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A method for automatic identification of saccades from eye movement recordings

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Abstract

We describe a technique for reliable and rapid automatic identification of saccades in eye movement records. The signal processing that we describe will be useful to anyone wanting to analyse large numbers (thousands) of eye movements. We describe a transform that is derived from the differentiated eye movement record, and which is related to a transform previously used to automate analysis of EMG recordings.

Keywords: Saccade; Automatic identification; EMG analysis

1. Introduction

We have previously demonstrated (Marple-Horvat and Gilbey, 1992) a linked double window technique that reliably identifies onset and offset of bursts of activity in EMG records, and present here a variation of that technique which is capable of routinely performing the large amounts of data analysis that is implied by long records of eye movement activity in behaving subjects. We have successfully used this technique to rapidly extract amplitude and timing of the large numbers of saccades (more than 10000) that are present in many hours of eye movement records. Our main interest was the accurate identification, and timing and amplitude measurement, of saccades in eye movement records containing a complex mixture of slow (pursuit or reflexly generated) eye movements and saccades obtained from walking subjects, whereas other techniques have been mainly concerned with removal of saccades. Ebisawa et al. (1988) used several stages of filtering which affected the duration and velocity profile of saccades, followed by complex procedures to generate a velocity threshold ideally suited to a sinusoidal tracking task (where expectations about the eye movements made were used) but not readily adaptable to a general situation. The sophisticated technique used by Engelken and Stevens (1990) based on order-statistic filters does not appear to outperform our method, which has the same advantages of no requirement for detailed assumptions concerning signal structure of the eye movement record, the ability to operate on unscaled (not calibrated) data, and equally operates primarily on local signal properties by use of a linked double window that scans through the data; and the method they describe is clearly much more computationally demanding. So although other techniques for automatic analysis of eye movements exist, the simplicity and generality of our method makes it an attractive and useful alternative: it is easily implemented on a modest PC, rapidly computed and as a result enormously time-saving.

2. Methods

2.1. Electrooculography

We monitor eye movements using both infra-red reflectometry (IR) and electrooculography (EOG) in walking subjects (Hollands et al., 1995). We obtain good quality EOG recordings using bought self-adhesive disc electrodes (10 mm diameter Ag/AgCl set in adhesive conductive gel; neonatal ECG electrode Biotrace-NS, 0713, MSB Ltd.) placed at the outer canthi for horizontal EOG. These have proved dependable and easily placed, but are a little heavy and large for optimal positioning for vertical EOG, just above and below the eye as close to the eyelid as possible.

