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Saccade detection during smooth tracking

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ABSTRACT

Saccade detection in an eye-movement trace provides a starting point for analyses ranging from the investigation of low-level oculomotor mechanisms to high-level cognitive processes. When the eye tracks the motion of the object of current interest (smooth pursuit), of the visual background (OKN), or of the resultant visual motion from a head movement (tVOR, rVOR), the smooth tracking movement is generally intermixed with rapid-phase saccadic eye movements, which must be excised to analyze the smooth components of tracking behavior properly. We describe a simple method to detect saccades on a background trace of variable velocity, compare our saccade-detection algorithm with the performance of an expert human observer, and present an ideal-observer analysis to benchmark its detection performance.

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1. Introduction

Saccade detection in an eye-movement trace provides a starting point for analyses ranging from the investigation of low-level oculomotor mechanisms to high-level cognitive processes. For example, metrics provided by the saccadic main sequence [1,2] allow for quantitative diagnosis of saccadic abnormalities [3]; intra-saccadic intervals define fixation duration, dwell time, and scanpath information useful to address perceptual or cognitive processing [4–7]; the proportion or frequency of saccades during smooth movement can be used as metrics to assess VOR failure [8], smooth pursuit pathology [9,10], or to evaluate display motion quality [11,12]. Filters for saccade detection have been developed and refined over several decades [13–16], often adjusted according to the experimental question and the eye-tracker signal quality at hand. In this paper, we propose a novel method designed to detect saccades superimposed on smooth tracking recorded using non-invasive video-based eye trackers (typically with position noise levels of more than a tenth of a degree). Previous methods using velocity and/or acceleration thresholds [15,17] work quite well with invasive eye tracking systems (e.g., eye coils) with eye-position noise on the order of a hundredth of a degree, but cannot be used robustly with video-based tracker data.

The smooth eye-movement responses to the motion of the object of current interest (smooth pursuit), of the visual background (OKN), or of the observer's head (tVOR, rVOR) is generally intermixed with rapid phase saccadic eye movements. To extract the information about cognitive, perceptual, and oculomotor function associated with saccades, a robust signal-processing method is needed to detect saccadic "pulses" superimposed on a background of varying "smooth" velocity [18], especially when the background velocity distorts the familiar saccadic velocity profile (e.g., catch-back saccades). Furthermore, correctly de-saccaded traces are an assumed starting point for any number of analyses of smooth movements: analysis of smooth tracking [19–21], perception–action linkages [22], assessment of visual stability during optokinetic nystagmus [23,24], or VOR compensation for translational [25–27] and rotational [8,28–30] head movements. To this end, we describe a simple method to detect saccades on a background trace of variable velocity, present an ideal-observer analysis to benchmark its detection performance, and compare our saccade-detection algorithm with the performance of an expert human observer on simulated trials with realistic background velocity profiles.

2. Algorithm

Our saccade-detection algorithm has three stages starting from the original eye-velocity trace (Fig. 1). The first stage uses a median filter to process the eye-velocity trace in such a way as to cancel out the velocity components related to smooth tracking. The second stage is a linear detector based on an ideal observer approach [31] that measures saccade likelihood at every sample during the movement, and uses a threshold parameter to flag potential saccade regions. The third stage is a clustering stage [32] to mitigate the effects of temporal uncertainty and tracker noise, and to reduce false alarms from noise transients.

2.1. Stage 1 – non-linear median filtering

Given a velocity trace at a known sampling rate, the first step is to estimate the smooth component of the oculomotor response

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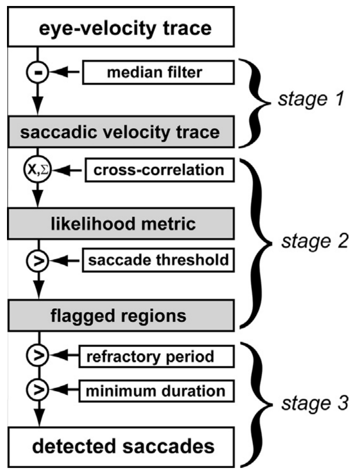

Fig. 1. Algorithmic steps. The first stage in the algorithm is to calculate the median filter, which is then subtracted from the original velocity trace to yield a saccadic velocity trace. The second stage takes the cross-correlation between the saccadic velocity trace and a saccade velocity template, yielding a likelihood metric. As the cross-correlation involves integration over time, the units of the likelihood metric are expressed in degrees rather than degrees per second; regions of the trace that exceed the threshold. The third stage compares the flagged regions against a minimum inter-saccadic refractory period and a minimum saccadic duration, combining nearby flagged regions and turning off regions less than a minimum duration. Regions that conform to these criteria are then detected as saccadic movements.

using a "median filter". The median-filtered trace is computed by sliding a window of odd size over the velocity trace, replacing each sample of the original trace with the median velocity inside the window [33], the size of which is one parameter of our algorithm. The output of this filter is then subtracted from the original velocity trace [34] yielding a "saccadic velocity" trace. Given a well-chosen window size, the median filter behaves similar to a low-pass filtered version of the original trace [8] except that the high-frequency saccadic velocity components remain largely intact, an interesting and critical nonlinear advantage of the median.

