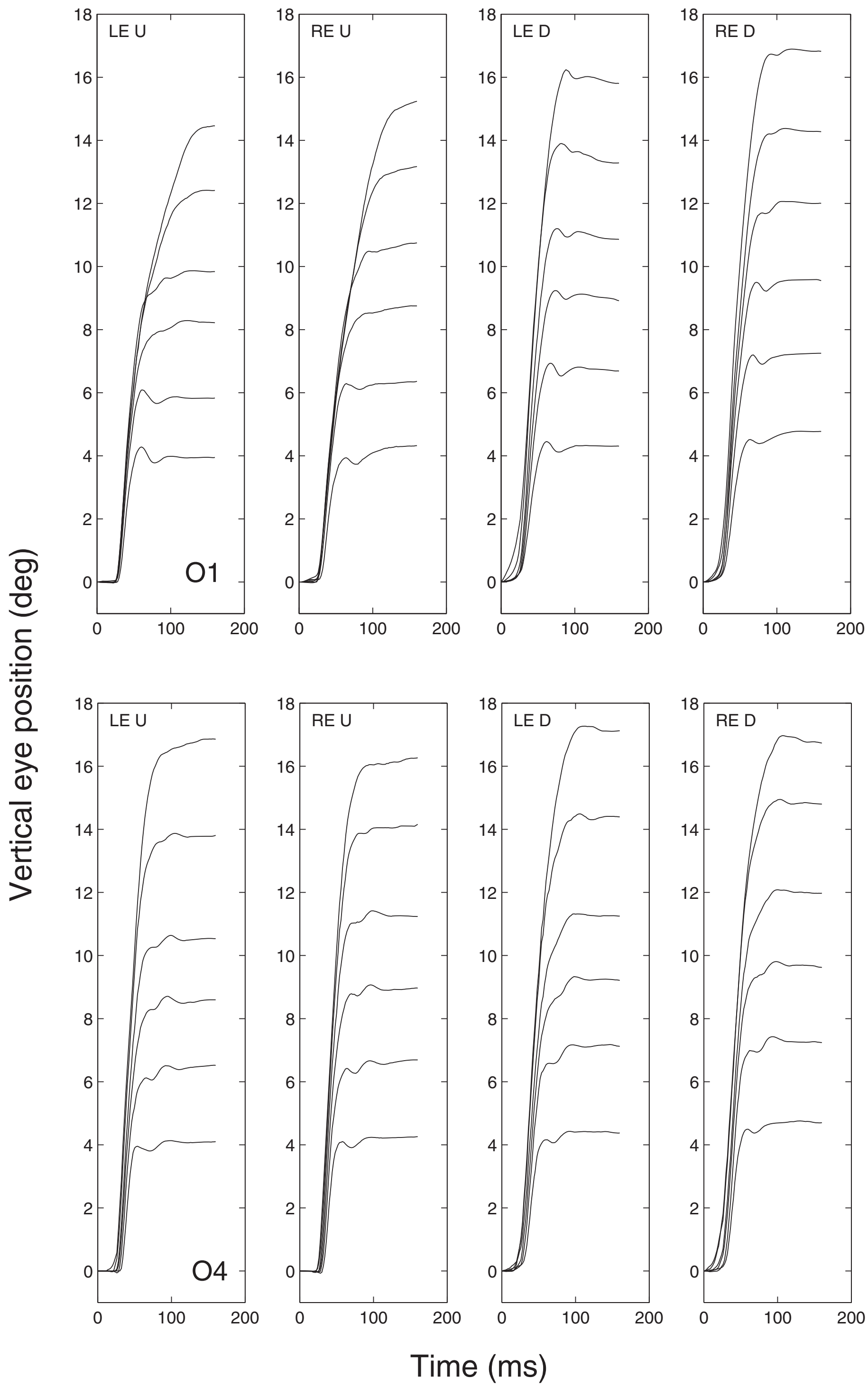


**Fig. 8.** Vertical saccades of O1 and O4. To enable comparison of the saccades, we aligned all saccade start points at 0° and we show vertical displacement on the *y*-axis. The saccades are labeled by eye (RE – right eye, LE – left eye) saccade direction (U – upward, D – downward). Thus LE U indicates upward saccades from the left eye.

