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Saccade Detection Using Polar Coordinates – a New Algorithm

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Over the past few decades substantial research has been conducted regarding saccades (rapid eye movements). There are two components of this research. First there is the detection of the saccades, and second how to interpret the saccades features (amplitude, length, and velocity) to inform specific areas of research. This involves both experimental research and clinical applications. The detection of saccades is typically accomplished using two approaches, including cameras and the electrooculogram (EOG). Both of these approaches require algorithms to process the raw data, detect saccades, and calculate the saccade features. The current effort focuses on detecting saccades in the EOG using a new algorithm based on polar coordinates. The details of this algorithm will be presented, as will a calibration procedure and validation of the algorithm's accuracy. This algorithm was used in a recent study in which operator workload was manipulated. The saccade features produced by the algorithm were analyzed with respect to the workload manipulations. These results will be discussed.

Saccades have been used in research for cognitive state assessment, investigation of drug effects, and clinical applications for neurological and psychiatric disorders (Romero, Mañanas, & Barbanoj, 2008). For cognitive state research, saccades have been used both directly and indirectly. Literature suggests that peak saccade velocity can be used directly for the evaluation of mental workload (Di Stasi, et al., 2010). An indirect use of saccades is to mediate ocular artifacts in the electroencephalogram (EEG), which is also often used for workload assessment.

In a recent study (Heopf, Middendorf, Epling & Galster, this volume) participants were asked to track targets using remotely piloted aircraft (RPA) while workload was experimentally manipulated. Participants were equipped with electrodes to measure EEG, vertical EOG (VEOG), and horizontal EOG (HEOG). The primary purpose of the EOG data was to support an ocular artifact mediation approach we refer to as artifact separation (Credlebaugh, Middendorf, Hoepf & Galster, this volume). Since both VEOG and HEOG data were collected, an opportunity was present to develop the polar saccade detection algorithm

The artifacts in the EEG resulting from vertical ocular activity (blinks and saccades) tend to propagate symmetrically from anterior sites to posterior sites (Romero, Mañanas, & Barbanoj, 2008). Horizontal eye movements (saccades) mainly affect lateral frontal electrodes (Lins, Picton, Berg, & Scherg, 1993). Polar coordinates are specified in angle and magnitude. Therefore, the polar coordinate detection approach allows for more specific propagation mapping using the saccade angle.

Background

In a prior study, VEOG was collected to support the development of a blink detection algorithm (Epling, et al., this volume). This was done to deal with blink artifacts when analyzing the EEG data. However, it was realized that there were also artifacts in the EEG due to saccades. A task-related effect was discovered that was a direct result of one of the experimental manipulations (Credlebaugh, Middendorf, Hoepf & Galster, this volume). Specifically, one of the manipulations introduced substantially more horizontal saccades. This made the analysis of EEG data difficult. This is the reason why the current study uses both channels of EOG data, and the polar saccade detection algorithm was developed. With the new algorithm EEG spectral results can be flagged as containing blink *and* saccade (regardless of angle) artifacts. This data can be separated from the artifact free data at the analysis stage.

One particular challenge in the development of the polar saccade detection algorithm was presented by blinks. Specifically, the up slope of a blink has very similar qualities as a saccade. Special queuing logic had to be implemented to prevent a blink from also being counted as a saccade. When an epoch of data contains a blink, saccades are not searched for. This essentially means that blinks "trump" saccades. This must be taken into account when analyzing EEG data using the aforementioned artifact separation technique (Credlebaugh, Middendorf, Hoepf & Galster, this volume). When blinks are removed, a higher density of saccades will be found in the remaining data.

How the Algorithm Works

The major components of the algorithm are signal filtering, threshold generation, saccade endpoint detection, dynamic linear fit, mathematical calculations, classification, and saccade queuing.

Signal filtering. The raw EOG data contains saccades that are evident to the naked eye. The distinctive shape of a saccade, shown in Figure 1, contains the pre-saccadic spike (Thickbroom & Mastaglia, 1986) followed by a sharp monotonic increase (or decrease for look down and look left). Then there is a slow decay back to zero due to the high pass filter used in the signal acquisition hardware. The raw EOG also contains micro-saccades, which unlike the major saccades, are very small in amplitude but, occur very frequently. These micro-saccades can occur in the middle of a major saccade (Figure 2). When this happens, the micro-saccades can cause the dynamic linear fit portion of the algorithm to make mistakes. Specifically, the full amplitude of the major saccade may not be reported. To prevent this problem, the raw EOG data is filtered using a first order Butterworth low pass filter with a break frequency of 50 Hz.