2.2. Stage 2 – linear template matching

We then take the cross-correlation between the eye-velocity trace and a saccadic velocity template as in similar approaches [13], which yields a likelihood metric [31] for saccade occurrence. The saccade-velocity template [35]

$$Velocity\_template(t) = \frac{35 \cdot amp}{16 \cdot duration}\left(1 - \frac{4t^2}{duration^2}\right)^3 \quad (1)$$

is scaled such that the value of the likelihood metric approximately equals the estimated saccade amplitude.

$$scale\_factor = \frac{\int velocity\_template}{sampling\_frequency \cdot \int velocity\_template^2} \quad (2)$$

Because the cross-correlation involves integration (i.e., the dot product of the saccade template and a template-sized window around each sample in the velocity trace), the units of the likelihood metric are expressed in degrees rather than degrees per second. Portions of the eye-movement trace where the likelihood metric exceeds the threshold are then flagged using the threshold parameter, specified in degrees.

2.3. Stage 3 – non-linear clustering

Brief flagged regions occurring in rapid succession less than a minimum refractory period apart are combined into a unified sac-

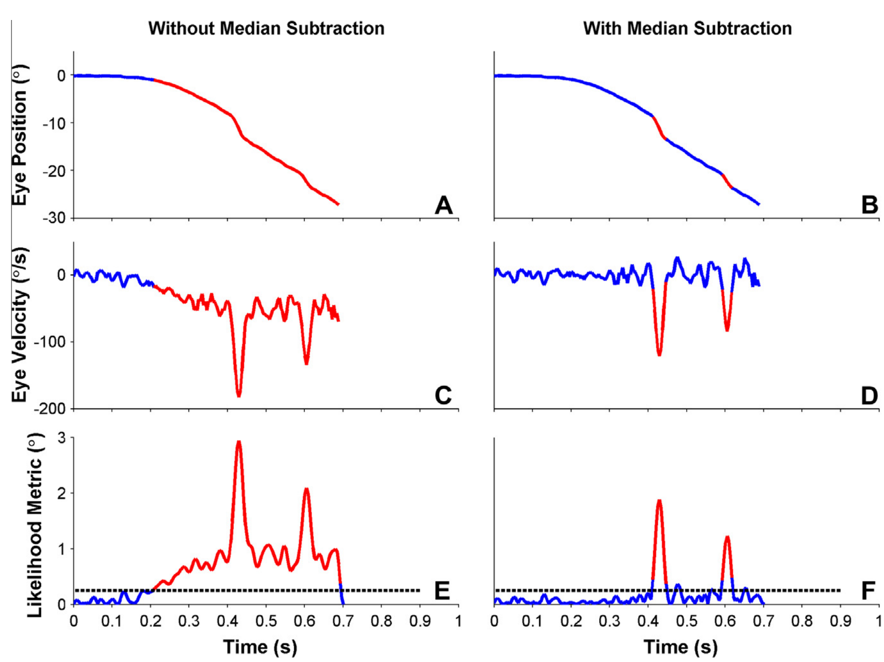

Fig. 2. Effect of median filter on detection of saccades during tracking. A–B plot one horizontal eye-position response to a 80 deg/s moving target spot containing pursuit and saccades detected (solid red) without (A) and with (B) median subtraction, sampled at 240 Hz with a video-based ISCAN tracker. Velocity traces are generated by applying a FIR low-pass differentiating filter (−3 DB at 32 Hz) to eye position. These filtered velocity traces are an attempt to isolate the velocities associated with saccadic movements, which is done much more successfully with the median filter (D) than without (C), illustrating the difference between the "saccadic velocity trace" (D) and the velocity trace containing both smooth and saccadic components (C). E–F plot our saccade likelihood metric showing how simple thresholding can cleanly detect saccades in the median filter case. The median filter allows the resolution of the three separate saccades along with minimization of any false positive portions of the trace (caused by tracker and biological noise). For this example, the width of the median filter was set to 170 ms (41 samples), the threshold (dashed black line) was set to 0.25° and the minimum saccade duration was 16 ms. On standard desktop hardware (3.2 GHz CPU), the Matlab implementation of this detection algorithm requires 226 ms of computation time for this ∼2 s trial (1.3 s fixation period not shown).

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