Evaluation of velocity-based saccade detection in the SMI-ETG 2W system

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Introduction

We present an analysis of velocity-based saccade detection in data recorded from a new mobile eye-tracking system (SMI-ETG 2W) with sampling rate of 120 Hz. We applied an algorithm developed for the detection of microsaccades from noisy data. Parameters of the algorithm were selected based on statistical analyses using surrogate data and velocity-amplitude correlations of the main sequence for saccades. Results on saccade amplitudes and fixation durations are compared to published benchmark dataset obtained from a desktop eye-tracking system with a sampling rate of 1000 Hz. We conclude that velocity-based saccade detection can be applied to the new system reliably.

Experimental methods

Stimuli and design

A set of 30 images of natural scenes (Engbert, Trukenbrod, Barthelmé, & Wichmann, 2015)[1] was presented to human observers on a projection screen at a distance of 210 cm using a video beamer. Image width (90 cm) and height (120 cm) were chosen in order to reproduce the viewing angle of the original study, where images were displayed on a CRT monitor. Images framed by white color were presented in a dark room.

Procedure

Each participant was required to keep her or his gaze on the projection screen, while standing in front of the screen. A 3-point calibration was done at the beginning of the experiments and before each 9th image. Data recorded by the scene camera were monitor by an operator/instructur to prevent participants to turn their heads away from the image area of the projections screen. Each image was presented for a duration of 10 s. Participants were instructed to explore the images for a memory test at the end of the experiment.

Apparatus

Eye movements were recorded using a prototype of the SMI-ETG 2W (SensoMotoric Instruments, Teltow, Germany) with a sampling rate of 120 Hz. Raw gaze coordinates from the scene-camera display were transformed to image coordinates using a projection provided by the computer vision toolbox of the MATLAB (The MathWorks, Natick/MA, USA) programming language.

[1] See `https://engbertlab.shinyapps.io/SceneWalk/`

Participants

Ten students of the University of Potsdam with normal or corrected-to-normal vision were tested. All participants received course credit or a payment of 10 EUR and were naive with respect to the purpose of the experiment. The experiment conformed to the Declaration of Helsinki.

Benchmark data

All images were used in an earlier study (Engbert et al., 2015), where 35 human observers were tested in a scene-viewing task. Eye movements were recorded binocularly with an Eyelink 1000 video-based eye-tracker (SR Research, Osgoode/ON, Canada) with a sampling rate of 1000 Hz (see Engbert et al., 2015).

Saccade detection

Our saccade-detection procedure was motivated by the observation that, in current mobil eye tracking devices with a sampling rate of 60 or 120 Hz, the number of data samples during a saccade is approximately 3 to 6, which is comparable to the number of samples obtained from a laboratory-based desktop system (500 to 1 000 Hz) during a microsaccade. Thus, we set out to explore the possibility for velocity-based saccade detection in the SMI-ETG mobile device.

Application of the binocular microsaccade algorithm

Saccade detection was performed with a velocity-thresholding algorithm developed for the detection of microsaccades (Engbert & Kliegl, 2003; Engbert & Mergenthaler, 2006)[2]. In a first step of the detection procedure, we estimate eye velocities from eye-tracking data. Since experimental data from video-based eye-tracking systems are contaminated by observational noise, we apply a running-average filter of the form

$$\vec{v}_n = \frac{\vec{x}_{n+2} + \vec{x}_{n+1} - \vec{x}_{n-1} - \vec{x}_{n-2}}{6\Delta t} \;, \tag{1}$$

which computes velocity samples from 5 subsequent data samples.

