Visual Neuroscience (1996), **13**, 1059–1067. Printed in the USA.

Endpoint accuracy in saccades interrupted by stimulation in the omnipause region in monkey

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(RECEIVED March 11, 1996; ACCEPTED May 10, 1996)

Abstract

Electrical stimulation of the omnipause neuron region (OPN) at saccade onset results in interrupted saccades (IS)—eye movements which pause in midflight, resume after a brief period, and end near the target location. Details on the endpoint accuracy of IS do not exist, except for a brief report by Becker et al. (1981). Their analysis emphasized the accuracy of IS relative to the visual target which remained on during the interrupted period. We instead quantified the metric properties of IS relative to nonstimulated saccades during a target flash paradigm. Our results show that IS tend to be slightly hypermetric relative to the nonstimulated saccades to the same target location. The amount of overshoot is not correlated with target eccentricity. Detailed analyses also indicate that the standard deviations of the endpoint in IS are not significantly larger than those for nonstimulated saccades, although there was a much larger variability produced in eye position during the interruption. Both these latter observations support the notion that saccades are controlled by an internal negative feedback system. Also, the size of the remaining motor error during the interrupted period is one factor influencing when an IS resumes, but the variability in this measure is large particularly for smaller motor errors. Recent results have suggested that the resettable neural integrator involved in the feedback loop may be reset after each saccade through an exponential decay process. To probe the properties of the neural integrator, we varied the duration of interruption between the initial and resumed saccades and sought a systematic overshoot in the final eye position with increasing interruption period and variable initial saccade size. Our results showed the neural integrator does not decay during the pause period of interrupted saccades.

Keywords: Saccadic accuracy and precision, Interrupted saccades, Omnipause neurons, Resettable neural integrator, Superior colliculus

Introduction

The invariant properties of the oculomotor plant and the stereotyped trajectories of saccades once suggested that these rapid eye movements might be controlled by preprogrammed neural signals that could be computed prior to saccade initiation. However, it has been clearly shown that electrical stimulation of the omnipause neuron (OPN) region in the monkey brain stem at the onset of a saccade resulted in a trajectory perturbation called an interrupted saccade (IS) that still positioned the eyes near the target after the stimulation was turned off (Keller, 1977; King & Fuchs, 1977). These experiments showed that, in fact, saccades are controlled by an error-sensing feedback system. Robinson and his colleagues (Van Gisbergen et al., 1981) provided the theoretical underpinning for the concept of a local or efference copy feedback mechanism in their modeling work on the saccadic system. These authors used an efferent copy of eye position in orbital coordinates provided by a neural circuit they called the oculomotor integrator to generate the error signal in their model. More recent evidence suggests that the feedback comes from an integrator that is reset at the end of each movement, and thus provides an eye displacement signal (see Moschovakis & Highstein, 1994, for a review).

Some quantitative proof in monkey that interrupted saccades are indeed accurate has been provided by Becker et al. (1981) in a study in which the visual target remained on for the duration of the trial. Because interrupted saccades are abnormally long in duration, it was not clear if visual feedback was able to affect the accuracy of these movements in their study. Furthermore, Becker et al. (1981) emphasized the accuracy and precision of interrupted saccades relative to the target location, not to the average behavior of the nonstimulated saccades to the same target eccentricity. Therefore, the primary goal of the present study is to quantify the metric properties of interrupted saccades relative to nonstimulated when both are made in the absence of continuous target information.

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Recent work in monkey has suggested that the neural integrator may not be reset rapidly at the end of each saccade, but instead is reset through an exponential decay process with a time constant of about 50 ms (Kustov & Robinson, 1995; Nichols & Sparks, 1995). The amount of decay would depend on both the time constant and the size of the initial saccade. If during interrupted saccades the period between the initial and resumed saccades, during which the eyes stop moving, is treated by the system as an intersaccadic interval, then the integrator would begin to decay and the resumed eye movement would have to be hypermetric before the integrated eye displacement signal would equal the desired displacement. The loss of a veridical eye displacement signal would result in more inaccuracy of final eye position during interrupted saccades than has been previously reported. Consequently, our second objective was to vary the duration between the initial and resumed saccades by systematically changing the stimulation parameters, to compute the expected decay in the integrator and to determine if the resettable neural integrator decays during the pause period in interrupted saccades.

Finally, stimulation of the rostral region of the superior colliculus also interrupts saccades in monkey (Munoz & Wurtz, 1993; Gandhi & Keller, 1995) and gaze shifts in head-free cats (Paré & Guitton, 1994; Pélisson et al., 1995). To compare the perturbed movements resulting from altering the activity in rostral superior colliculus and the OPN region, we need quantitative details on the metrics of the interrupted saccades produced by stimulations at both sites. As yet, a thorough data base is unavailable for either case. Hence, a final aim of this work was to provide a complete quantitative analysis for interrupted saccades resulting from OPN stimulations. A similar detailed study of the interrupted saccades generated from superior colliculus stimulation will be presented in a future report.