(1) According to the "gentle braking" hypothesis we expect PSO amplitude to be smaller or PSOs to be absent in large horizontal saccades (>30°) and large vertical saccades (>15°).
(2) We want to rule out the possibility that the findings of experiment 1 are related to a specific SMI eye tracker and its internal filters. Therefore experiment 2 is conducted with an EyeLink 1000.

## 6. Methods experiment 2

### 6.1. Observers

Four male observers took part in the experiment (including the first and second author). Ages of the observers ranged from 32 (O1) to 48 (O4) year. Three of these observers (O1, O3 and O5) also participated in experiment 1. We removed data from two additional

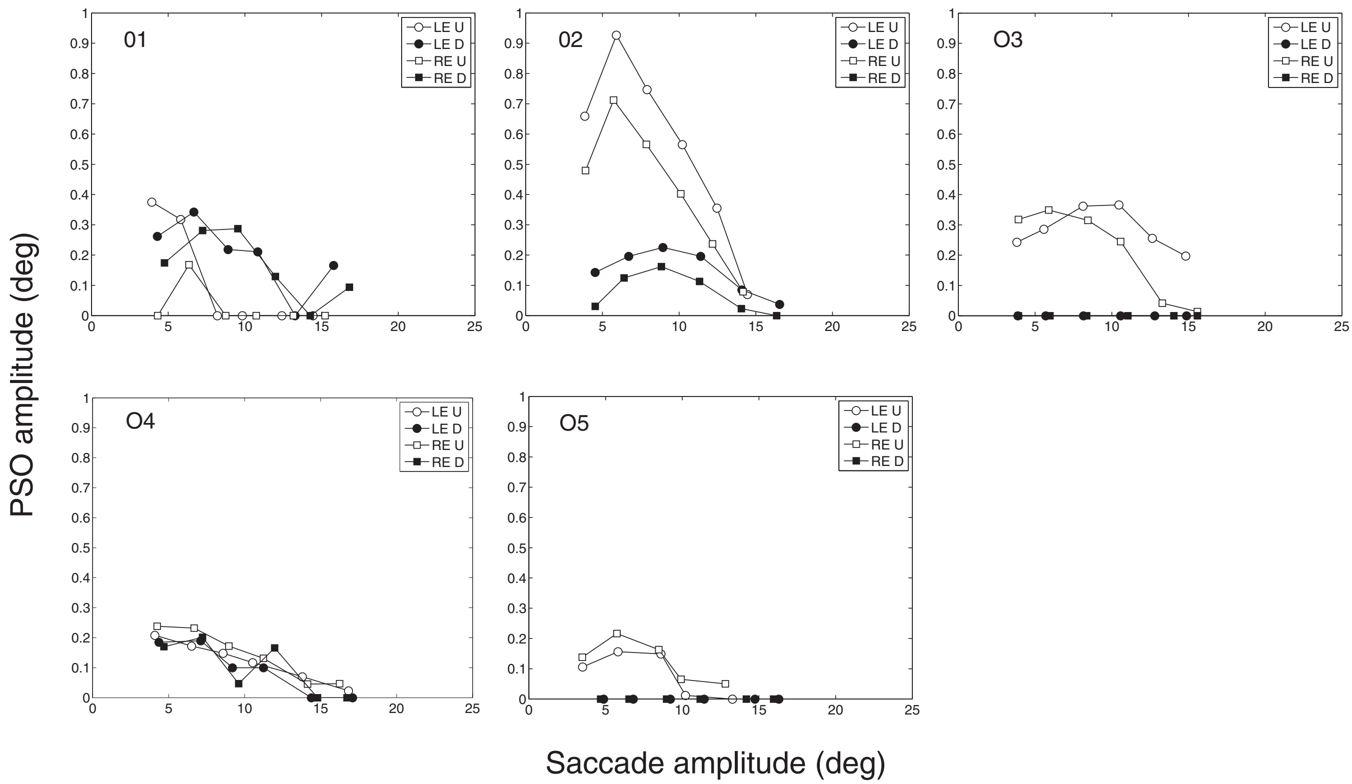


**Fig. 9.** PSO amplitude versus saccade size for vertical saccades. Black symbols denote downward saccades. White symbols denote upward saccades. In general PSOs are smaller in vertical saccades than in horizontal saccades. PSO is absent in many downward saccades (black symbols) indicated by amplitudes of 0°. This is the case for O3 and MN. RE – right eye, LE – left eye, U – upward, D – downward. Thus LE D indicates downward saccades from the left eye.

observers from the analysis. One wore glasses that were just too small to enable measurement of vertical saccades of 30°, the other observer had one loosely connected contact lens resulting in bad data quality for the data of the right eye.