Second, a threshold velocity for saccade detection in 2D velocity space is computed, separately for horizontal and vertical velocity components using estimators for the fluctuation ranges, σ_x and σ_y, defined as

$$\sigma_{x,y} = \sqrt{\langle (v_{x,y} - \langle v_{x,y} \rangle)^2 \rangle} \;. \tag{2}$$

The brackets $\langle . \rangle$ denote the median estimator of the fluctuations, which is important to suppress a potential bias from high-velocity samples during microsaccades. The detection thresholds $\eta_{x,y}$ are chosen as multiples of the fluctuation ranges,

$$\eta_{x,y} = \lambda \sigma_{x,y} \;, \tag{3}$$

where λ is a free parameter for the detection algorithm that needs to be chosen appropriately.

[2]See `https://engbertlab.shinyapps.io/Microsaccades/`

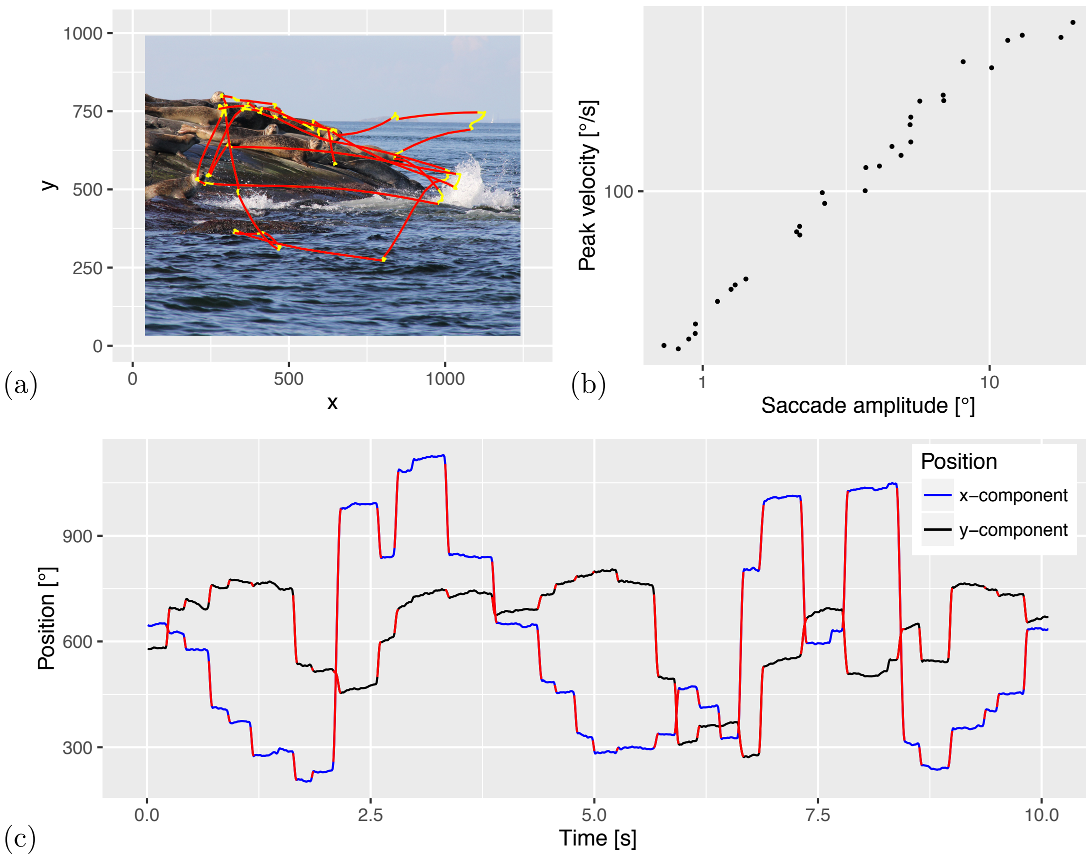

Figure 1. Application of velocity-based saccade detection to a single experimental trial. (a) Sample image and gaze trajectory (yellow=fixations, red=saccades). (b) Main sequence of peak velocity against saccade amplitude (log-log plot). (c) Horizontal (blue) and vertical eye position (black) over time with saccades indicated by red color.