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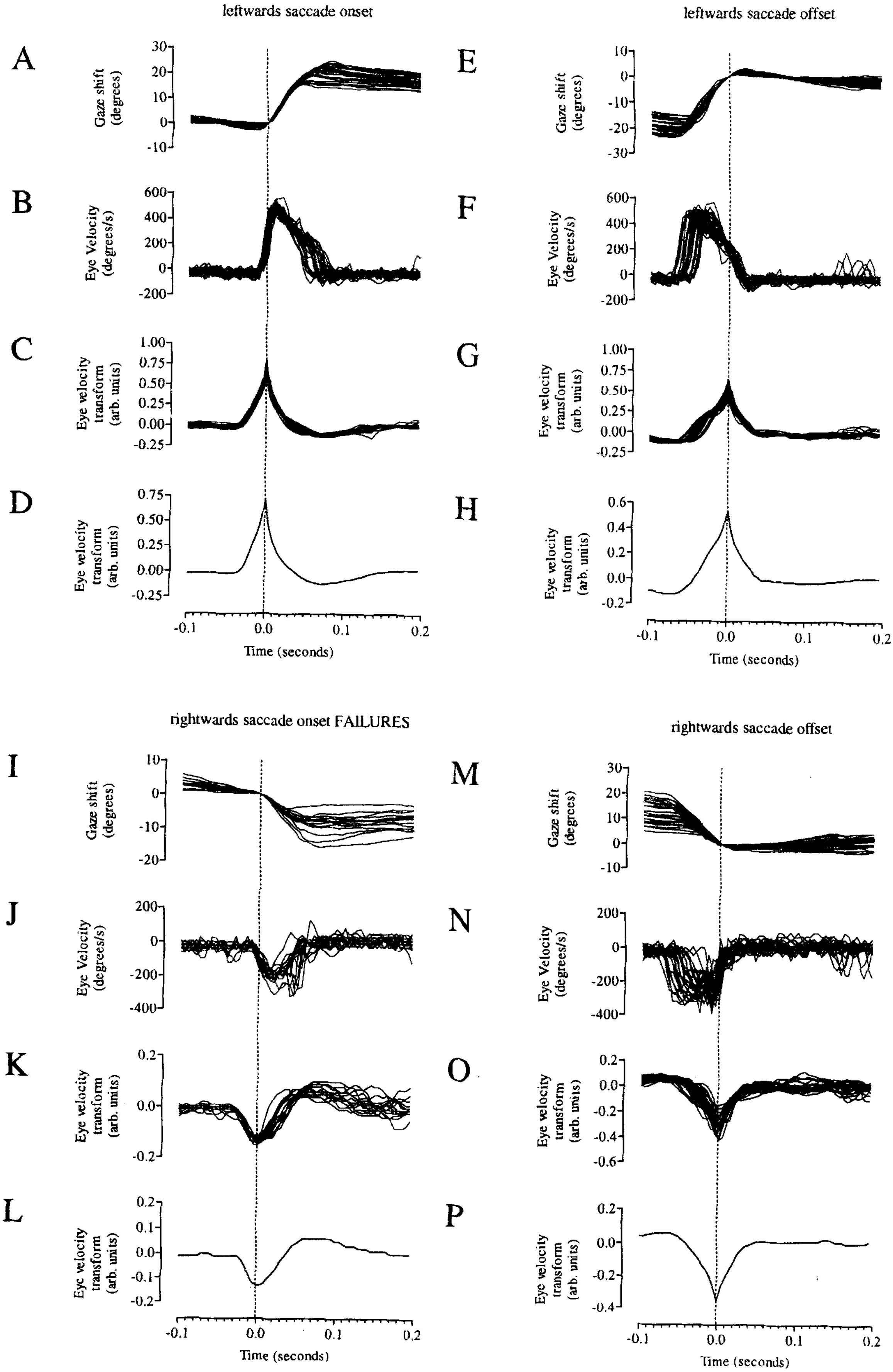
leftwards saccade onset
leftwards saccade offset
A
B
C
D
E
F
G
H
Gaze shift (degrees)
Eye Velocity (degrees/s)
Eye velocity transform (arb. units)
Time (seconds)
rightwards saccade onset FAILURES
rightwards saccade offset
I
J
K
L
M
N
O
P
Gaze shift (degrees)
Eye Velocity (degrees/s)
Eye velocity transform (arb. units)
Time (seconds)

We have therefore used for vertical EOG smaller Ag/AgCl pellet electrodes (length 3 mm, diameter 1 mm, E205, Clark Electromedical Instruments) inlaid into a 5 mm × 15 mm strip of adhesive conductive gel cropped from the edge of the bought disc electrodes. All electrodes were further secured in place with millipore tape.

2.2. Data acquisition and signal conditioning

Both vertical and horizontal EOG (or IR) signals, together with contact signals to monitor left and right footfall patterns, were recorded on a modified Sony PCM/videorecorder (Applegarth Electronics) providing digital recording with a sampling rate of 3.75 kHz, and incorporating input filtering to 1 kHz (−6 dB point, 3rd order Butterworth). All signals were recorded down to true DC levels (i.e. no low cut). Signals were played back off the tape and digitised using a CED 1401 at 200 Hz (sampling interval 5 ms) for computer-based analysis (after verification from the Fourier transform (power spectrum) of the eye movement signal sampled at the higher rate of 1 kHz that this signal contained negligible power above 100 Hz).