### 6.2. Set up

Both the left eye and the right eye were recorded with an SR-Research EyeLink 1000 operating at 500 Hz in binocular mode. Visual stimuli were presented on an Asus VG248QE monitor (refresh rate 144 Hz) at a distance of 55 cm from the eye. The resolution of the monitor was set to 1920 pixels by 1080 pixels (16:9 ratio). Physical size of the image area of the screen measured 53.0 by 29.8 cm. We used a standard 9-point EyeLink calibration and validation (software version 4.56) that was carried out binocularly.

### 6.3. Stimulus and task

The stimulus consisted of two white circles dots (diameter 1.31°) with a one pixel black border and a center black dot (diameter 0.18°) placed on a gray background. The observers were asked to produce accurate but quick saccades between the two dots in a self-paced manner for the period of one minute. In experiment 2 we measured horizontal and vertical saccades. The horizontal distance between the saccade targets was either 5°, 20° or 50°. In the vertical condition the distance was either 5°, 15° or 30°. The center of the line connecting the two targets coincided with the center of the screen.

### 6.4. Data analysis

Data analysis was similar as in experiment 1. This resulted in averaged saccades based on 17–60 saccades (mean = 33.5, sd = 12.6). PSO amplitude was estimated by the method of Fig. 4.

## 7. Results experiment 2

Fig. 10 shows saccades for one observer. PSO amplitude decreases with increasing saccade size, and PSO amplitudes are smaller in vertical saccades than in horizontal saccades. Fig. 11 shows PSO amplitudes against saccade size for four observers. We see a similar pattern for the other observers as for observer O1 in Fig. 10. PSO amplitude decreases for large amplitudes in both vertical and horizontal saccades. The effect is stronger for vertical saccades. In large vertical saccades, PSO amplitude decreases to 0°. Comparing Fig. 11 with Fig. 5, we can also see that the EyeLink and SMI systems provide similar results for O1, O3 and O5.

## 8. Discussion experiment 2

Experiment 2 two is a replication of experiment 1 with saccades from a larger amplitude range and measured with a different eye tracker. We were able to measure large vertical (30°) and horizontal (50°) saccades reliably with an EyeLink 1000. As expected, PSOs are present in EyeLink 1000 data. Based on the data shown in Fig. 11 we do not reject the “gentle braking” hypothesis. PSO amplitude decreases clearly with increasing saccade size; in vertical saccades this effect is even stronger.

## 9. General discussion

We investigated PSOs in small and large, horizontal and vertical saccades. We found PSOs in all our observers in data obtained by two different video-based eye trackers (an SMI Hi-Speed 1250 and an EyeLink 1000, both operating 500 Hz). The main results are summarized as follows.

