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Predicting Final Eye Position Halfway Through a Saccade

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***Abstract*—When the visual environment is to be changed during a saccadic eye movement, it is useful to predict the final eye position before the eye comes to rest. We have built a microcomputer-based instrument to make such predictions. Two techniques were used: one based on the saccadic peak-velocity versus magnitude relationship, and the second based on peak-velocity occurring in the middle of the saccade. The second technique has been tailored to take advantage of the differences between temporal and nasal saccades. Depending on saccade duration, final eye position was predicted 4 to 60 ms before the end of the saccade.**

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Introduction

It is often useful to predict the future. To predict the future value of a signal corrupted by noise, a Kalman filter is useful [1]. To predict the future value of a repeatable waveform, such as an ECG waveform, a matched filter is useful [2]. We were interested in predicting the final eye position for saccadic eye movements. Eye movements can be measured with little noise, so the complexity of a Kalman filter was not needed. Consecutive saccadic eye movements vary in shape, so a matched filter was not appropriate. We had to do the predicting in real time, therefore, we wanted a simple prediction algorithm. We will discuss the two methods we used for predicting eye position, but first let us explain why we were interested in predicting the future.

To save lives and money, pilots sometimes fly simulators rather than aircraft. The use of simulators allows training for otherwise impossible maneuvers, such as engine failure during

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takeoff. To be realistic, the visual display in the simulator must change in response to a pilot's actions: this precludes the use of motion pictures. Therefore, simulators typically produce the visual scene with computer image generators (CIG's).

Present CIG's cannot display a full 360° image. Humans, however, do not have uniform visual acuity: they only see fine details where the fovea of the eye is directed. So, in future simulators one CIG channel can compute foveal-limited-resolution images for the 20° by 20° area centered on the line of sight, while another CIG channel can compute lower resolution images for the 90° by 70° peripheral field of view. Because the size of the foveal-limited-resolution region is 20° X 20° and the fovea is 1° in diameter, predictor errors of up to 9° can be tolerated.

When a pilot makes a head or an eye movment, the new area of regard should have detailed resolution when the eye gets there. However, the CIG needs 80 ms to change the display. We have developed an instrument that monitors eye position and predicts the final position before the saccade is over. This instrument gives the CIG a 4 to 60 ms head start in computing the detailed foveal display for the pilot's new direction of gaze. This head start is not as large as the CIG's delay, but coupled with the 20 ms afforded by saccadic suppression [3], [4] it may be sufficient to make the change unnoticeable to the pilot.

METHODS

We used two different instrumentation systems for measuring eye movements: one for normal horizontal saccades, and one for vertical saccades and large horizontal saccades. For horizontal saccades smaller than 20° we used a standard binocular photoelectric system [5], [6] with light emitting diodes (National Semiconductor Xciton XC88PA) and phototransistors (Fairchild FPT 120) mounted on spectacle frames worn by the subject. The linear range (±2 percent) extended ±10° from primary position. Linearity was obtained by adjusting the equipment while the subject tracked a sinusoidally moving target. To maximize the signal to noise ratio, we set the amplifier gains so that the range of the analog to digital converter slightly exceeded the linear range of the sensors; full scale represented 25°. With these gain settings instrumentation noise was then less than 10 mV, corresponding to an error of 1.2 minutes of arc. The error resulting from the 12 bit analog to digital conversion was 0.3′. Biological noise was about 1.5′. So the total noise in the eye movement records was about 3′. For vertical eye movements and for horizontal saccades larger than 20° a dark pupil oculometer was used [7]. It used an X-Y photodiode (United Detector Technology PIN-SC/25) to detect the horizontal and vertical position of the centroid of the pupil. The pupil was illuminated by infrared light. The infrared light and the image of the eye were reflected off an infrared mirror, so that the only intrusion in the subject's field of view was the infrared mirror, which appeared as a lightly tinted piece of glass. It was easy to adjust the instrument to achieve linearity for 40° horizontal saccades, and 20° vertical or oblique saccades. For certain subjects (perhaps those with astigmatic corrections), linearity could not be achieved. Both instrumentation systems used single-pole 100 Hz analog low-pass filters. For both instruments we fixed the head with a bite bar and a headrest. Therefore, neither of the above instruments are presently suitable for use in a simulator. However, the predictor described in this report can work with any device that provides a voltage proportional to eye position.