Methods

Three juvenile, male monkeys (two *Macaca mulatta* and one *Macaca fasicularis*) were used for this study. The experiments involved recording eye movement signals as the monkeys made saccades to flashed visual targets and stimulating the OPN region of the brain stem to interrupt the eye movements in midflight. All experimental protocols were approved by the Institutional Animal Care and Use Committee at the California Pacific Medical Center and complied with the guidelines of the Public Health Service policy on Humane Care and Use of Laboratory Animals.

Preparation

The monkeys were prepared for eye movement recordings by implanting a scleral eye coil and head restraint system under sodium pentobarbital anesthesia and aseptic surgical conditions. Anesthesia was induced with an intramuscular injection of ketamine. Heart rate, respiratory rate, and body temperature were monitored for the duration of the surgery. A coil of Teflon-coated stainless-steel wire was implanted under the conjunctiva of one eye using the procedure of Fuchs and Robinson (1966), as modified by Judge et al. (1980). Stainless-steel tubes were embedded in dental acrylic attached securely to the animal's skull with orthopedic bone screws, permitting painless immobilization of the animal's head during the experimental sessions. Animals were returned to their home cage at the completion of these surgical procedures. Antibiotics (Ancef) and analgesics (Buprenex) were administered as needed in the postoperative period. Following complete recovery, the animals were trained to climb voluntarily from their cages into a customized primate chair for daily experimental sessions. The scleral eye coil, when used in conjunction with a pair of orthogonally aligned 20-kHz magnetic fields maintained electronically in temporal quadrature, produced a vertical and horizontal eye position measurement system with a sensitivity of 0.25 deg, zero drift, and a bandwidth of 1 kHz (Robinson, 1963). Horizontal and vertical eye velocity was obtained directly by analog differentiation (with a cutoff frequency of 170 Hz) of the position signals yielding an r.m.s. velocity noise of about 1 deg/s. Data presented here are given as radial eye position and velocity, each computed by the Pythagorean sum.

Two stainless-steel chambers, one over the superior colliculus region and the other over the OPN region, were implanted as described by Keller and Edelman (1994). Studies, for which these monkeys were used as subjects, exploring the role of superior colliculus and OPNs for saccadic control have been published elsewhere (Gandhi et al., 1994; Keller & Edelman, 1994; Gandhi & Keller, 1995). Microelectrode penetrations were made in the OPN chamber until the OPN region was located. Determination of this location was based on the unique discharge characteristics of the neurons in the region and their relationship to saccadic eye movements (Keller, 1974). A stimulating microelectrode was then implanted at this site, as described by Keller and Edelman (1994). This stimulating electrode was a commercially purchased tungsten microelectrode (Frederick Haer #25-08-21535) surrounded by a concentric stainless-steel guide tube which extended to a depth of about 6 mm above the microelectrode tip. There did not appear to be any adverse effects on the animals' behavior caused by these implanted electrodes.

Behavioral procedures

During the recording sessions, the monkeys were seated in a primate chair with their heads restrained for the duration of the session (3–4 h). The animals were trained to execute behavioral paradigms for liquid rewards, and were allowed to work to satiation during experimental recording sessions. Records were kept of each animal's weight and health status and supplemental water was given as necessary. The animals typically were scheduled for experimental sessions for five weekdays and then were allowed free access to water on the weekends.

Behavioral paradigms, the visual displays, and the storage of data were under the control of a real-time program running on a laboratory PC system. Horizontal and vertical eye position and velocity recordings were sampled at 1 kHz and stored on computer disk. Visual targets were backprojected on a translucent screen with an oscilloscope projector system (Crandall & Keller, 1985). This system produced a 0.25-deg diameter spot (2.0 cd/cm^2) on the 90-deg × 90-deg screen located at 40 cm in front of the monkey. Also, the tangent screen was diffusely illuminated by dim homogeneous background illumination (0.05 cd/cm^2).

For the purposes of the present study, the experimental paradigm was a simple variation of the standard visually guided eye movement. The monkey was required to initially fixate a central fixation target. After a random interval (500–900 ms), the central fixation target was extinguished and, simultaneously,

a peripheral target was briefly flashed (typically for 80–120 ms). The use of a flashed target ensured that all visual stimuli were off before saccade onset, which typically occurred about 150 ms after the fixation point offset, and that the saccade was completed without further visual feedback regarding target location. For approximately 50% of the trials within each block, electrical stimulation, triggered at the onset of the eye movement, was applied through the microelectrode implanted in the omnipause region chamber. Off-line inspection revealed that the trigger point occurred 4 ms (±2 ms) after the beginning of saccades. Within a block of trials, the nonstimulated and stimulated (interrupted) saccades were randomly interspersed.

The analog stimulator controls were set to produce symmetrical bipolar pulses of constant current (0.25-ms pulse widths for each pulse in the pair). Pulse train frequency was varied between 300–400 pulses/s and train length was varied between 10–25 ms. The number of pulses in a stimulating train ranged from 3 to 10. Current intensity was controlled by an optical isolator (Tektronix model 2620 constant current stimulator) that delivered its output pulses across the microelectrode implanted in the OPN region and its concentric stainless-steel guide tube. Current intensity was set at a value that produced an interrupted saccade effect on ~90% of the stimulated trials. This threshold intensity varied from 10–30 μA.