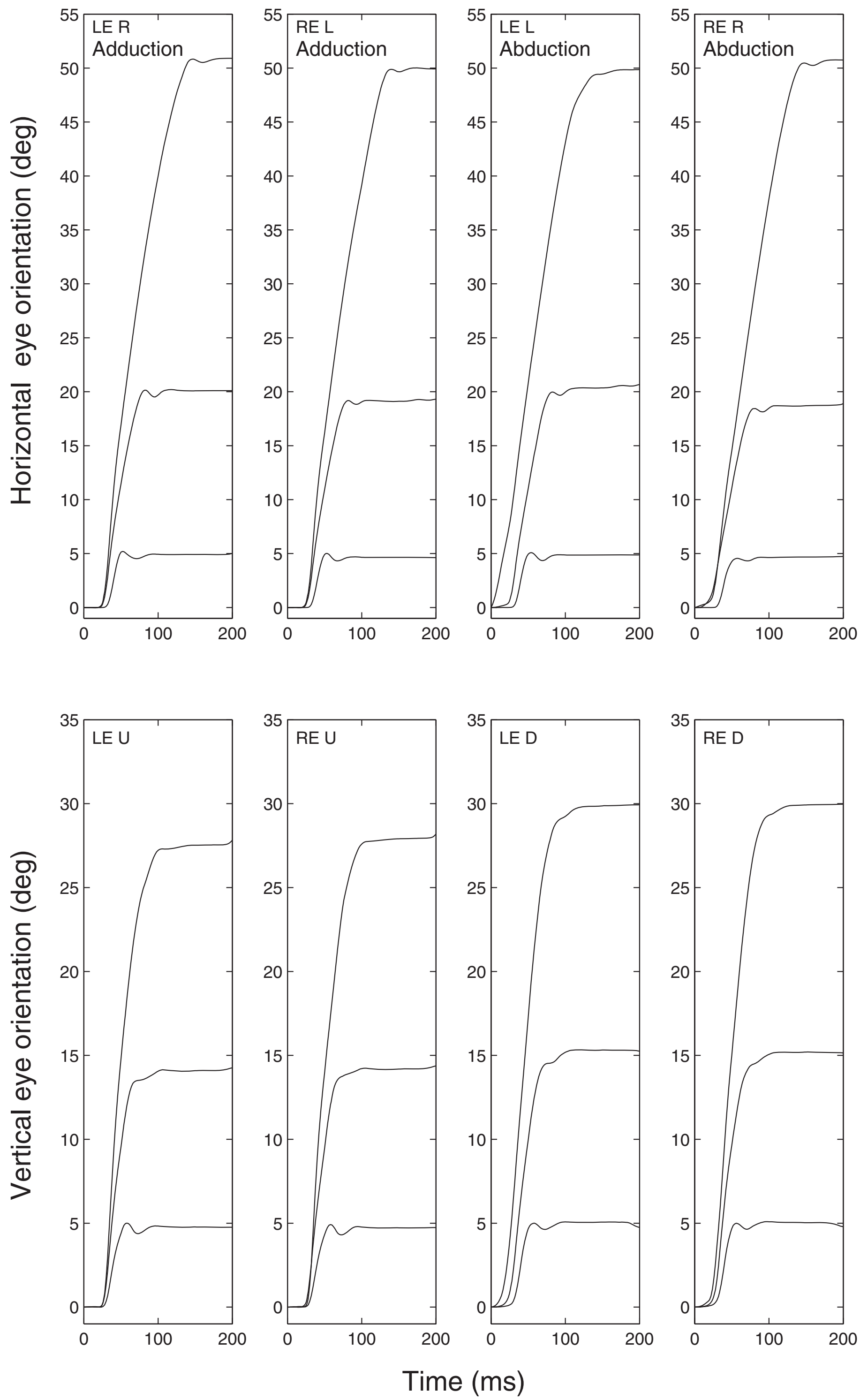


**Fig. 10.** Upper four panels contain horizontal averaged saccades of observer O1. Bottom four panels contain vertical averaged saccade of observer O1. Larger horizontal saccades have PSO with lower amplitude. This decrease of PSO amplitude is even stronger in vertical saccades. In the upward saccades of the right eye (RE U) PSO is absent (or amplitude is 0°). RE – right eye, LE – left eye, R – to the right, L to the left, U – upward, D – downward. Thus RE D indicates downward saccades from the right eye.

(1) A video eye tracker signal contains at least two superimposed post saccadic waveforms, namely post saccadic drift and post-saccadic oscillation.
(2) PSOs are very reproducible within participants in horizontal and vertical saccades of various sizes.
(3) PSO amplitude is observer dependent, eye dependent, saccade direction dependent and saccade size dependent.
(4) For saccade size larger than 8°, PSO amplitude decreases with increasing saccade size. Vertical saccades yield smaller PSO amplitudes than horizontal saccades.

As in Nyström, Hooge, and Holmqvist (2013) PSOs are very reproducible within participants. This enabled us to use the episode averaging method to increase the signal to noise ratio in the