Prior to saccade identification, signal processing was as follows. Digital differentiation was achieved using a fourth-order differentiator with the differential of the signal y at point i in the sampled eye movement record given by the following formula

$$\dot{y}_i = \frac{1}{12\partial t}\left\{y_{i-2} + 8(y_{i+1} - y_{i-1}) - y_{i+2}\right\}$$

where ∂t is the sampling interval (in s).

A narrow differentiator performed best, and the design principle with differentiators such as this, which is a finite impulse response (FIR) filter, is that they should operate on as few samples, or have as few coefficients/terms as give a good result (this differentiator, with four non-zero coefficients/terms obtains the derivative at i using the two preceding and two following signal values). Differentiators with different value coefficients, and different numbers of coefficients, can be obtained using standard methods (for further information, see Appendix A and Antoniou, 1993).

2.3. Identification of saccade onset and offset

Automatic identification of saccades (in any direction) was achieved using a variation of the linked double window technique previously described for automatic identification of bursts of activity in EMG records (Marple-Horvat and Gilbey, 1992). The double window must be of suitable width to gather information over a relevant period before and after the point under inspection as it scans through the differentiated eye movement (i.e. eye rotational velocity) record searching for saccades. The leading and trailing window are linked and move together. They are of unequal width: the leading window is 25 ms (5 samples) wide – looking ahead by this brief amount is appropriate for detecting the sharply rising high velocity peak of a saccadic eye movement. The trailing window is 75 ms (15 samples) wide – this looks back over a long enough portion of the eye velocity record for comparison with the leading window. Between saccades the 75 ms of record spanned by the trailing window will have consistently low velocity values. The junction between leading and trailing window (leading edge of trailing window and trailing edge of leading window) defines the point under inspection in the record.

The mean value of the signal is computed within each window (lwm_{25} and twm_{75}), and the difference between these obtained (leading minus trailing). This variable will peak (attain its maximum value) when the signal is consistently low in the trailing window and high in the leading. This situation arises when the leading window spans a (differentiated) leftwards saccade (in our recordings left and leftwards correspond to positive values), the trailing window spans a period of slow or no eye movement, and the junction between windows is aligned at the moment of saccade onset.

A local maximum of the 'difference between means' function, plotted against time, therefore develops at the start of the saccade. For the purpose of analysing EMG signals we divided the difference between means by a trailing window mean squared term, (twm^2_{25}). (Note that in that application the trailing window was the same width as the leading window, 25 ms.) This effectively suppressed peaks that would otherwise have arisen in the difference between means within EMG bursts, due to the spikey or 'noisy' nature of the signal within bursts. In this present application, such noisy bursts do not arise, rather the eye velocity signal rises rapidly and 'noise-free' from near-zero values at saccade onset. Division by (twm^2_{75}) is therefore not required, and indeed would prevent the difference between means function from rising to a sizeable peak (since when just a single sample in the trailing window is taken from the rapidly rising phase of the differentiated saccade, the term (twm^2_{75}) becomes very large). We have found that a much less severe divisor ($\sqrt[2]{|twm_{75}|}$) is opti-

Fig. 1. Individual (overlaid) traces of digitised eye movement records (A, E, I, M) together with corresponding eye velocity records (after differentiation, B, F, J, N) and transform records (onset transforms C, K; offset transforms G, O). Leftwards saccade onset and offset are illustrated top left and right (respectively) and rightwards saccade offset bottom right. 14 instances of failure to identify rightwards saccade onset are shown bottom left. Beneath individual traces are the average transform profiles for all such features in a 20 min record (D, H, L, P. n = 327, 330, 14, 247, respectively). For further information, see text.

mal, not to suppress peaks that would arise as a result of noisiness, but to suppress the negative going phase of the difference between means that develops at the end of the saccade (since the difference between means is akin to a differential of the velocity signal, each positive velocity peak generates a positive/negative 'acceleration' type transform). The requirement for effective suppression at the end of the saccade is another reason why the trailing window needs to be 75 ms (not less) in length. This suppression is required to avoid confusion with the negative going 'peaks' that arise at the start of rightwards saccades (which we also wish to identify, see below).