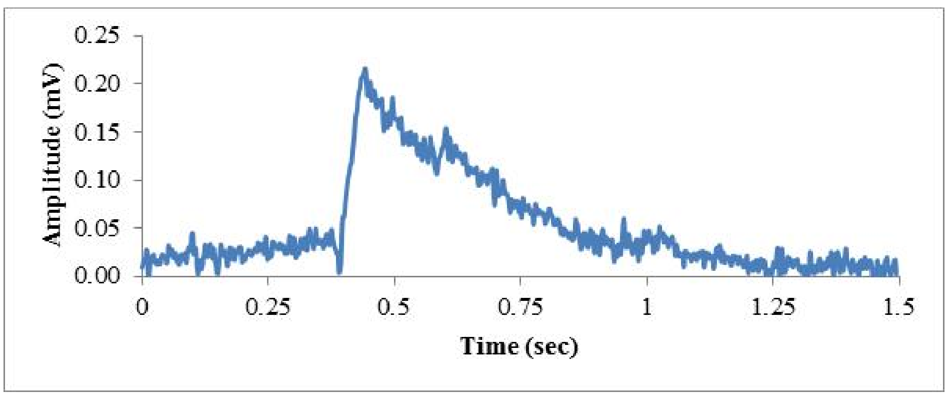

Figure 1. The typical shape of a saccade. This is a horizontal saccade to the right.

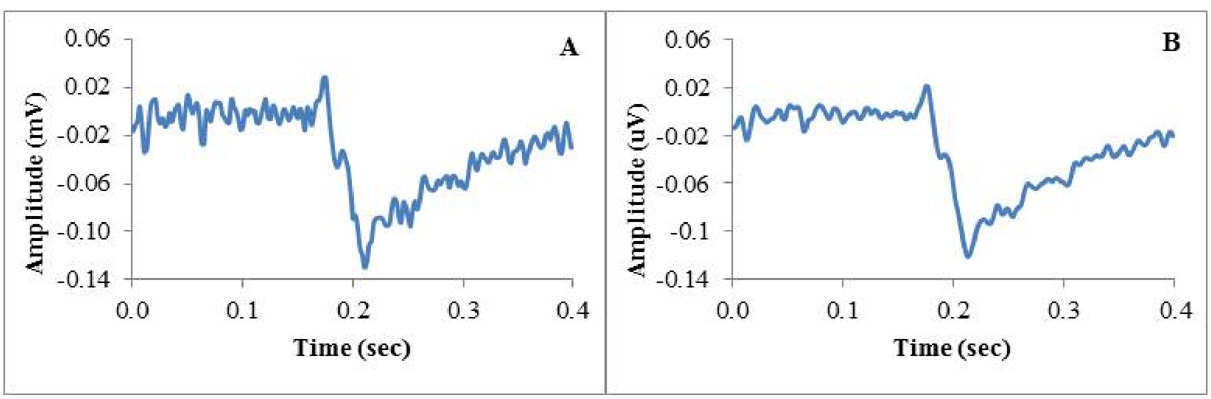

Figure 2. This horizontal saccade is from a leftward eye movement. It has a micro saccade in the middle of it (A) that causes the linear fit to fall short of the full saccade amplitude. After filtering (B) the micro saccade is reduced enough so that it does not interfere with the full linear fit.

Threshold generation. A robust threshold generation approach was developed for the blink detection algorithm (Epling, et al., this volume). A scaled value of this threshold value is used for the polar saccade detection algorithm. The threshold generation approach uses a sliding five second window of raw VEOG data. To minimize the effects of blinks and eye movement on the threshold, the data is high pass filtered using a first order Butterworth filter with a break frequency of 10 Hz. This essentially leaves in the "noise" from which the threshold is calculated. The filtered signal is then rectified and the median is taken for the raw threshold value. The median is used because the data in the five second window can be highly skewed when there is a blink in the window. Limits are imposed on the raw threshold. Note that the threshold used in the polar saccade detection algorithm is circular (Figure 3).