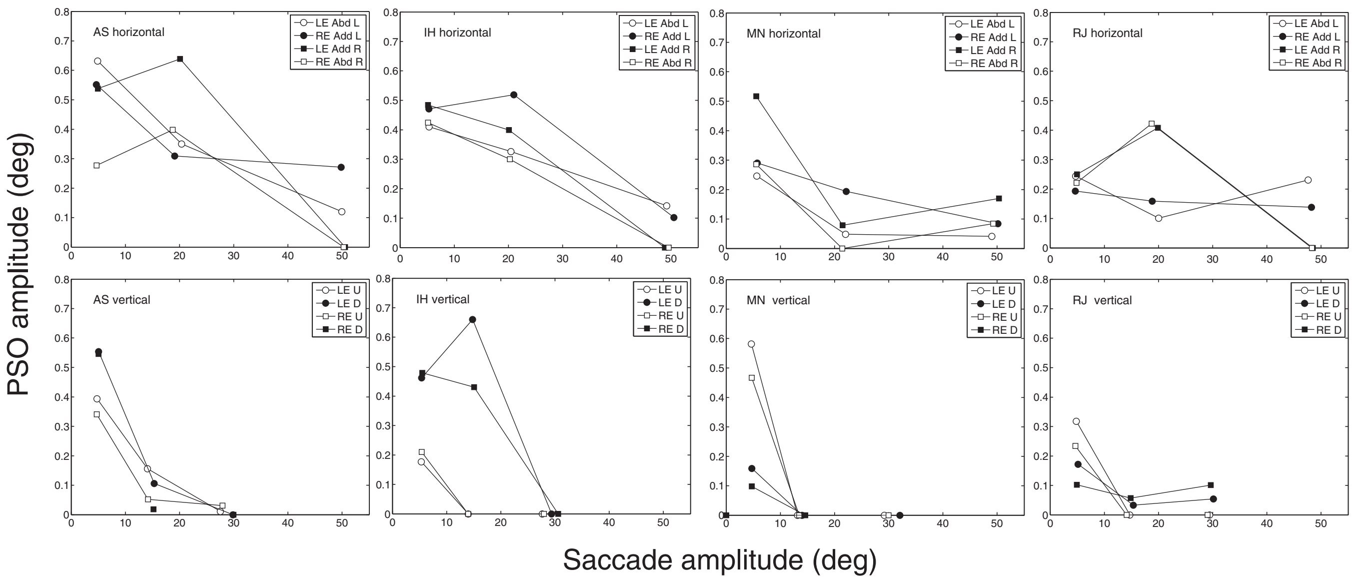


**Fig. 11.** Upper panels show PSO amplitude for horizontal saccades, bottom panels show PSO amplitudes for vertical saccades. PSO amplitude decreases with saccade size. This effect is even stronger in vertical saccades. RE – right eye, LE – left eye, R – to the right, L - to the left, Abd – abduction, Add – adduction, U – upward, D – downward. Thus LE U indicates upward saccades from the left eye.

averaged eye tracker signal by a factor of about 5–7.5. One of the disadvantages of video eye tracking compared to coils and DPI is the lower signal to noise ratio. The episode averaging method enabled us to study the v-signal in the same detail as the c and the d-signal.

In our video eye tracker signal post saccadic drift resembling c-drift (described by Kapoula, Robinson, & Hain, 1986) is present *together with* post-saccadic oscillations, as described by Nyström, Hooge, and Holmqvist (2013). The presence of the drift component complicated quantification of PSO properties (amplitude and frequency). To be able to measure PSO amplitude and frequency we introduced a new method that is less sensitive for post saccadic drift than the methods used by both Hutton (2013) and Nyström, Hooge, and Holmqvist (2013).

### *9.1. Visible and invisible PSOs and the eye tracker signal*

All v-eye trackers signals may contain PSOs. However, the eye tracker has to be fast, and precise enough to be able to produce clearly visible PSOs in the eye tracker signal. Without being exhaustive, PSOs are visible in the eye tracker signal from Tobii TX300, EyeLink 2 and EyeLink 1000 systems and in the signal from SMI Hi-Speed eye trackers. PSOs with large amplitude may be problematic in the eye tracker signal of low frequency eye trackers. If the eye trackers signal is sampled at approximately 60 Hz, PSOs may appear as unpredictable patterns (aliasing) because PSO frequency (±30 Hz) is of the order of the Nyquist frequency. If the eye tracker has low precision (a high variable error) aliasing artifacts probably go unnoticed, but for an eye tracker with high precision aliasing artifacts may be a potential problem.

### *9.2. PSOs and event detection*

If careful determination of saccade end (for computing saccade duration, fixation duration, saccade curvature, binocular saccades etc.) is important, then video-oculography is not the ideal technique because the saccade end is often masked by PSOs. Traditional saccade detection algorithms that were not specifically designed for v-eye tracker signals may add PSO episodes to the saccade episode and sometimes to the fixation episode. Nyström and Holmqvist (2010) recognized this problem and presented the first method for v-saccade detection that takes PSOs into account. Their algorithm categorizes episodes in the eye tracker signal as saccade, PSO, or fixation. However, they left another problem unsolved. Their algorithm uses a rule similar to that of Deubel and Bridgeman (1995a), where the saccade ends at the peak of the first overshoot. D-eye tracker signals contain large PSOs and Deubel and Bridgeman (1995a) recognized this to be problematic for saccade-end determination. They wrote: “Further, it is interesting to note that the peak of each overshoot coincides approximately with the time of the conclusion of the coil-measured saccade”. But depending on the observer, saccade size and direction, v-PSOs may appear very differently. In many cases the PSO is absent (or has a very small amplitude), or has a non-standard shape. This may be problematic for the Nyström and Holmqvist algorithm; it may also overestimate saccade size by the PSO amplitude if the saccade ends in the first overshoot (if present). In algorithms that do not take into account the PSO-episode, the problem may be even larger.