Third, we identify all data samples with velocities higher than the threshold, Eq. (3). For these data samples k, the test function $t(k)$ has the property

$$t(k) = \left(\frac{v_{k,x}}{\eta_x}\right)^2 + \left(\frac{v_{k,y}}{\eta_y}\right)^2 > 1 \; . \tag{4}$$

In the fourth step, we consider only *binocular* events, i.e., microsaccades occurring in both eyes with a temporal overlap of at least one data sample. Consider a sequence of data samples (a candidate sequence) recorded from the right eye, where the eye's velocity is above threshold between time r_1 and time r_2. We can easily find overlap with the left eye beginning at time l_1 and ending at l_2 by the inequalities

$$r_2 \geq l_1 \qquad \text{and} \qquad r_1 \leq l_2 \; . \tag{5}$$

We applied our algorithm to the raw eye position data of left and right eyes recorded with the SMI-ETG 2W system. We used a minimum duration of 3 subsequent samples to identify

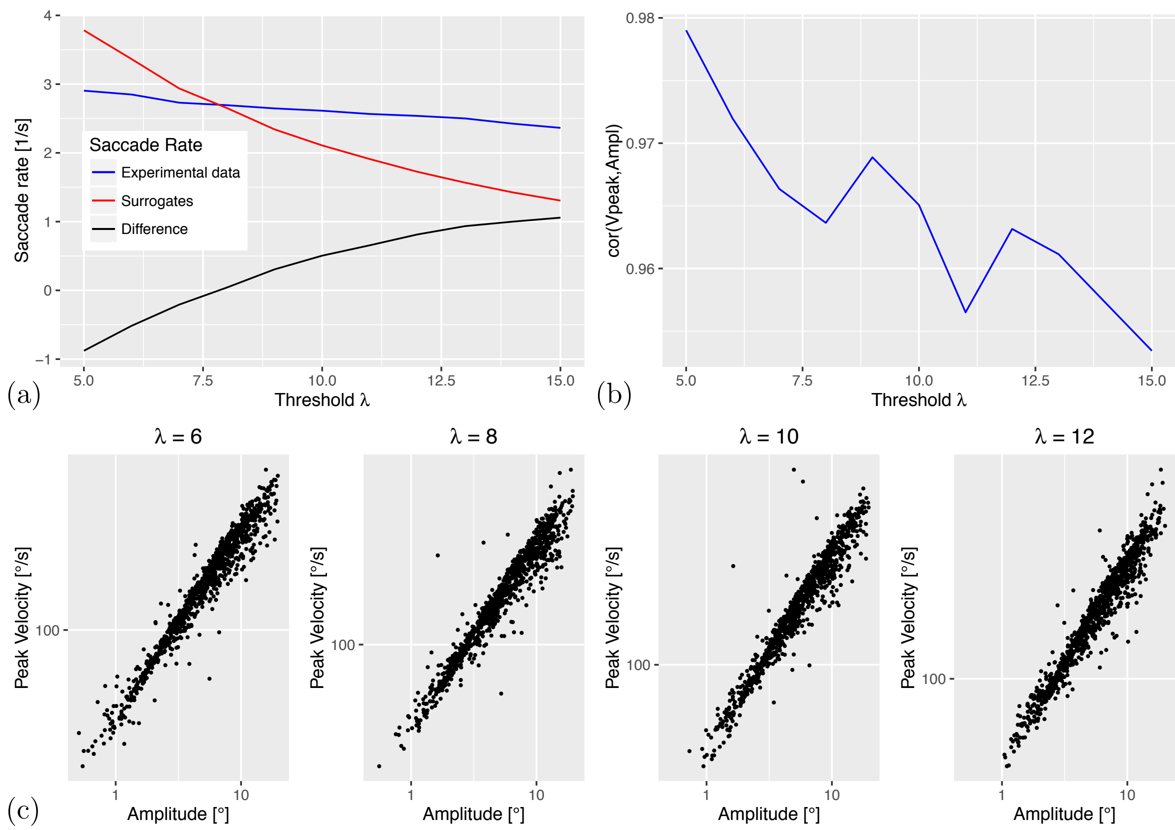

Figure 2. Statistical evaluation of the detection algorithm. (a) Surrogate data analysis obtained from constrained randomization (see text). (b) Correlation of the main sequence as a function of λ. (c) Double-logarithmic plots of the main sequence for four different value of lambda.