The target was a small (3 mm diameter) red laser dot projected on a white screen in front of the subject. The target voltages drove a pair of a galvanometers that had small mirrors attached. The movements of the mirrors deflected the laser beam to produce a moving dot on the screen. The bandwidths for the galvanometer and the dc amplifier exceeded 200 Hz. Subjects viewed the target binocularly in a dimly illuminated room (vision was photopic).

We used two different computer systems for analyzing the data: one for off-line calculations and the other for real-time calculations. For *off-line calculations*, floating point arithmetic operations were performed on a PDP 11/34 minicomputer. Target and eye movement data were passed through a 12 bit analog to digital converter sampling at 1000 Hz, and were then stored on a disk for future calculations. Calibration factors were derived from segments of the data when the subject tracked a target that jumped between points ±5° from primary position. Calibration factors for each eye were computed by averaging 1-2 s of data from 4 to 10 manually selected periods when the eye was stationary and looking at the target. Whereas, for *on-line real-time calculations,* integer arithmetic operations were performed on an LSI-11/2 microcomputer. Eye movement data were sampled at 1000 Hz by a 12 bit analog to digital converter, processed by the predictor algorithm, and finally passed through a digital to analog converter.

For the off-line calculations, eye velocity was calculated with the following two-point central difference algorithm.

$$\dot{y}(kT) = \frac{y([k+3]T) - y([k-3]T)}{6T} \tag{1}$$

where T is the sampling interval and k is an index of discrete time intervals. This produced velocity records with (for 1 ms sampling) 3 dB bandwidths of 74 Hz [8], [9]; whereas, for the real-time calculations, eye velocity was calculated with the following backward difference algorithm.

$$\dot{y}(kT) = \frac{y(kT) - y([k-8]T)}{8T}. \tag{2}$$

This produced velocity records with (for 1 ms sampling) 3 dB bandwidths of 55 Hz. With proper scaling, this algorithm requires no division operation, merely a shift right of 3 bits.

Operation of the predictor was enhanced by a blink detecting program, and an error detecting program. Events were called blinks if 1) the apparent eye velocity exceeded 1000°/s (because real eye velocities do not exceed 1000°/s [6], [10]), or 2) the apparent velocities of the two eyes differed by more than 300°/s (because the velocities of the eyes are approximately the same [11]), or 3) the apparent eye velocity reached 800°/s in either less than 20 ms or more than 50 ms (because saccades that reach 800°/s do so between 20 and 50 ms [6], [10]). The blink detecting program was designed for the photoelectric method of measuring eye movements, but it also worked with the dark pupil oculometer. The error detecting program monitored the velocity channel after a prediction had been made. If it detected a second peak velocity higher than the one that had been used to make the prediction, it issued a warning that noise may have influenced the original prediction, and then issued a new prediction.

Results

We used two concepts in constructing the predictor: main sequence diagrams and the multiplier factor. Main sequence diagrams show the relationship between saccadic peak velocity and saccadic magnitude [10]. To predict the end point of a saccade, we computed eye velocity, waited for the velocity to peak, used the peak velocity to find the appropriate saccadic magnitude, and then used this magnitude as a prediction of the final eye position. The equation for this algorithm was derived from the main sequence data of 13 individuals [6]. The algorithm was tested on a set of data collected from four different subjects. The predicted saccadic magnitude Y was plotted as a function of the actual saccadic magnitude θ and a linear regression line was fit to the data. The linear regression line for the main sequence predictor was

$$Y = 0.86\theta + 1.7 \text{ with correlation of } 0.856.$$

The linear regression equation can be used as a figure of merit for the predictor. If the predictor were perfect, the slope of the linear regression line would be 1.0, the intercept would be 0, and the correlation would be 1.0.

