Vision Research 118 (2016) 17–24

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Why have microsaccades become larger? Investigating eye deformations and detection algorithms

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ARTICLE INFO

Article history:
Received 21 July 2014
Received in revised form 15 November 2014
Available online 4 December 2014

Keywords:
Eye tracking
Microsaccade
Dynamic overshoot
Eye deformation
Event detection
Ocular structure

ABSTRACT

The reported size of microsaccades is considerably larger today compared to the initial era of microsaccade studies during the 1950s and 1960s. We investigate whether this increase in size is related to the fact that the eye-trackers of today measure different ocular structures than the older techniques, and that the movements of these structures may differ during a microsaccade. In addition, we explore the impact such differences have on subsequent analyzes of the eye-tracker signals. In Experiment I, the movement of the pupil as well as the first and fourth Purkinje reflections were extracted from series of eye images recorded during a fixation task. Results show that the different ocular structures produce different microsaccade signatures. In Experiment II, we found that microsaccade amplitudes computed with a common detection algorithm were larger compared to those reported by two human experts. The main reason was that the overshoots were not systematically detected by the algorithm and therefore not accurately accounted for. We conclude that one reason to why the reported size of microsaccades has increased is due to the larger overshoots produced by the modern pupil-based eye-trackers compared to the systems used in the classical studies, in combination with the lack of a systematic algorithmic treatment of the overshoot. We hope that awareness of these discrepancies in microsaccade dynamics across eye structures will lead to more generally accepted definitions of microsaccades.

1. Introduction

1.1. Why are microsaccades interesting to study?

Microsaccades have been studied since the early 1950s, and we know today several important aspects of their relation to visual and neural processes, which are comprehensively reviewed elsewhere (Collewijn & Kowler, 2008; Martinez-Conde, Macknik, & Hubel, 2004; Rolfs, 2009). Still, there is a debate whether they serve an essential role or are merely noise in the oculomotor system (Collewijn & Kowler, 2008). One reason for the intensity of this debate may be due to the lack of a generally accepted description of the exact spatial and temporal characteristics of a microsaccade. The aim of this paper is to understand why it is so hard to agree on the shape of microsaccades and propose an explanation to why their appearances have changed so dramatically over time.

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http://dx.doi.org/10.1016/j.visres.2014.11.007

1.2. What do microsaccades look like?

At the coarsest level, microsaccades are "small, fast, jerk-like eye movements that occur during voluntary fixation" (Martinez-Conde, Macknik, & Hubel, 2014). Compared to voluntary saccades, microsaccades generally have smaller amplitudes and a proportionally larger overshoot (Møller, Laursen, & Sjølie, 2006; Zuber, Stark, & Cook, 1965).

Even though the overall shape of microsaccades is generally agreed on, there are several basic properties where remarkably different values can be found in the literature. Most prominently, the possible range of microsaccade amplitudes has been debated. One of the strongest opinions is expressed by Collewijn and Kowler (2008) who—supported by the majority of work until about 1980—argue that the upper limit of microsaccade amplitude is about 10–12 min arc, and that it "distorts the nature of the debate" to call saccades larger than 0.5 degrees microsaccades. On the contrary, one degree is today perhaps the most common threshold used to reject too large microsaccades (Engbert & Kliegl, 2004), but even those with a size of two degrees have been considered (Martinez-Conde, Macknik, Troncoso, and Dyar, 2006). In line with these examples of early and late reports of microsaccade amplitudes and as mentioned in previous review papers on microsaccades, Fig. 1 illustrates how the mean amplitudes have changed over time from the 1950s until today. The different types of symbols represent whether the eye-tracking data are best approximated by features investigated in this paper: the first Purkinje reflection (P_1), the fourth Purkinje reflection (P_4), and the pupil. We consider data recorded with the optical lever technique as well as scleral search coils equivalent to tracking the P_1 in the sense that all three methods correspond to eyeball rotation. Along similar lines, the P_4 reflects movement of the lens and is therefore equivalent to data recorded with a dual Purkinje eye tracker. Finally, the video systems[1] of today estimate the gaze direction from the location of the pupil center, and therefore output 'pupil equivalent' data.

While it remains unclear why the microsaccade amplitudes have become larger in recent studies (Rolfs, 2009), a number of plausible hypotheses has been provided. Perhaps the most apparent hypothesis is that the techniques to record eye movements have moved from analog systems providing very high precision and accuracy to video systems that are restricted by the spatial and temporal resolution of the video camera. Data from an EyeLink II, which is perhaps the most commonly used system in microsaccade studies over the past decades, was used to show that the detection of 5 min arc saccades is unreliable due to noise in the signal, but it was also emphasized that this does not explain why the maximum size of microsaccades has become larger (Collewijn & Kowler, 2008). Five min arc exceeds the average microsaccade size of 4.5 min arc reported in early work. Other possible explanations they discuss include differences in the amount of head movements (e.g., bitebar versus chinrest), changes in behavioral strategies due to contact lens wear, and differences in visual recording environments. In addition, it has been suggested that the inclusion of naive participants could be a major factor to why we now see larger microsaccades; the classical works used participants—usually the authors—who were highly trained in fixating, and possibly had a higher fixation stability (Collewijn & Kowler, 2008; Rolfs, 2009). This is supported by Winterson and Collewijn (1976), who found that naive subjects can easily be trained to suppress their microsaccades, although it is not clear to what extent the amplitude of the microsaccades changed.