Fig. 1A shows (overlaid) 24 successive leftwards saccades from a portion of the digitised horizontal eye movement record (sampled at 200 Hz) and the corresponding differentiated eye velocity records in (B) together with the corresponding transform records generated by the equation

$$f(t) = k\frac{(\mathrm{lwm}_{25} - \mathrm{twm}_{75})}{1 + \sqrt[2]{|\mathrm{twm}_{75}|}} \tag{1}$$

in (C). The individual transform records have been aligned so that the maximum value in each is at time zero, and it can be seen that this results in the corresponding velocity and eye movement records being aligned at the moment of saccade onset. (D) illustrates the average transform profile of all the identified leftwards saccade onsets contained in the 20 min record.

Once the transform given by Eq. 1 has been generated, it is a simple task to identify its local maxima, i.e. the start times of leftwards saccades. We set a threshold level at (2 mean + 2.8 SD) of the entire transform record that was above zero (i.e. replacing negative values with 0; half-wave rectification), and identified the maximum value of the transform in the 50 ms period following a positive-going threshold crossing; the position of the maximum defined saccade onset. Technical note: Our program was written in Turbo Pascal, which imposes a limit for the length of arrays of 64 kbytes. At any time, the program is therefore operating on a block of data of length 32K samples (160 s with sampling interval 5 ms) and it is one such block that we mean by 'entire transform record', and for which mean and SD are calculated. The program serially processes any number of such blocks (calculating a new mean and SD for each) until it reaches the end of the raw data file (we usually digitise 20 min of data in each file).

Identification of the end of a leftwards saccade is by the same process, but scanning after time reversal of the differentiated eye movement file so that the double window scans through the data backwards. The lead window then encounters the end of the saccade in exactly the same way as it did the start of the saccade when passing in the usual, forward direction. The end of the saccade is then identified as described above. Fig. 1 (E,F) illustrate the same 24 superimposed individual traces of the raw saccades and the differentiated eye velocity profiles that are illustrated in (A–C), but (G) now shows the saccade offset transforms, and the eye movement and velocity records are now aligned at the end of the saccades. (H) is the average offset transform profile of all the identified leftwards saccade offsets contained in the record.

Finally, onsets of rightwards saccades (not illustrated in the figure) are identified from the times at which the transform attains its *minimum* value (as opposed to *maximum* for leftwards saccades) following a negative going threshold crossing, with the threshold set at (2 mean + 2.8 SD) of all the negative values in the transform (having replaced all positive values with 0, i.e. positive and negative thresholds determined separately). Following time reversal the ends of these rightwards saccades are identified; 24 individual successive saccades are illustrated in Fig. 1 (M–O), and the average transform profile for all rightwards saccades identified in the record in (P).

The program places an event marker upwards or downwards from zero at saccade onset and offset respectively, generating two channels of these markers, for leftwards and rightwards saccades separately (or for upwards and downwards saccades when operating on a vertical EOG record). We visually inspect these event markers against the eye movement and transform record to manually insert markers at saccades that have been missed or delete false positives. The failure rate is sufficiently low (typically between 1 and 5%) that this process is not unduly time consuming. The program writes to file lists of the timing of these markers, and signal values at those times, from which other measures such as saccade amplitude or duration can be rapidly computed in spreadsheets (we use Borland's Quattro Pro).