In two animals (monkeys *G* and *M*) the amplitude of the target displacement was fixed within a block of trials at 20, 25, or 30 deg and target direction was fixed at an angle within ±45 deg of horizontal. For monkey *H*, a target was selected at random on each trial from a grid of points that varied in radial amplitude (20, 25, 30, 35, 40, and 45 deg), and direction was fixed near horizontal as in the first two animals. Because preliminary analysis showed that the saccade dynamics did not vary within the restricted range of directions for a particular target amplitude, we have grouped and present here data on saccades in terms of amplitude alone.

Results

We stimulated the OPN region in three monkeys as the animals attempted to make saccadic eye movements to briefly flashed targets. Fig. 1 illustrates typical interrupted saccades in animal *H* from a block of trials for a target amplitude of 25 deg. Similar results were produced in all three animals. The set of saccades shown on the left illustrate nonstimulated (control) trials while those on the right are stimulated trials taken from the block in which trials of each type were randomly interleaved. These raw results indicate that the endpoint accuracy for both types of trials was qualitatively very similar even though the trajectories of the interrupted movements were highly perturbed temporally in comparison to controls.

To quantify the impressions made by the data shown in Fig. 1, we made the measurements illustrated in Fig. 2 on each interrupted saccade in the complete data set for each animal. In particular, we wished to determine the accuracy of the interrupted movements in comparison to noninterrupted saccades. The measure of accuracy we used was the difference between the endpoint after the resumed movement of each interrupted saccade and the mean endpoint for nonstimulated movements

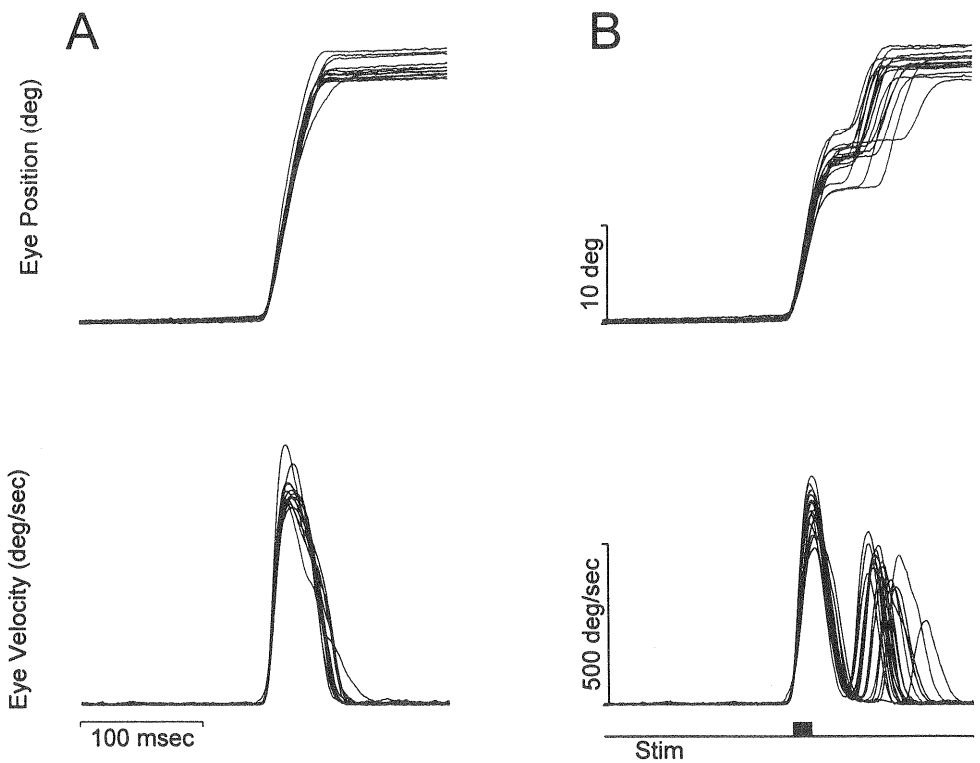

Fig. 1. Typical interrupted saccades from a block of trials for a target displacement of 25 deg. The trials are sorted into nonstimulated (A) and stimulated (B) examples and aligned on saccade onset. The upper set of traces in each are radial eye position and the lower set of traces are eye velocity. In (B), the lowest trace shows the envelope of the electrical stimulation applied in the OPN region.