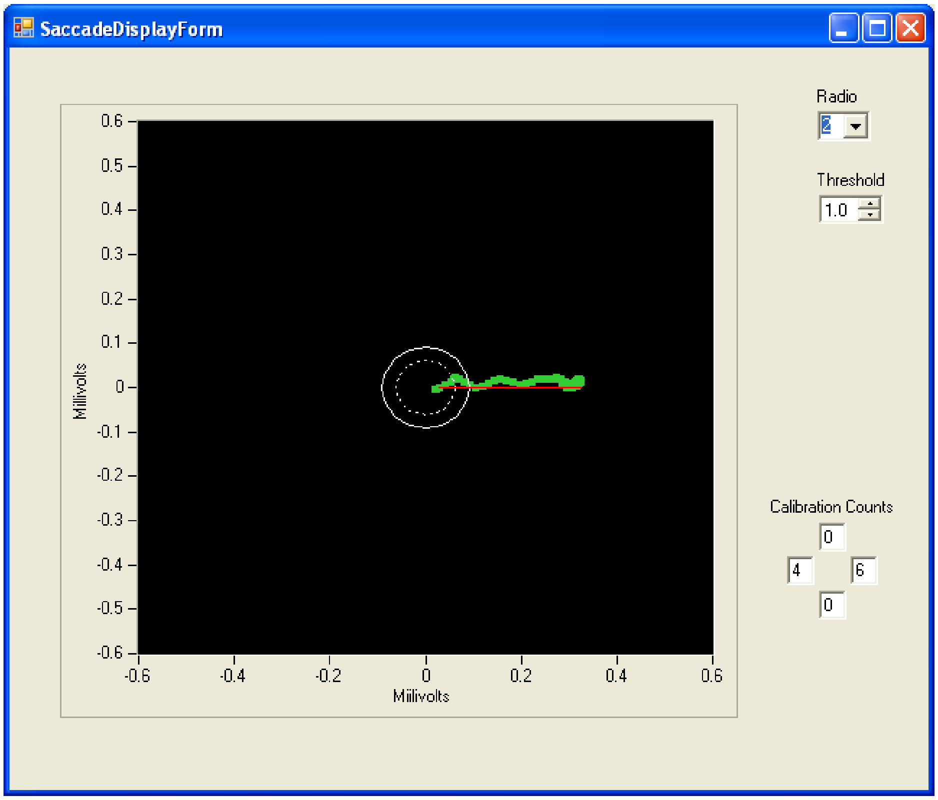

Figure 3. Screen shot of the polar saccade display. HEOG is displayed on the x-axis and VEOG on the y-axis. The solid circle is the threshold and the dashed one is the return circle. The green line is the last 100 EOG samples (VEOG & HEOG). The red line is the saccade detected by the algorithm.

Saccade endpoint detection. The filtered EOG data is evaluated in Cartesian coordinates with HEOG on the x-axis and VEOG on the y-axis. The circular threshold is centered about the x/y origin. Initial saccade detection follows three simple steps. First, the x/y position must start inside the circular threshold. Second, the x/y position must travel outside the circular threshold. Third, the x/y position is allowed to move away from the origin for as many samples as possible until it moves back toward the origin for two samples in a row. The last sample that is moving away from the origin is the end point of the saccade.

The above approach had to be enhanced to prevent many small false positives from being reported due to noise in the EOG signals. This happened when the signal was returning from outside the threshold to inside of it. When the returning signal was near the threshold, the noise in the signal could cause the signal to jump back and forth across the threshold, thus triggering the false positives. To prevent this, a second circle was added (Figure 3) called the return circle. This circle is centered about the origin and its radius is equal to two-thirds of the threshold circle. The saccade endpoint detection logic was modified so that the signal must return to inside the return circle before it can be tested for traveling outside the threshold. The saccade endpoint detection is accomplished using a state machine.

Dynamic linear fit. The linear fits are performed in rectangular coordinates. That is, the VEOG and HEOG are processed separately based on the saccade endpoint. Two vectors are used to find the saccade starting point for each signal (VEOG & HEOG). These two vectors are referred to as the small vector and the big vector. The initial length of the two vectors is the same, which is 20 milliseconds (Chen & Wise, 1996). The heads of the vectors are set to the saccade endpoint and the tails are 20 milliseconds backwards in time.