monocular candidate epochs for saccades, Eq. (4). The most important parameter of the detection algorithm is the threshold multiplier λ, Eq. (3). We started with a value $\lambda = 8$. A statistical evaluation will be presented below. After application of the binocularity criterion, Eq. (5), we obtained saccade sequences that are highlighted by red color in Figure 1a,c. The main sequence of peak velocity as a function of saccade amplitude (Fig. 1b) indicates a high correlation in a double-logarithmic plot ($r = 0.992$)

These results indicate that velocity-based saccade detection might be viable alternative to fixation-detection algorithms that are typically used in mobile eye-tracking device with low sampling rate (< 100 Hz). Next, we carried out a systematic analysis with varying threshold multiplier λ to identify detection parameters for obtaining robust results.

Statistical analysis using surrogate data and main sequence

To evaluate the robustness of our algorithm and the parameter dependence of the results, we varied the threshold multiplier λ (Abedian-Amiri, Trukenbrod, & Engbert, 2015). The four panels of Figure 2c show main sequences for different values of λ. The correlation of the logarithm of peak velocity and the logarithm of saccade amplitude are plotted as a function of the threshold multiplier λ in Figure 2b. Results indicate that the main sequence correlation is robust and does

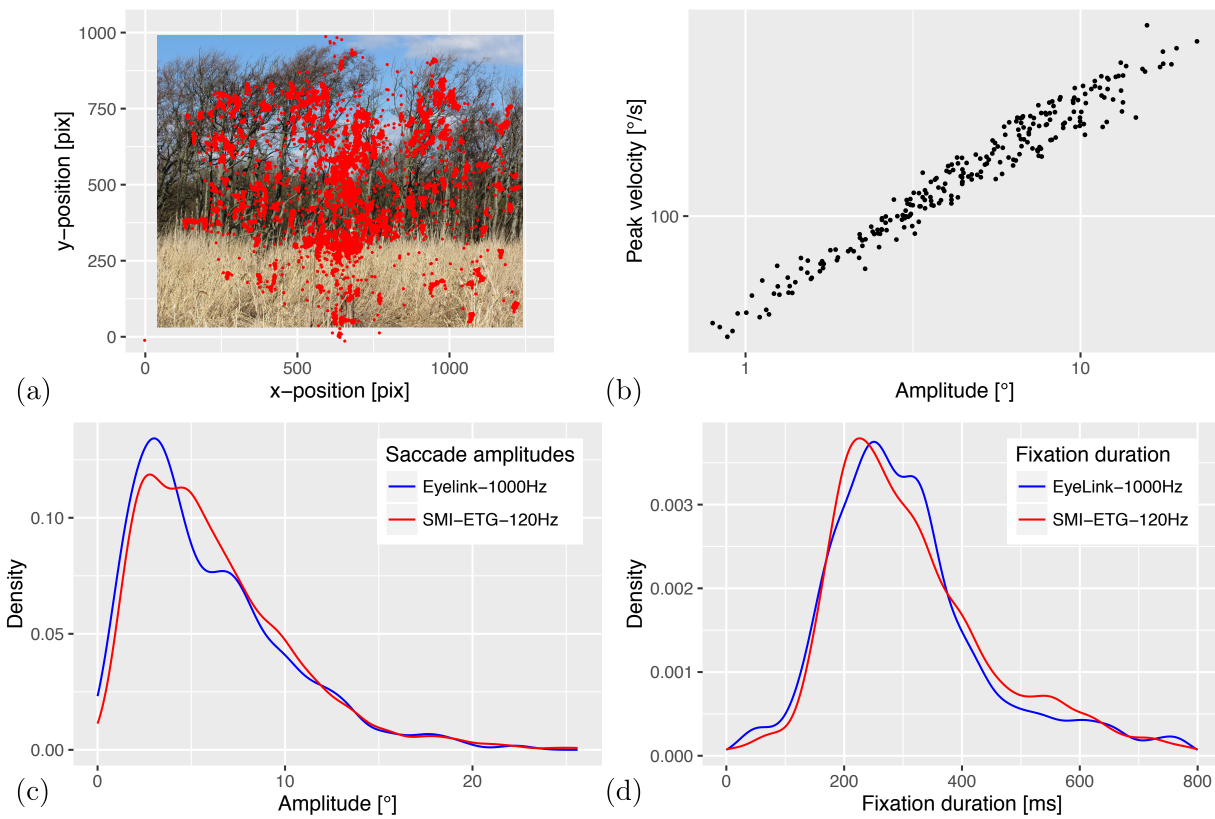

Figure 3. Statistics of fixations and saccades in comparison to a benchmark study. (a) Fixations of all participants indicated by red dots on a sample image of the study. (b) Main sequence (double-logarithmic plot). (c) Distribution of saccade amplitudes (red=SMI-ETG, blue=Eyelink-1000). (d) Distribution of fixation durations.

not depend sensitively on the choice of the value for λ.

Next we carried out an analysis of the detection algorithm based on surrogate data. For each trial, we computed surrogate data from constrained randomization (Engbert & Mergenthaler, 2006). In this procedure, random permutations of eye velocity sample were computed under the constraint of reproducing the autocorrelation function of the velocity samples. Saccadic events detected in these surrogates are counted as false detections. The number of false detections was compared to the number of detections in the experimental data. Results indicate (Fig. 2a) that more saccades are detected in the experimental data than in the surrogate as long as $\lambda \geq 8$. Therefore, we identified a threshold multiplier of $\lambda \approx 8$ as the smallest value for obtaining reliable results.