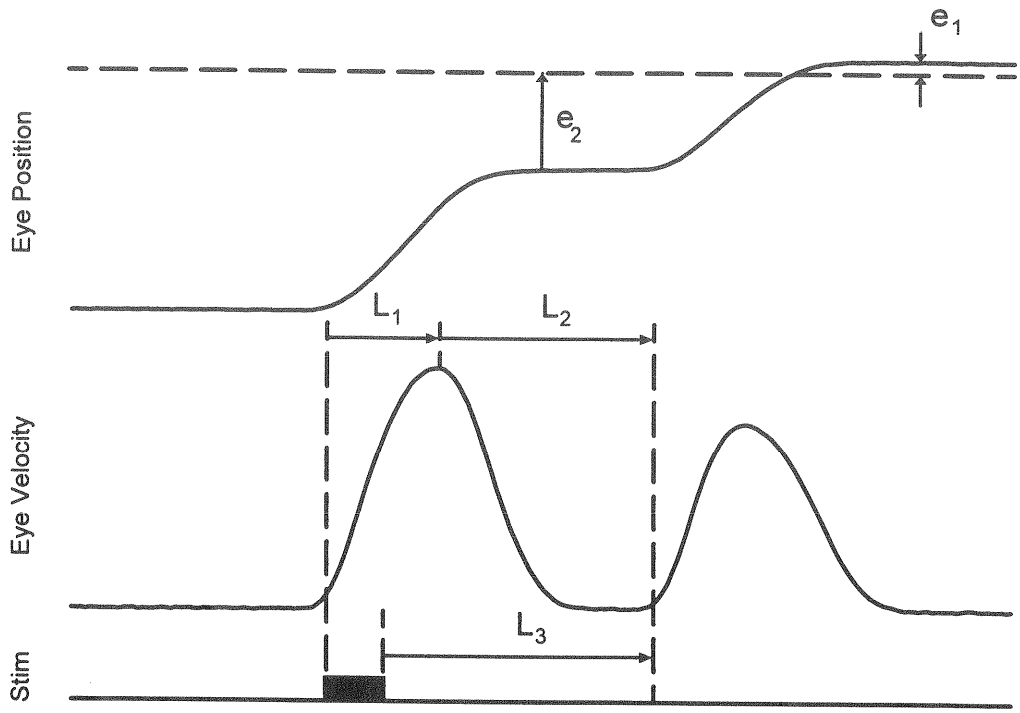

Fig. 2. Schematic drawing that illustrates the various measurements made in the current study on each interrupted saccade. The upper trace is radial eye position, the middle trace is radial eye velocity, and the lower trace is stimulus envelope. The horizontal dashed line indicates the mean saccadic endpoint for nonstimulated saccades to targets of the same amplitude. The error, e_1, is the difference in final position between the average nonstimulated saccade and the individual interrupted trials. The error, e_2, is the difference in the eye position between the average saccadic endpoint for nonstimulated saccades and the individual endpoints at the time of interruption for stimulated trials (i.e. remaining motor error). The temporal intervals marked by arrows on the eye velocity schematic illustrate the time after stimulus onset until movement interruption (L_1), the time from movement interruption until movement resumption (L_2), and the time from the end of the stimulation until the resumption of the saccade (L_3).

(horizontal dashed line) for the same target amplitude. This measure is indicated as e_1 on Fig. 2. Positive values of e_1 mean that the interrupted movement was hypermetric with respect to the average behavior for control movements (for the same target displacement), whereas negative values indicate hypometric relative behavior. We also measured the remaining motor errors (e_2), the differences between the mean final eye position obtained in control trials, and the eye positions at the onset of the interrupted periods.

We measured the latency (measurement L_1) from the onset of the stimulation to the onset of the interruption. The onset of the interruption was determined by two methods: (1) the time of eye velocity peak in the first movement, and (2) the time point for which each interrupted saccade's velocity trace fell more than two standard errors below the mean velocity plot of the nonstimulated saccades for that particular target amplitude and that particular animal. We found that these two values agreed systematically within 2–3 ms, so we adopted the peak velocity method on the interrupted movements as the standard measure for all of the analyses reported here. We also measured the latency from the time of interruption to the time of resumption of the individual stimulated movements (measurement L_2). An eye acceleration method was used to compute the times of the resumed saccade onset (Keller & Edelman, 1994). A closely related measurement of the latency of movement resumption (L_3), as described by Becker et al. (1981) and illustrated in Fig. 2, was defined as the time from the end of the stimulus train to the resumption of the movement.

Accuracy and precision of interrupted saccades

We show in Fig. 3A the mean endpoints and the standard deviations for nonstimulated saccades for movements made to targets at eccentricities from 20 to 45 deg for monkey *H* and from 20 to 30 deg for monkeys *G* and *M*. The data show that the animals in general made hypometric saccades to the location of the targets (that been turned off prior to movement onset) with the exception that monkey *H* made slightly hypermetric saccades to targets at the 20- and 25-deg locations. The amount of hypometricity increased as target eccentricity increased (reaching about 7 deg for the largest target eccentricity of 45 deg in animal *H*). The standard deviations of the nonstimulated movements remained rather constant for target displacements up to 40 deg, but then increased somewhat for the largest target displacement. Actual values for these variables are given in Table 1.

Fig. 3B shows similar data for interrupted saccades, except that accuracy now is plotted as error of the endpoint of the interrupted saccades relative to the mean endpoint for control saccades made to the same target location (the measurement e_1 in Fig. 2 and Table 1). From Fig. 3B, it can be seen that the eye

