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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.

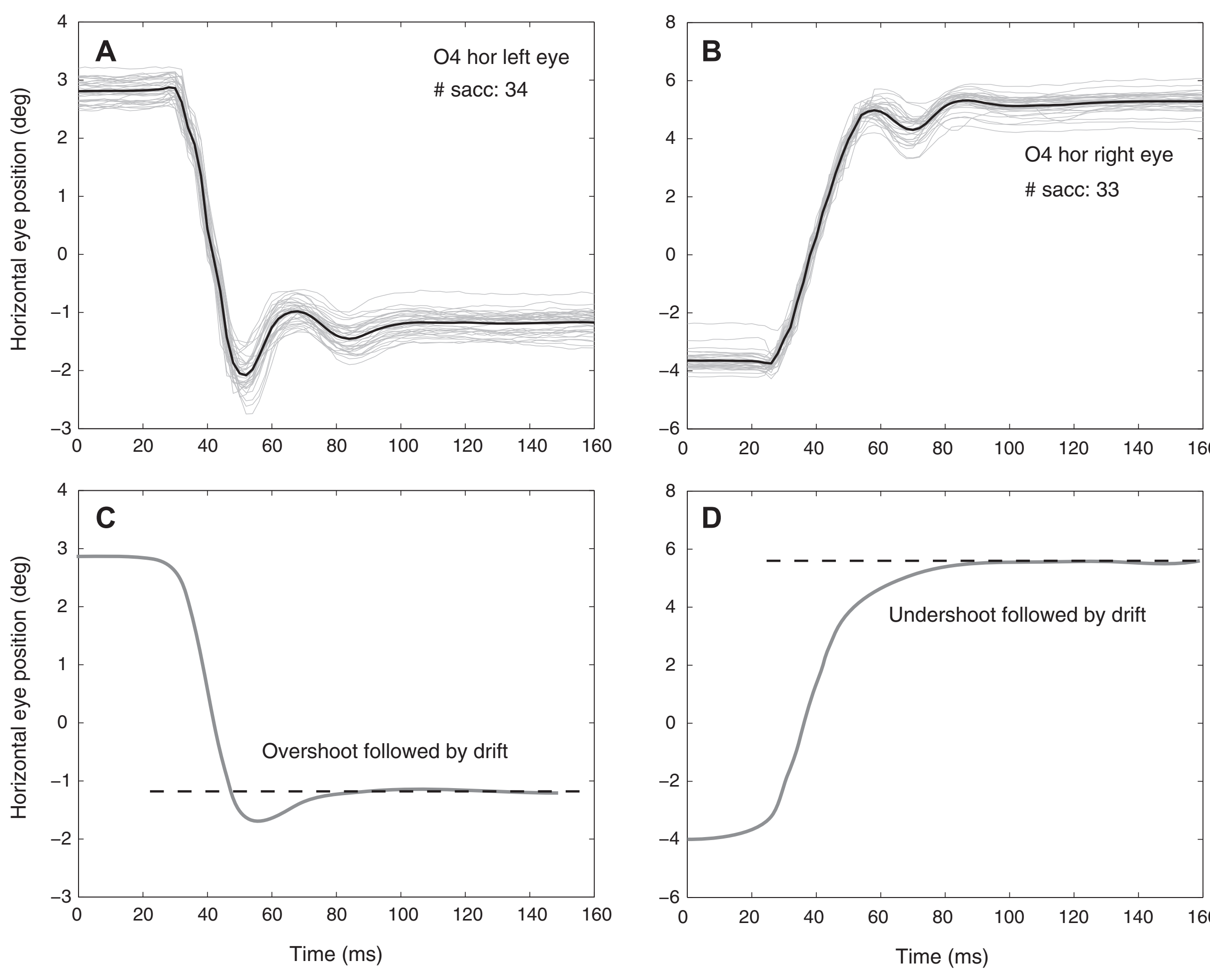

Fig. 1. Saccades of observer O4. Grey lines in A and B denote individual saccades, the thick black lines denote the mean of 34 saccades in A and 33 saccades in B (note the different *y*-axes). (C) Depicts a hypothetical saccade without PSO modeled after the saccades of A. Panel D depict hypothetical 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.