If the saccadic velocity profile were symmetric about peak velocity, we could continuously compute eye velocity, detect the peak velocity of the saccade, note how far the eye had moved since the start of the saccade, and then predict that the eye would go twice this distance before it came to rest. However, saccadic velocity profiles are not symmetric: most saccades reach peak velocity before or after the middle of the saccade. Therefore, for our second technique the distance the eye had moved at the time of peak velocity was not merely doubled, but rather it was multiplied by the multiplier factor defined in Fig. 1. For small saccades, there was little difference between nasal saccades (toward the nose) and temporal saccades (toward the temple). As the saccadic magnitude became larger, the difference between the multiplier factors for temporal and nasal saccades increased, as shown in Fig. 2. For this subject the multiplier factors were always greater than two, meaning the peak velocity always occurred before the middle of the saccade. For these data the multiplier factor for temporal saccades increased with saccadic magnitude. These multiplier factors were derived from saccades symmetric about the center line, and they were calculated with the off-line computer system.

There was intersubject variability in the multiplier factor. But we wanted our predictor to work well for any subject. Therefore, we averaged data from eight subjects to calculate the multiplier factors for our predictor algorithm. The average value of the multiplier factor for temporal saccades (mft) was less than two and increased with increasing saccadic magnitude.

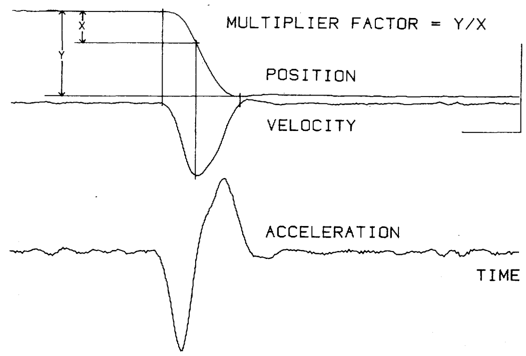


Fig. 1. Definition of the multiplier factor. If the change in eye position at the time of peak velocity x is multiplied by the multiplier factor, then the final eye position y will be predicted. The three traces are (from top to bottom) eye position, velocity, and acceleration as functions of time for a saccadic eye movement. The calibration key represents 10°, 500°/s, 30 000°/s^2, and 100 ms. This was a temporal movement of the left eye.

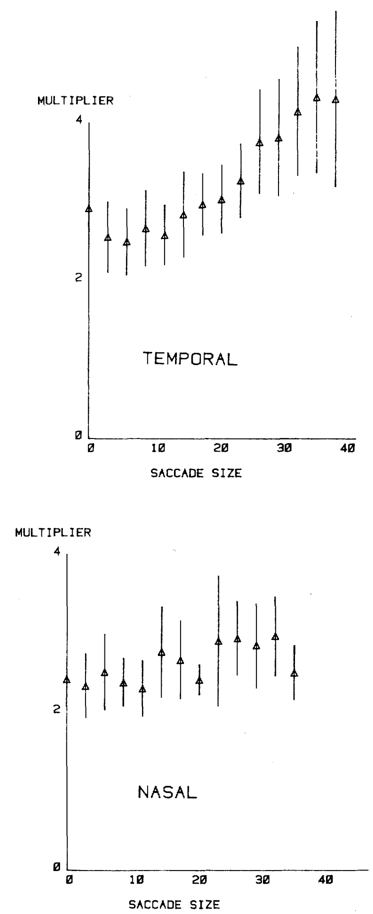


Fig. 2. Multipler factors for 412 saccades of one subject for (top) temporal saccades and (bottom) nasal saccades. Multiplier factors are a function of saccadic magnitude. The triangles represent the mean and the vertical lines show the range of the data.