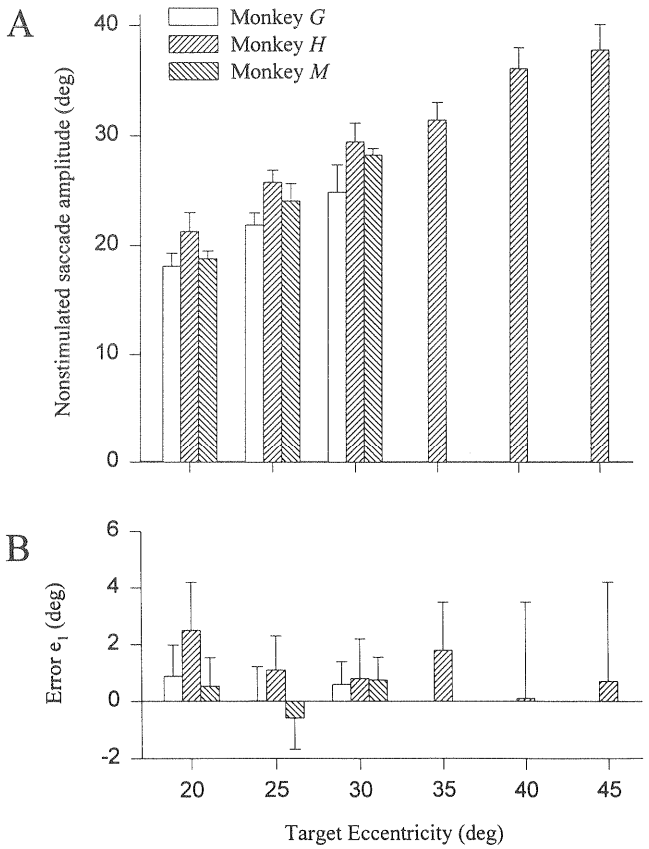

Fig. 3. A: Mean values for the amplitudes of nonstimulated saccades as a function of target eccentricity in the three animals. See Table 1 for the number of measured saccades of each size. B: Mean values of the accuracy of interrupted saccades relative to the mean behavior obtained during noninterrupted movements as a function of target eccentricity (error measure e_1). The magnification of the vertical scale in (B) was increased so that the small values of the error could be seen. In both (A) and (B), the error bars indicate the standard deviations.

position reached at the end of interrupted saccades was in general almost the same as that for nonstimulated saccades. The errors, although small, did however tend to be hypermetric with respect to nonstimulated saccades except for the case of 25-deg target displacements in animal *M*. Fig. 3B imparts an impression that this small degree of hypermetria did not vary systematically with target amplitude. We confirmed this impression by fitting the data for each animal with separate linear regressions for error as a function of target eccentricity. In all cases, the slopes of the regressions were not significantly different than zero (two-tailed *t*-tests, $P > 0.5$). The values of the correlation coefficients were 0.19, 0.10, and 0.02 for monkeys *H*, *G*, and *M*, respectively. Since the hypermetria did not depend systematically on target size, we combined all of the error measurements and computed a grand mean value of error for each animal, which were +1.25 deg, +0.49 deg, and -0.28 deg for monkeys *H*, *G*, and *M*, respectively.

The precision of endpoint control at the termination of resumed saccades was only slightly degraded from that observed at the end of nonstimulated saccades, except for the two largest target displacements. This is seen by comparing the standard deviations of the endpoints for nonstimulated saccades with the standard deviations of the errors as given in Table 1. The standard deviations for the latter were not significantly larger (*F* tests, $P > 0.05$) for any target displacements in any of the animals, but the standard deviations did become noticeably larger for interrupted movements to 40- and 45-deg target displacements in animal *H*.

We measured the eye positions reached during the interrupted period for each interrupted saccade and compared the variability (the standard deviation) present in these measurements with those generated at the end of the resumed movements in the same trials. The data for the eye positions during the interruptions are given in Table 1 for all animals. The results of this comparison indicate that precision was greatly improved (usually by a factor of about 2) at the end of the resumed saccades in interrupted trials in comparison to that present during the interrupted period. The exception was again for the largest target displacements in monkey *H* where the variabilities at the end of the resumed movements were about the same as those present at the end of the initial saccade.

Relationship of hypermetria to latency of the resumed movement

We have shown above that interrupted saccades are on average slightly hypermetric with respect to the behavior obtained for nonstimulated saccades to the same target eccentricity, i.e. the direction of the error that is predicted by a system that has a resettable integrator that keeps track of eye displacement and is reset exponentially in time at the end of each saccade (Kustov & Robinson, 1995; Nichols & Sparks, 1995). We next asked whether the hypermetria depended on the length of the interrupted period (the measurement L_2 in Fig. 2) and the size of the initial movement, as it should if a resettable integrator coding the change in eye position were decaying during this period. The open circles in Fig. 4 show scatter plots of error versus latency L_2 for all 124 interrupted saccades in monkey *H* (top) and all 95 saccades in monkey *G* (bottom). The data suggest that the sign and magnitude of the error do not depend on how long the movement was stopped, and this impression was confirmed by fitting the data with a linear regression line. The slope of the regression line for the data shown in Fig. 4 was found to be not significantly different than zero (*t*-test, $P > 0.5$; correlation coefficient, 0.13 and 0.02 for monkeys *H* and *G*, respectively). Similar conclusions were reached in monkey *M* ($r = 0.14$).

