EYE MOVEMENTS, PUPILLOMETRY, METHODS, SIGNAL PROCESSING

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A simple way to reconstruct pupil size during eye blinks

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Here I describe a simple way to reconstruct pupil-size data during eye blinks. Blinks are detected using a velocity threshold and reconstructed using cubic-spline interpolation. Although it is debatable whether this reconstruction procedure is theoretically meaningful, it has considerable practical benefits during analysis and data presentation, compared to treating blinks as periods of missing data.

Aim of the algorithm

Pupil-size data is represented as a continuous signal over time. In this signal, eye blinks are clearly visible as brief, pronounced dips in pupil size, usually accompanied by a full loss of the signal (see Figures 1-3). The aim of the algorithm is to detect eye blinks in the signal, and reconstruct pupil size during these blinks. Because there is no objective measure of what the signal should look like during blinks, the algorithm aims to create a smooth and continuous signal that is a subjectively convincing reconstruction.

Blink detection

Because the original signal is often too noisy to create a reliable velocity profile, the signal is first smoothed using a moving window average (here I use an 11 ms Hanning window). The amount of smoothing depends on the noise in the signal, and in rare cases smoothing may not be required at all. Based on the smoothed signal, a velocity profile is generated. The onset of a blink is detected as the moment at which the velocity drops below a negative threshold (here I use a velocity threshold of -5 in arbitrary units; this depends on the output of the eye tracker), which reflects a rapid shrinking of the pupil due to closing of the eyelid. The 'reversal period' of a blink is detected as the moment at which the velocity exceeds a positive threshold (here I use 5 in arbitrary units), which reflects a rapid reopening of the eye. The offset of a blink is detected as the moment at which the velocity drops back to 0. A blink corresponds to an onset, reversal, and offset, necessarily in that order. Because this detection algorithm tends to underestimate the blink period by several milliseconds (compared to a visual inspection of the data), a margin (here I use 10 ms) is subtracted from the onset time and added to the offset time.

Thus, the algorithm has four parameters that need to be adjusted based on the particulars of the data: the amount of smoothing, the (negative) onset velocity threshold, the (positive) reversal velocity threshold, and the temporal margin.

Pupil-size reconstruction

For each blink, four equally spaced time points are required. `t2` is the blink onset; `t3` is the blink offset; `t1=t2-t3+t2`; `t4=t3-t2+t3`. Based on these four time points and the associated pupil sizes (from the original, unsmoothed signal), a cubic-spline fit is generated. The original signal between `t2` and `t3` is replaced by the cubic spline. Thus, the signal is left unchanged, except for the blink period.

Efficacy

It appears that this algorithm reliably detects and reconstructs most typical blinks, as can be seen in Figures 1-3. However, atypical distortions of the pupil size are frequently not detected and therefore not reconstructed. This includes pupil loss for a sustained period of time, and 'pseudo blinks' during which the eyelid closes only partly and with a relatively low velocity. 'Blink trains', periods of many blinks in rapid succession, also pose a challenge, although they are usually reconstructed adequately (Figure 3).

Examples

The figures below represent pupil size recordings from a single participant who was particularly prone to blinking. Detected blink periods are indicated by grey shadings in the velocity profile. The points used for cubic-spline interpolation are indicated as orange circles in the reconstructed signal. Only the signal between each pair of central circles (`t2` and `t3`) has been reconstructed. More examples are linked to from this manuscript on FigShare.