$$\text{mft} = 1.4 + 0.05x$$

where x is the angle between the eye position at the start of the saccade and the eye position at peak velocity as shown in Fig. 1. The average value of the multiplier factor for nasal saccades (mfn) was also less than two, but it decreased with increasing saccadic magnitude.

$$\text{mfn} = 1.4 + 0.04x.$$

For nasal saccades, x is negative. Using these multiplier factors, the equations for the predicted saccade size were

$$Y = (1.4 + 0.05x)x \quad \text{for temporal saccades (positive } x) \quad (3)$$

$$Y = (1.4 + 0.04x)x \quad \text{for nasal saccades (negative } x). \quad (4)$$

The quantities in parentheses are the multiplier factors, and x is the angle between the eye position at the start of the saccade and the eye position at peak velocity. The algorithm of (3) and (4) was tested on a set of data collected from four different subjects. (We derive our multiplier factors from one set of data and test our predictor on a different set.) The predicted saccadic magnitude Y was plotted as a function of the actual saccadic magnitude θ, and a linear regression line was fit to the data. The linear regression line was

$$Y = 0.73\theta + 2.7 \text{ with correlation of } 0.887.$$

The largest errors in prediction occurred for saccades larger than 30°. Therefore, we modified our algorithm so that it used the following equation when x exceeded 15°.

$$Y = 2x. \quad (5)$$

When the algorithm described by (3), (4), and (5) was tested on the four subject data set, the linear regression line was

$$Y = 1.04\theta + 0.71 \text{ with correlation of } 0.936.$$

Because the algorithm worked so well, we did not try to remove the discontinuity in the nasal multiplier factor at $x = 15$. To further test this final algorithm we applied it to the data sets of two individuals. Fig. 3(a) shows its best results, which yielded a linear regression equation of

$$Y = 1.07\theta + 0.07 \text{ with correlation of } 0.934.$$

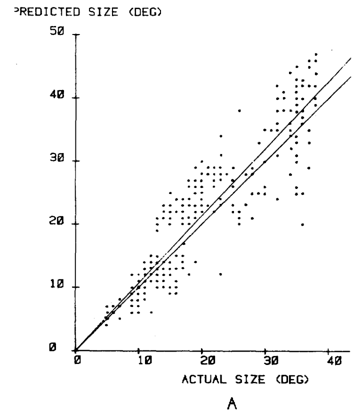
Fig. 3(b) shows its worst results, which yielded a linear regression equation of

$$Y = 0.93\theta + 1.17 \text{ with correlation of } 0.916.$$

One of the solid lines in Fig. 3 represents perfect prediction, and the other is the linear regression line fit to the data. The data of Fig. 3 were calculated with the on-line computer system.

Predictions of the final position of the eye were usually made within 8 ms of the actual peak velocity. So, for a symmetric 20° 60-ms saccade, the prediction would occur 22 ms before the end. However, due to asymmetries, varying durations of the saccades, irregularities of the velocity waveform, and glissades, we have observed predictions between 4 and 60 ms before the eye came to rest.

Because many instruments sample the eye position at 60 Hz, we decided to make this predictor work at a 60 Hz sampling rate. The multiplier factor for saccades larger then 20° was changed to 1.2, i.e., $Y = 1.2x$. This choice of multiplier factor was made empirically by fitting a regression line to the data. Predictions almost as good as with the 1000 Hz sampling rate were obtained. The linear regression estimates for the data of



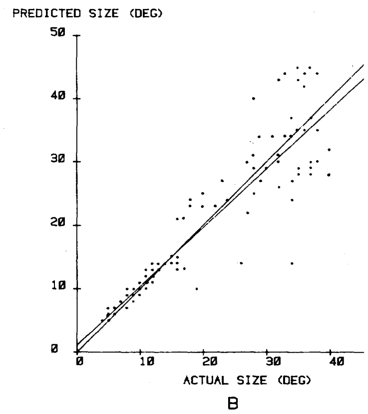


Fig. 3. Predicted versus actual saccadic magnitude for two subjects; the predictor did better for subject A (top) than for subject B (bottom).