The filled circles in Fig. 4 represent the hypermetria predicted by the leaky integrator model with time constant of 40-ms versus latency L_2 for the same saccades in both monkeys. This time constant was chosen as a conservative estimate of that found in other studies (Kustov & Robinson, 1995; Nichols & Sparks, 1995). The expected overshoot is equivalent to the decay in the resettable neural integrator. Thus, if T is the amplitude of the initial saccade and τ is the time constant of the decay, then the values of the closed circles in Fig. 4 equal

$$T(1 - e^{-L_2/\tau}) \quad (1)$$

Factors that influence the length of time of the interrupted period

Becker et al. (1981) suggested that the size of the remaining motor error at the time of interruption (the measurement e_2 on

Table 1. *Metric and temporal parameters of nonstimulated and interrupted saccades*

		Target displacement (deg)															
		20			25			30			35			40			45	
Measure	Monkey[a]	*n*	Mean	S.D.	*n*	Mean	S.D.	*n*	Mean	S.D.	*n*	Mean	S.D.	*n*	Mean	S.D.	*n*	Mean	S.D.
Endpoint of nonstimulated saccades	*H*	42	21.3	1.7	24	25.8	1.1	38	29.5	1.7	20	31.5	1.6	21	36.2	1.9	11	37.9	2.3
	G	41	18.1	1.2	28	21.9	1.1	37	24.9	2.5									
	M	39	18.8	0.7	33	24.1	1.6	10	28.3	0.6									
Error (e_1) for interrupted saccades	*H*	15	2.50	1.7	24	1.10	1.2	33	0.80	1.4	32	1.8	1.7	12	0.1	3.4	8	0.7	3.5
	G	30	0.88	1.1	31	0.02	1.2	34	0.59	0.8									
	M	19	0.53	1.0	31	−0.59	1.1	7	0.75	0.8									
Eye position during interruption	*H*	15	15.4	2.4	24	17.2	2.2	33	19.0	2.4	32	18.8	2.7	12	20.1	3.4	8	18.9	3.2
	G	30	10.6	3.2	31	10.9	2.0	34	11.9	2.6									
	M	19	12.4	0.9	31	13.5	3.4	7	18.1	1.6									
Latency (L_1)	*H*	15	19.5	1.2	24	20.2	2.0	33	22.5	10.3	32	25.8	16.4	12	24.1	10.5	8	26.3	17.7
	G	30	35.1	24.0	31	28.4	19.4	34	33.1	22.5									
	M	19	20.1	3.8	31	23.7	10.2	7	21.0	1.0									
Latency (L_2)	*H*	15	38.0	54.5	24	26.7	40.9	33	16.9	15.7	32	14.3	12.3	12	7.8	4.5	8	13.4	14.6
	G	30	35.6	23.2	31	9.1	15.3	34	11.6	11.3									
	M	19	34.3	33.4	31	50.4	38.9	7	18.3	13.8									
Latency (L_3)	*H*	15	57.9	51.3	24	47.3	37.5	33	32.3	12.5	32	29.0	6.6	12	26.6	1.7	8	29.3	3.8
	G	30	47.5	21.8	31	29.1	6.7	34	31.4	9.3									
	M	19	55.4	35.8	31	66.8	35.6	7	39.9	11.6									

[a]Saccades to 35-, 40-, and 45-deg target displacements were collected only in monkey *H*. The unit of measurements in the first three rows is degrees and in the last three rows is milliseconds.