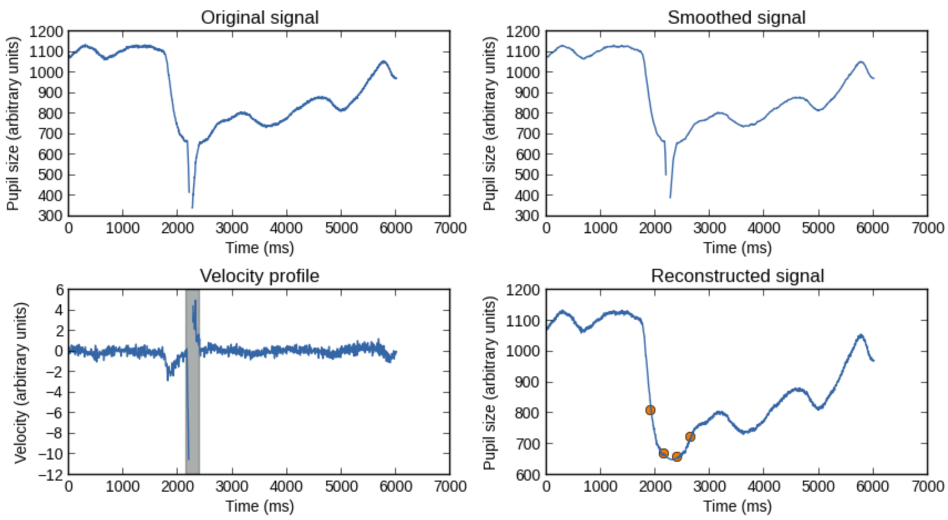

Figure 1. A typical blink.

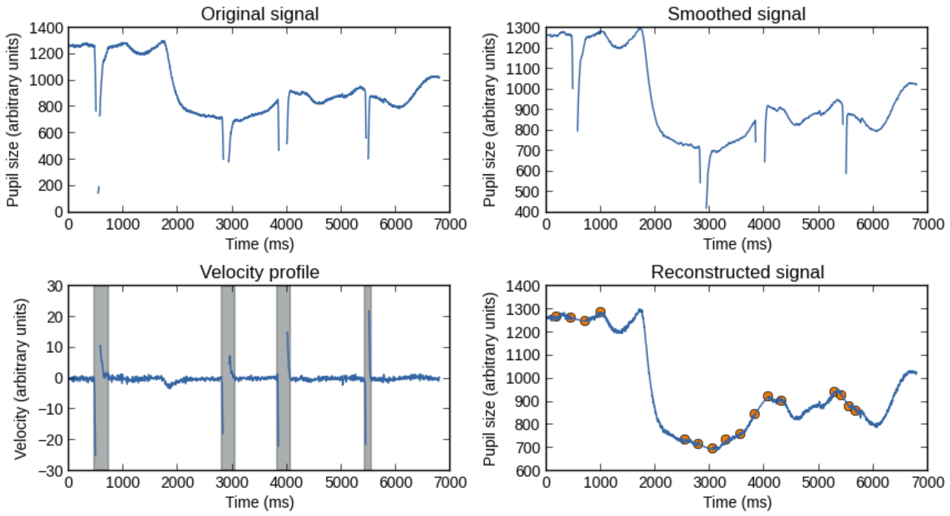

Figure 2. A series of typical blinks.

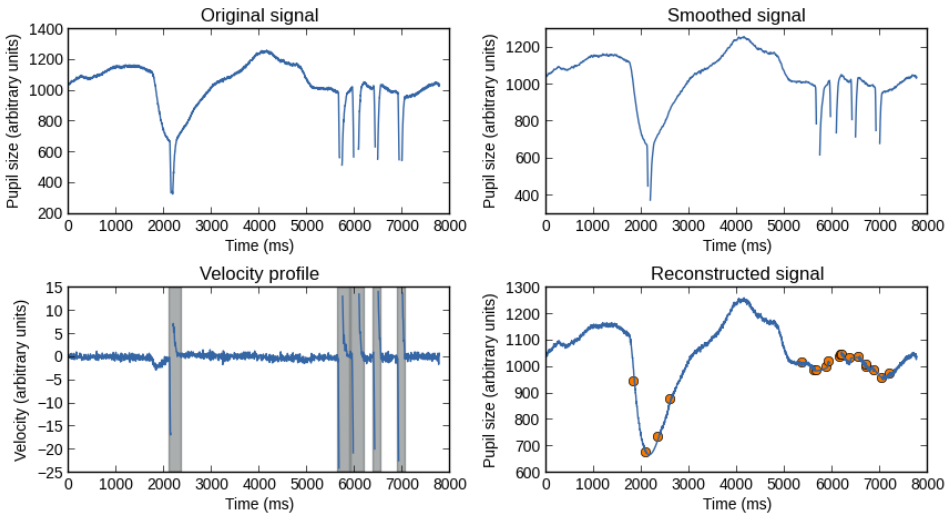

Figure 3. A typical blink followed by a 'blink train' (i.e. a rapid series of blinks).