3. Discussion of errors and failure rate

A typical 6 min portion of eye movement record was analysed and yielded failure rates of < 1% (1/152), 5% (8/153) and 3% (3/135) in identifying leftwards saccade onset, leftwards saccade offset and rightwards saccade offset, respectively. Only 2 false positives were generated, the remainder were misses or failure to identify features that were judged by eye to be saccades. Assessing the failure rate for rightward saccade onset was more problematic. There were 14 occasions on which additional information led us to expect that a small oblique saccade including a rightwards component would be made between two close visual targets. Without the benefit of additional information, by visual inspection of the record alone it was not always possible to identify a clear saccade onset. The trace was sometimes ambiguous (7/14) with a smoothly increasing rate of rightwards eye rotation (to maintain target fixation during leftwards head translation) taking rotational eye velocity smoothly from low values (less than 50° s^{-1}) to those typically obtained within saccades. The 14 individual traces are shown superimposed in Fig. 1 (I–K), and the average transform profile in (L). The absence of a clear inflexion in 7 of the eye movement records means that neither automatic nor visual inspection of these records can identify a saccade. Rather than a failure of automatic analysis, these 7 occasions probably reflect more of an unwanted feature in experimental design. After exclusion of these records the residual failure rate (in which saccade onset could be identified by eye but was missed by the algorithm) was 5% (7/137). These failures are all small oblique saccades which have a low horizontal velocity component, and this results in a small transform peak which, although in the appropriate place, fails to reach the threshold for detection. It is worth noting that slow eye rotation (which may be reflexly driven) in one direction with interposed saccades in the *opposite* direction (as in slow and fast phase of nystagmus) yields the highest success rates of all (approx. 1% failures).

Our records do not contain sufficient numbers of small (2 or 3° or less) and therefore brief saccades to assess failure rates, but with a sampling interval of 5 ms on digitisation, it would be unsafe to count features of less than 15 ms (3 data points) duration. Above this limit, there is no suggestion in our data that failure rate is related to saccade amplitude or duration. Records with many very small saccades (less than 15 ms duration) would require higher digitisation rates, but we cannot say how well the method would perform.

We chose the threshold level of (2 mean + 2.8 SD) of the entire half-signal (above 0 for leftwards saccades, below for rightwards). The SD term particularly reflects the extrema of the transform. Higher values (than 2.8 SD) led to progressive missing of small or oblique saccades (having lower horizontal component velocities). Lower values led to increasing numbers of 'false positives'. The exact threshold chosen is probably a matter for individual preference, within a suggested working range of 2.5–3 SD.

The method described here has made possible rapid automated analysis of large volumes of eye movement recordings obtained from freely walking subjects. The simplicity of computation involved means that it is easily implemented on a modest PC and therefore a useful alternative to other methods currently available. We commend the technique as being time-saving, simple and reliable.

Appendix A

The fourth-order differentiator was obtained using the first two terms of the Stirling formula

$$\dot{y} = \frac{1}{2\partial t}\{y_{i+1} - y_{i-1}\} - \frac{1}{12\partial t}\{y_{i+2} - 2y_{i+1} + 2y_{i-1} - y_{i-2}\}$$

which, on rearranging, yields

$$\dot{y}_i = \frac{1}{12\partial t}\{y_{i-2} + 8(y_{i+1} - y_{i-1}) - y_{i+2}\}$$

Use of additional terms (which have progressively smaller coefficients and therefore make progressively smaller contributions) produces higher order differentiators (see Antoniou, 1993 which includes a worked example).

The denominator in Eq. 1 is $(1 + \sqrt[2]{|twm_{75}|})$ to ensure that the minimum value of this suppression term is 1, since values < 1 would be counterproductive, amplifying rather than suppressing. The units here are digitisation levels; $|twm_{75}|$ typically ranges from near zero (outside saccades) to several hundred (within saccades).

We have automatically identified saccades from eye movement records gained either by infra red reflectometry or by electrooculography. The latter is more susceptible to mains interference and, as always, care should be taken to keep this to a minimum by screening.

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