The length of the small vector remains constant. The big vector grows in length backwards in time. The tail of the small vector is anchored to the tail of the big vector. The small vector is used to terminate the growth of the big vector. Specifically, when the slope of the small vector differs substantially the slope of the big vector, the saccade starting point has been found. After the dynamic linear fit has been performed on both axes, the x and y coordinates of the saccade starting point and ending point are known. Note that these coordinates represent a potential saccade, which must be subjected to classification criteria to determine if the coordinates represent an actual saccade. This is an important distinction because the EOG signals can cross the threshold due to other reasons (e.g., noise, blinks, and slow eye movements).

Mathematical calculations. Once the coordinates of a potential saccade are known several variables must be calculated. The rectangular coordinates need to be converted to polar coordinates (magnitude & angle). The amplitude, length, velocity, and peak velocity are computed for the potential saccade. The two R^2 values from the dynamic linear fits must be combined into a single R^2 value. Finally fixation duration is computed.

Classification. Three of the variables computed above (R^2, velocity, and length) are compared to criteria values to determine if the potential saccade is an actual saccade. All three of these criteria must be met for a positive classification to occur. The criteria values, shown in Table 1, were determined using data from a mini-study with four participants. All of the detected potential saccades were hand scored using EOG playback to generate truth data.

Table 1.
Criteria values used for saccade classification.

Criteria	Minimum Value	Maximum Value
Combined R^2	0.85	N/A
Velocity (mV/sec)	1.0	6.9
Length (sec)	0.28	0.125

Saccade queuing. Special queuing logic needed to be developed to ensure that the identified saccade is not actually the up slope of a blink. While waiting for the excursion of the EOG signal to reach its maximum distance from the origin, the blink detection algorithm is monitored. If the blink detector is active a flag gets set to indicate that the saccade must get queued. Following a positive classification the flag gets checked, and the saccade gets queued if needed. On future updates, if there is a saccade in the queue, the blink detector gets monitored. If a blink occurs the queued saccade is discarded. If the blink detector returns to its initial state and a blink was not detected, the queued saccade gets recorded.

Algorithm Use and Validation

Experimental results. The polar saccade detection algorithm was used in a recent study in which operator workload was manipulated. Although the focus of this paper is on the algorithm, a brief discussion of study results is presented. This is important to illustrate the sensitivity of the saccade measures (amplitude, length, velocity, and peak velocity) to the experimental manipulations. For the sake of brevity, a very condensed description of the experiment is given.

In the study, the participants performed two separate tasks using video feeds from remotely piloted aircraft (RPA). First there was a surveillance task (find the high value target (HVT) walking around in a compound), followed by a tracking task (follow HVTs travelling on motorcycles). In the surveillance task there were two experimental factors, sensor fuzz (on vs. off) and the number of distractors (high vs. low). When sensor fuzz was on (high workload), the video feed was degraded. A high number of distractors (high workload) means there were 48 other people walking around in the compound in addition to the HVT, as opposed to 16 in the low number of distractors condition. In the tracking task the two experimental manipulations were route type (city vs. country) and the number of targets (1 vs. 2). Tracking targets in the city is harder than the country and tracking two targets is harder than one.

The EOG data was processed by the polar saccade algorithm to generate the measures. The measures were statistically analyzed using a repeated measures ANOVA. For the sake of brevity, only the peak velocity plots are shown (Figure 4). For the surveillance task, the fuzz manipulation did not have a statistically significant effect on the saccade measures. The number of distractors manipulation was significant for all four saccade measures.

Although the mean differences were small, they are in the correct direction (Di Stasi, et al., 2010). Specifically, peak velocity was lower in the high workload condition (high distractors). In the tracking task, the route manipulation was not statistically significant. The number of targets manipulation had a significant effect on saccade amplitude, velocity, and peak velocity. These results make sense, even though they are not in the expected direction. In the one target condition participants focused on a single video feed, which did not require large gaze angle changes (i.e., saccades). In the two target condition, participants had to regularly shift their gaze between two video feeds, thus introducing several large saccades. It is reasonable to suggest that this task-related effect caused large mean differences that overwhelmed small differences (in the opposite direction) that may result from increased workload.