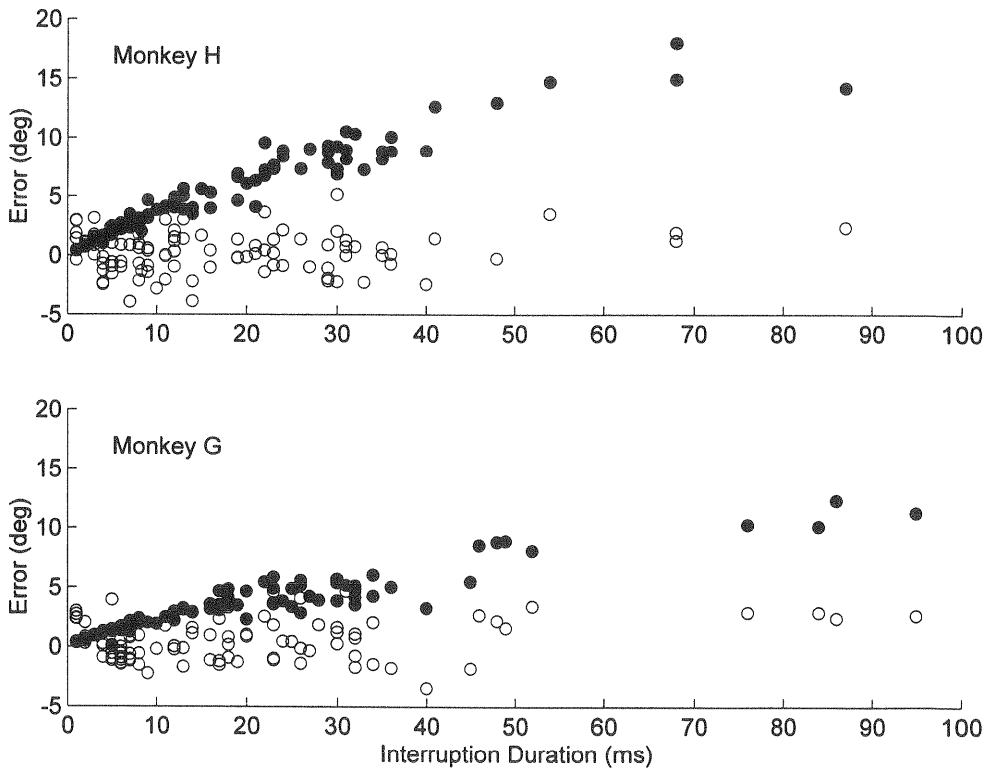

Fig. 4. Relationship between error and the amount of time the saccade was interrupted. Error was defined as measurement e_1 and the duration of interruption was defined as L_2 (see Fig. 2). The open circles are the errors obtained from interrupted saccades data and the filled circles are the expected hypermetria (for the observed L_2 measurement and initial saccade size) due to a leaky integrator model with time constant of 40 ms. Top: Data from 124 saccades in animal *H*. Bottom: Data from 95 saccades in animal *G*.

Fig. 2) affected how long the movement was interrupted. They found that the interrupted period was short and remained rather constant for larger residual motor errors, but then showed a sharp increase in duration as motor errors became smaller than about 10 deg. They measured the time of interruption from the end of the stimulation train. To compare our results with theirs, we made a similar measurement for each interrupted saccade (measurement L_3 in Fig. 2). Fig. 5 shows the relationship of interrupted time to residual motor error for all interrupted saccades in all three monkeys. The results are qualitatively similar to those obtained by Becker et al. (1981), but our values for the duration of the interrupted period were considerably longer and showed more scatter than theirs. The mean value of duration of the interrupted period for our data for residual motor errors larger than 10 deg was 33 ms in comparison to a value of 18 ms, calculated from data given in Fig. 3 in Becker et al. (1981).

Latency of the onset of interruption

The latency of the onset of saccade interruption (measurement L_1 on Fig. 2) showed very little scatter and was nearly the same for all three monkeys. The overall mean latency was 20.2 ms (S.D. = 1.5 ms, $n = 276$).

Discussion

Saccadic accuracy and precision

Overall, the present results support earlier, more limited reports which suggested that interrupted saccades are very accurate (Keller, 1977; King & Fuchs, 1977; Becker et al., 1981). The grand mean error for the 276 interrupted saccades measured in the three animals, where error was defined in our study as the difference between saccadic endpoint at the termination of interrupted saccades and the mean endpoint of nonstimulated saccades to the same target position was 0.67 deg (S.D. = 1.64). This degree of accuracy is rather remarkable given the temporally perturbed trajectories and the wide range of interruption durations (latency L_2) produced by electrical stimulation in the OPN region for all target eccentricities (see Table 1). The results add quantitative proof to support the original hypothesis of Robinson (1975) that saccades must be controlled by internal feedback and not generated by preprogrammed neural signals.

The present results were carried out under conditions in which the visual target that elicited the saccade was turned off before the onset of the movement so that afferent visual feedback of retinal error was eliminated as a possible source of error feedback. Because longer duration interrupted trials could be 100 ms or longer before the eyes reached their final position, earlier studies in the monkey, in which the visual target remained on for the duration of each trial, had not eliminated the possibility of some visual contribution to the accuracy achieved by the saccadic system in interrupted movements.

Our results indicate that visual feedback cannot contribute to the accuracy of interrupted saccades. The information which can be extracted from Fig. 4B of Becker et al. (1981) implies that interrupted saccades tend to be hypermetric relative to nonstimulated saccades to the same target location and that the hypermetria decreases as the target eccentricity decreases. The former finding is also evident in our study (Fig. 3B), but our