Fig. 3 sampled at 60 Hz were

$$Y = 0.87\theta + 4.2 \quad \text{with correlation of } 0.961$$

$$Y = 0.78\theta + 5.2 \quad \text{with correlation of } 0.927.$$

The 60 Hz sampling rate prevented the predictor from making predictions on saccades smaller than 10°. The average time savings was reduced. The final eye position was predicted either 0, 17, or 34 ms before the eye came to rest.

Vertical saccades had more variability, but the predictor still worked. Predictor equations were derived from one data pool and then the predictor was used on a different data pool. Linear regression equations for two subjects were

$$Y = 0.63\theta + 3.74 \text{ with correlation of } 0.870$$

and

$$Y = 0.70\theta + 1.97 \text{ with correlation of } 0.774.$$

Discussion

Which are faster, nasal saccades (toward the nose) or temporal saccades (toward the temple)? Here is a sampling of the answers given by a few 20th century scientists: nasal (Dodge and Cline, 1901 [12]), temporal (Bruckner, 1902 as cited by [13]), nasal (Dodge and Benedict, 1915 [13]), temporal (Miles, 1924 [14]), temporal (Dodge, 1927 [15]), temporal (Robinson, 1964 [16]), nasal (Fuchs, 1967 [17]), temporal (Bahill, Clark, and Stark, 1975 [10]), and nasal (Dick, 1978 [18]). These answers refer to the durations of saccades. If faster is interpreted as higher peak velocity, the story becomes more muddled. The answers become sometimes temporal, sometimes nasal (Hyde, 1959 [19]), temporal (Robinson, 1964 [16]), nasal (Fuchs, 1967 [17]), nasal (Boghen *et al.*, 1974 [20]), temporal (Fricker and Sanders, 1975 [21]), sometimes each (Baloh *et al.*, 1975 [22]), nasal (Bahill *et al.*, 1975 [10]), and nasal (Oohira and Okamoto, 1981 [23]). A careful analysis of the data in these papers reveals that, in general, for large saccades, of most normal subjects, the nasal saccades have longer durations and, paradoxically, higher peak velocities than temporal saccades of the same size. These differences, however, are smaller than those caused by daily variations. Some reports have shown slight differences for small saccades [24], but these differences were not consistent [6].

Our studies of the multiplier factor have shown a *consistent* difference between temporal and nasal saccades; the multiplier factor for temporal saccades is larger than the multiplier factor for nasal saccades; i.e., temporal saccades reach peak velocity before nasal saccades [21], [25], although they start at the same time [26]. In Fig. 4 we superimpose simultaneous temporal and nasal saccades. It can be seen that the velocity of the temporal saccade increases faster, reaches its peak sooner, and drops to zero before the velocity of the nasal saccade. The same change in eye position is made in each case so the area under the two velocity curves must, obviously, be the same. Therefore, the shapes of the two velocity curves must be different. This record shows 10° saccades, because high-speed, low-noise, linear binocular recordings for large saccades are hard to obtain. The velocity profiles for large saccades were similar to those shown in Fig. 4, except that the differences between temporal and nasal saccades were larger.

Our predictors were only designed to work on saccadic eye movements. However, most shifts of human gaze are accomplished with coordinated head and eye movements. We did not concern ourselves with head movements because in most coordinated head and eye movements the eye moves first with a saccade size equal to the final shift in gaze angle. Therefore, predicting final gaze position based on only the eye movement data would be accurate. Furthermore, in the flight simulators head position will be measured. Head movements should be slow enough for the CIG's to keep up, so no prediction of head position will be necessary.