We also ran an analysis (not reported here) using binocular data that indicated a high number of false detections over a very broad range of λ values. Thus, our statistical results lend support to a binocular detection procedure.

Distributions of saccade lengths and fixation durations

To evaluate data quality and the reliability of detected events (i.e., saccades), we compare distributions of saccade amplitudes and fixation durations obtained from the SMI-ETG 2W with results from a published study (Engbert et al., 2015). Figure 3 presents statistics of fixations and saccades. Fixations of all participants are shown in Figure 3a. The main sequence (Fig. 3b) for saccades of all participants indicates a high correlation of $r = 0.979$. The distribution of saccade amplitudes obtained from the SMI-ETG system is in remarkably good agreement with the benchmark data (Fig. 3c). The same is true for the distribution of fixation durations (Fig. 3d).

Summary

We investigated velocity-based saccade detection based on a binocular algorithm (Engbert & Kliegl, 2003; Engbert & Mergenthaler, 2006) that was originally proposed for the detection of microsaccades. The main results are summarized in the following five statements:

1. The new 120 Hz eye-tracking technology permits the use of a velocity-based saccade detection procedure (Engbert & Kliegl, 2003; Engbert & Mergenthaler, 2006) originally developed for the detection of microsaccades.

2. Statistical analyses using surrogate data indicate that saccades of all sizes above the micro-range (i.e., mean amplitude $> 1°$) can be identified reliably.

3. Analyses of surrogate data also show that binocular saccade detection is more robust than a monocular procedure based on the binocular output of the eye-tracking system.

4. A comparison of saccade amplitudes and fixation durations with results from a benchmark dataset (Engbert et al., 2015) indicates that distributions of saccade amplitudes and fixation durations are in good agreement with results from desktop systems with higher sampling rates.

Our preliminary analyses of saccade lengths and fixation durations show that the 120 Hz SMI-ETG 2W system might represent an alternative technology to desktop systems for high-resolution eye-tracking research.

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