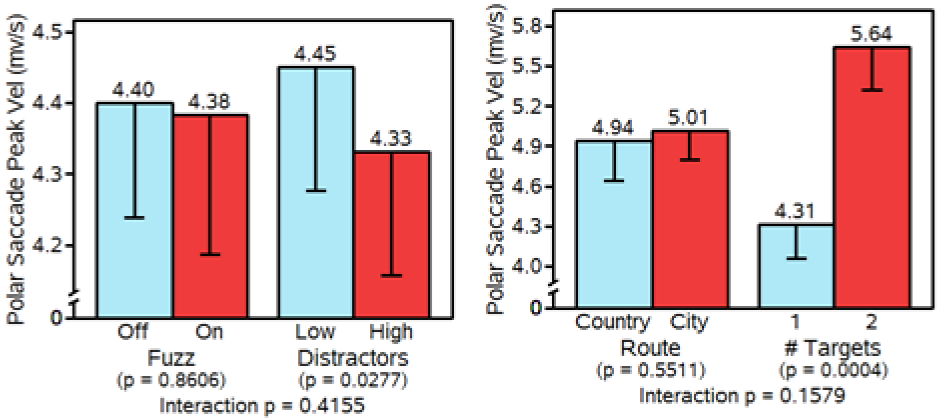

Figure 4. Peak saccade velocity was measured using the polar saccade detection algorithm. The left panel shows results for the surveillance task, and the right for the tracking task. The error bars are standard error.

Truth data validation. A study was conducted to test the performance of the polar saccade detection algorithm. In this study visual stimuli were presented at known angles and distances at regular intervals (1.5 seconds). Two researchers independently reviewed the raw VEOG and HEOG signals to verify that the saccades were present in the signal. This truth data was used to validate the algorithm. Results show that the algorithm had zero false positives, but did have occasional misses. Overall the algorithm had an accuracy rating of 92.6%.

Discussion

The polar coordinate saccade detection approach has an advantage over approaches that independently perform detection on each axis (VEOG & HEOG). The magnitude of a saccade in polar coordinates is almost always larger than the amplitude in the rectangular axes. This makes it easier to detect saccades and makes it possible to detect smaller saccades.

The present approach for saccade detection using a state machine for endpoint detection is computationally friendly. This is because linear fits are *only* performed when an endpoint has been detected. This is in contrast to approaches that perform sliding linear fits in the raw data, which is computationally intensive due to the high number fits that are performed

There is a scaling issue with the EOG data that had to be addressed. The electrical values measured for VEOG and HEOG are not equal for the same angular movement of the eyes. The VEOG is typically smaller than the HEOG, sometimes by as much as a factor of two. This causes the EOG measures to be elliptical rather than circular, thus distorting the calculation of saccade angle. The EOG data needed to be normalized. To accomplish this, a calibration procedure was developed. Visual stimuli are presented on a computer monitor in the vertical and horizontal axes at equal distances from center (Figure 3). The measured responses for each axis are then averaged and used to compute a scale factor. The scale factor is used to normalize the EOG data is real time. It is important to note that the computed scale factor is very stable from calibration to calibration, and from day to day. Additional testing is under way, but it appears that an individual only needs to be calibrated once.

The seating position of participants should be adjusted so that their eyes are near the center of the monitor. Otherwise some error will occur in the calculation of saccade angle. This is true for calibration and experimental trials. A future enhancement is planned that will allow offsets to be entered for the participants position relative to the monitor.

For the purpose of artifact mediation in EEG, an algorithm was written to detect saccades directly in the EEG signal itself (Credlebaugh, Middendorf, Hoepf, & Galster, this volume). To improve the accuracy of the EEG-based saccade detection algorithm, it will be coupled with the polar saccade detection algorithm. Future work will be performed to corroborate the EEG-based results with the polar saccade results. Specifically, if an EEG-based saccade is detected, then there must be a corresponding polar saccade within the correct angle range.

Conclusion

The measures produced by the polar saccade detection algorithm have been shown to be sensitive to experimental manipulations. In the results reported above, the manipulations introduced a task-related effect that caused a systematic change in eye behavior. Therefore it cannot be concluded that the saccade measures are indicators of cognitive workload, but it is encouraging that the algorithm is capable of measuring small changes. The algorithm produces these measures in real time and in a computationally efficient manner.

A calibration approach was developed to allow the two axes of EOG to be normalized, thus improving the accuracy of the reported saccade angles. The calibration procedure allows researchers to account for individual differences. Early results indicate that participant calibration is stable from day to day. Another positive aspect of the current work is it will support artifact mediation approaches when performing EEG analysis.

This algorithm will be used in future research to determine its usefulness for assessing cognitive workload. Careful consideration will be taken to ensure that experimental manipulations do not systematically change eye activity. Enhancements need to be made to the algorithm to improve overall accuracy of 92.6% (see results section).

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