A good example of the event detection problem in the v-signal was found in the present study. We are interested in properties of post-saccadic oscillations, but we had difficulty determining PSO amplitudes. This difficulty is related to not being able to determine the saccade end in an objective and standardized way. There is no clear criterion for saccade-end determination in the eye tracker signal of high quality video-based eye trackers. We think that solving this problem is one of the big challenges for eye movement researchers in the near future.

### *9.3. PSOs in other eye tracker signals*

Different eye trackers measure from different structures from the eye (e.g. globe-coils, lens-DPI and pupil-VOG). There is ample evidence from the literature that the different eye tracker signals contain post saccadic oscillations with different characteristics. Careful inspection (Fig. 4 Kimmel, Mammo, & Newsome, 2012) of data from coil implants reveals post-saccadic oscillations. These coil implant PSOs have smaller amplitude and longer periods than pupil PSO. Another structure of the eye is the lens, and DPI-signals show the largest PSO-amplitudes (Deubel & Bridgeman, 1995a,b). Nyström, Hooge, and Holmqvist (2013), finally, report oscillation of the iris with smaller amplitude than pupil PSOs, resembling c-PSOs. The latter is unsurprising because both c-PSOs and iris PSOs are related to structures that have almost identical locations and sizes. The previous results are in agreement with signals of Fig. 2 from Tabernero and Artal (2014). They show results of a custom built optical device (Dynamic Purkinje-meter). In their figure PSO-amplitude is smallest for the P1 signal (probably comparable but NOT identical to a scleral coil signal or limbus tracker signal), PSO-amplitudes are larger for the pupil signal (comparable to the video eye tracker signal), and the largest for the signal representing lens movements (comparable to the dpi-signal). Here a simple rule seems to apply: the longer the chain of visco-elastic structures between the point where the muscles attach to the globe and the structure measured by the eye tracker, the larger the post saccadic overshoots. In this view, the complicated v-PSO-shapes reported in this study may be the result of an oscillation (already present at the level of the globe) fed to the iris, resulting in a complicated oscillation of the inner iris border.

### 9.4. The proper test for the gentle braking hypothesis

Based on the results in experiment 2 we did not reject the gentle braking hypothesis. That does not necessarily mean that v-PSO is caused by abruptly decelerating eyes, and a more direct test of the relation between v-PSO amplitude and deceleration of the eyeball at the end of a saccade would be desirable. We looked to deceleration in our signals, but our v-signals do not show deceleration of larger structures of the eye, because low deceleration during that episode of the saccade is masked by the high deceleration and acceleration of the oscillating pupil. To conduct a proper test of the *gentle braking hypothesis* the eye should be tracked with two eye trackers simultaneously. One video eye tracker is required to track the pupil and a second eye tracker is required to measure a structure larger than the pupil or lens. The pupil based eye tracker will provide us with PSO amplitudes; the eye tracker measuring the larger structure should provide us with the deceleration values at the end of the saccade. We would not reject the gentle braking hypothesis if PSO amplitude decreases with decreasing deceleration values. This second eye tracker should be able to measure saccades from a large range because the saccades involved in the test must be large enough to slow down at the end not to cause v-PSO. We have no preference for coils because they are suspected to slow down large saccades (Frens & Van der Geest, 2002). Good candidates for the second eye tracker are a limbus tracker or a video-tracker that tracks the iris. Both suggested eye-tracking methods are limited to horizontal saccades. The results of this hypothetical experiment can also be used for modeling pupil movements relative to the globe (or iris).

## 10. Conclusion

We investigated PSOs for small and large saccades in the horizontal and vertical directions with two video eye trackers that are known for their good quality. PSOs decrease with increasing saccade size. They are reproducible within observers and depend on observer, saccade size and saccade direction. We elaborated on how that v-PSOs are harmful for determination of the saccade end, and we have as yet no solution for this problem.

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