1.3. Understanding the origin of the eye-tracker signal

To understand the signal generated by modern video systems the whole process—from image capture to the detection of a microsaccade—must be considered. The majority of video systems detect the pupil and one or several corneal reflections (CRs) in the eye image, and use these features in combination with a calibration procedure to estimate where people look (Hansen & Ji, 2010; Holmqvist et al., 2011). The exact eye and gaze models used by the systems are however typically proprietary and we therefore consider the eye tracker a 'black box', which is defined by its input (eye image) and output (t, x, y, pupil size). The eye-tracking data typically undergo some kind of post-processing, either within the black box or provided as an option to the user during or after the recording. Common examples are the Heuristic filters in the EyeLink-family of eye trackers (Stampe, 1993). Filtering is also necessary in conjunction with numerical differentiation to compute velocity and acceleration from the eye movement position data. Finally, before the parameters of a microsaccade can be calculated, a decision of where it starts and ends needs to be made, known as event detection.

[1] video systems refer in this paper to video-based eye trackers that use the pupil along with the corneal reflection(s) to estimate the gaze direction.

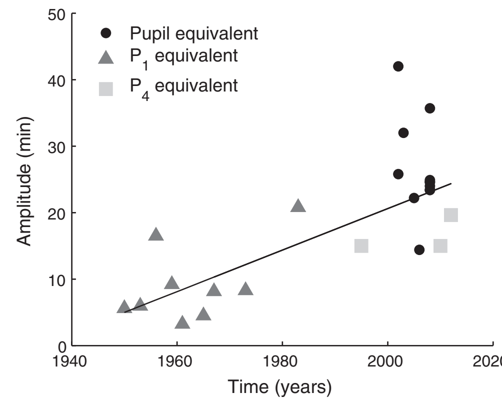

Fig. 1. Microsaccade amplitudes in a pseudorandom selection of articles between 1950 and 2012. Each dot represents the average microsaccade amplitude reported in an article. The line is the result of a robust regression (`robustfit` in Matlab) of the data showing the trend of increasing amplitudes.

1.3.1. Microsaccades and event detection

In the classical studies between 1950 and 1970 using the optical lever technique, the record of eye movement was stored on film and manually inspected to detect the microsaccades (Steinman, 1965). For instance, Cunitz and Steinman (1969) write that we counted the number of microsaccades that occurred during pauses in normal reading. While they used an amplitude criterion to separate between saccades and microsaccades, there was no mention of the exact computation of onset, offset, or amplitude, even though results including amplitudes were reported. In general, articles from this era contained very few, if any, details about the precise criteria used detect the microsaccades as well as how to compute the basic measures reported in the papers.

In more recent years, computer algorithms have been used to find the interval that the microsaccade spans along with basic parameters such as amplitude, duration, and peak velocity. The most widespread algorithm defines microsaccades as samples that exceeds a certain peak velocity for a minimum amount of time (t_{min}) (Engbert & Kliegl, 2003; Engbert & Mergenthaler, 2006). The velocity thresholds are applied separately in the horizontal and vertical dimensions, and set as a multiple (λ) of the estimated noise level in the data. Common choices of the thresholds are $\lambda \in \{4, 5, 6\}$ and $t_{min} \in \{6, 12\}$ ms. To reduce the number of erroneous detections a binocularity criterion can be applied such that only microsaccades that occur simultaneously in the left and the right eyes are considered.

Several papers address the problem that overshoots cause in the detection of microsaccades. Due to its large velocity, the overshoot often gets detected as a separate microsaccade directly following the primary microsaccade. As an example, one paper contains the sentence "We identified dynamic overshoots as saccades that occurred less than 20 ms after a preceding saccade (Møller, Laursen, Tygesen, & Sjølie, 2002) and did not consider them as new saccades" (McCamy, Jazi, Otero-Millan, Macknik, & Martinez-Conde, 2013b).

1.3.2. The non-elastic eye and tracking different structures

To be able to understand and interpret the eye-tracker signal we also need to consider the fact that the eye is not a rigid object, but deforms during high accelerations and should be considered as a set of ocular structures that do not move synchronously. The most prominent example of when a structures moves relative to the eyeball is perhaps the overshoots in Dual Purkinje eye-trackers (DPIs), which originate from the fact that the lens is attached to elastic zonular fibers, which make the lens continue to move and oscillate even after the eyeball has come to a stop (Deubel &