The multiplier factors of Fig. 2 were computed with the zero-phase two-point central difference differentiation algorithm (1), and they were plotted as functions of final saccadic magnitude. Therefore, this data should be usable by other investigators. However, for use in the real-time predictor, the multipliers were formulated differently. First, velocity was calculated using the backward difference algorithm (2). This variation allowed real-time implementation, but had the effect of adding a time delay. Second, to avoid predictions on small saccades, and to avoid false predictions on noisy data, the predictor did not start computing until the eye velocity exceeded

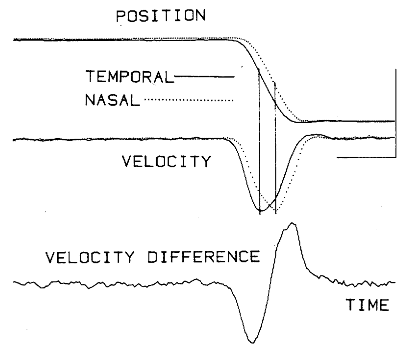


Fig. 4. Position (top) and velocity (middle) for a temporal (solid) and a simultaneous nasal (dotted) saccade. The bottom record shows the difference between the temporal and the nasal velocities. The calibration key represents 10° (top record), 500°/s (middle record), 200°/s (bottom record), and 100 ms.

100°/s. This had the effect of making the angle x in Fig. 1 smaller. Third, the multiplier factors were functions of the angle x, not saccade size. Therefore, although our predictors were tailored for our specific application, we think the general principles of operation can be generalized.

The principal constraints on the predictor algorithm were real-time operation and the use of integer arithmetic. The real-time requirement meant that a new output value had to be calculated every millisecond. This limited the number of arithmetic operations that could be performed, particularly multiplication and division operations. The integer arithmetic requirement created overflow and truncation problems; intermediate results could not be larger than 32 767 because the words would overflow, but on the other hand intermediate results could not be near zero because numbers such as 9/10 would be truncated to zero. If these constraints were removed predictions could be improved.

There are a continuum of predictor algorithms that trade off accuracy for time saved by prediction. At one extreme would be an algorithm that predicted as soon as the saccade began and had zero accuracy, and at the other extreme would be an algorithm that predicted at the end of the saccade but with perfect accuracy. We studied several algorithms that fell somewhere in between. We tried more sophisticated derivative algorithms, but his did not increase the accuracy or save time. We also made predictions using acceleration. The acceleration data were too noisy to be used without extensive low-pass filtering, and this filtering slowed down the prediction process. For our experiments the fastest and most accurate predictions were made using velocity alone.

Our predictor was designed to work with no individualization. However, the multiplier factors varied substantially from subject to subject. So, the accuracy of prediction could be increased by tailoring the multiplier factors for each individual. This could be done adaptively as the training session progressed, or it could be based on a set of calibration data collected before each session. At the very least multiplier factors should be derived using the equipment and subject population that would be used in the actual system.

The data of Fig. 3(a) show that 80 percent of the time the final eye position was predicted to within ±5° and that 98 percent of the time the final eye position was predicted within ±8°. In terms of the simulator, at the end of a change in gaze, 98 percent of the time the fovea would have been in the high resolution area of the scene. The accuracy of prediction could be increased by using floating point arithmetic, or by tailoring the algorithms to fit each individual. The fly in the ointment is that the 4 to 60 ms gained by predicting is not yet as large as the CIG's 80 ms time delay.

Acknowledgment

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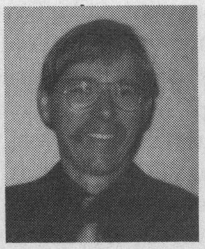

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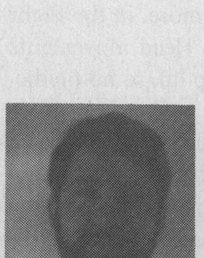

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