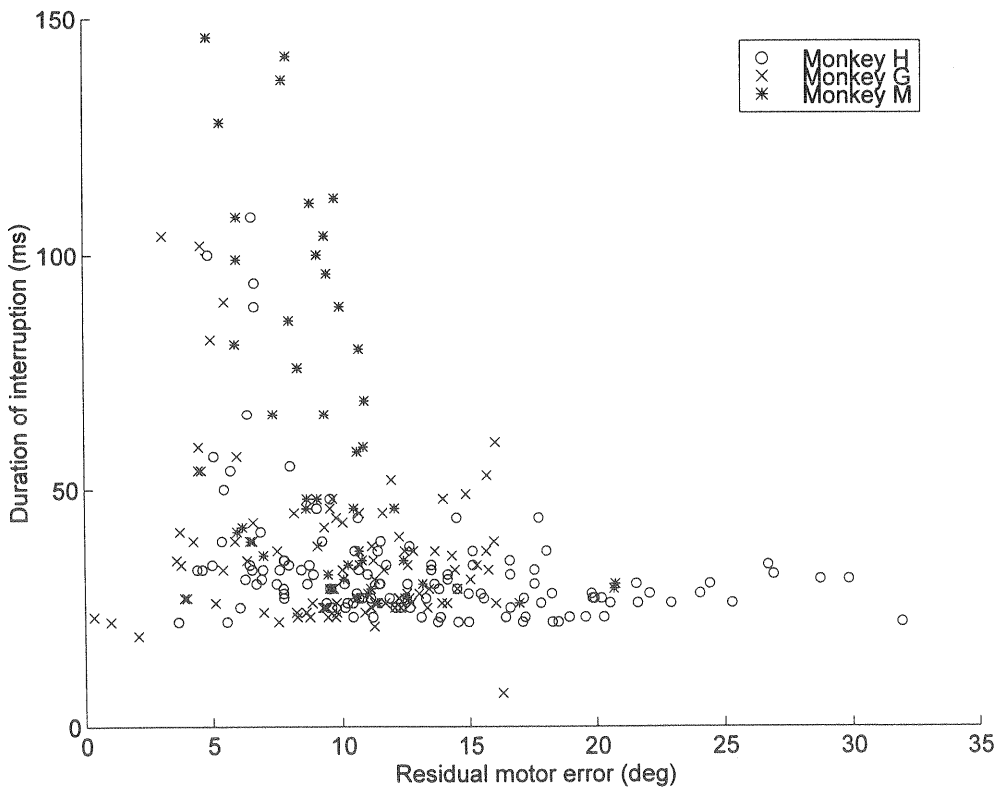

Fig. 5. Relationship between the duration of the period of interruption to the residual motor error. Residual motor error was defined as e_2 and interrupted period as L_3 on Fig. 2. The data is presented by separate symbols for each of the three animals.

more quantitative analysis indicates that the latter trend is not statistically significant.

Properties of the resettable neural integrator

Although the errors were small, there was a tendency for all of the mean errors for all target eccentricities and for all animals to be hypermetric. This is the direction of the error that is predicted by current models of the saccadic system that form the controlling internal error signal by comparing present eye displacement from a leaky neural integrator with desired total eye displacement. To see this, consider the equation that represents mathematically this hypothesis for the neural generation of the error signal:

$$e(t) = \Delta E_d - \Delta E(t) \quad (2)$$

where $e(t)$ is instantaneous internal error, ΔE_d is the desired final eye displacement, and $\Delta E(t)$ is the feedback signal from a leaky integrator encoding current eye displacement. If the feedback signal came from an ideal resettable integrator that was zeroed instantaneously after each saccade, then any subsequent saccade, even if made shortly after the end of another saccade, should be equally accurate to the first. Recent experiments in the monkey in which the superior colliculus was stimulated to evoke a new saccade near the end of an ongoing visually guided saccade have suggested instead that the integrator is actually reset along an exponential time course with a time constant of about 50 ms (Kustov & Robinson, 1995; Nichols & Sparks, 1995). In the simplest case when the eye movement evoked by the collicular stimulation is in the same direction as ΔE_d, the leaky integrator will retain a nonzero eye position signal from the just completed movement for a period of time (e.g. three time constants). Thus, when the collicular-stimulation evoked saccade begins, the resulting saccades were found to be smaller than the movements evoked by that superior colliculus site when the stimulation was delayed after the end of a normal saccade by several hundred milliseconds. In the case of interrupted saccades, if the interrupted period (during which the eyes can stop completely) were treated by the system as the end of a saccade, then the integrator would begin to decay and the resumed movement would have to become hypermetric before the integrated eye displacement signal would equal ΔE_d. The data in Fig. 4 show that this is not the case. The hypermetria is not correlated with the length of time that the saccade is interrupted, and the amount of overshoot is not nearly as large as would be expected if a leaky memory of current eye displacement were the cause of this systematic error. We conclude that interrupted saccades are treated as one movement and the integrator is not allowed to decay during the interrupted periods which can be very variable in duration and last for nearly 100 ms as shown in Fig. 4.

Instead, we think that it is more likely the first term in the equation (ΔE_d) might point to the source of the small, but consistent, observations of hypermetria present in interrupted saccades. The neural representation of the desired change in eye position signal is at the present time unclear, but it is most likely a distributed signal from a place-coded structure like the superior colliculus. Keller and Edelman (1994) have shown that saccadic burst neurons in the superior colliculus are rapidly and totally inhibited by OPN stimulation and remain silent until near the end of the interrupted period. These same neurons then show a second burst of discharge during the resumed movement, and the amplitude of this burst is slightly, but systematically, larger than that expected for the size of the remaining movement. If these neurons were part of a neural circuit providing distributed coding of ΔE_d, then equation (2) and the results of Keller and Edelman predict that interrupted saccades would be hypermetric. Exactly the opposite effect would be predicted by models that use a precomputed stereotyped superior colliculus signal for ΔE_d that would continue to decline in amplitude during the interrupted period (Scudder, 1988).

Another possible interpretation of our results is that the leaky integrator model is simply wrong. While Kustov and Robinson (1995) claimed that the resettable neural integrator decays during and after a saccade and Nichols and Sparks (1995) argued that it decays after a saccade, both studies appeared to have observed the same phenomenon as demonstrated by the agreement about the time constant of the decay. Since the accuracy of interrupted saccades shows that the resettable neural integrator does not decay during saccades, one must consider the possibility that the observations of the previous studies may not reflect a decay in the resettable neural integrator.

Examination of the variability present in the final end position in interrupted saccades (the standard deviation of the measure e_1 in Table 1) in comparison to the variability present at the time of interruption (the standard deviation of the measure called eye position during the interruption in Table 1) provides additional evidence that saccades are controlled by an error-sensing internal mechanism. The mean overall variability present during the interrupted period in the three animals was 4.3 deg. This large scatter was reduced to a overall mean value of 1.3 deg at the end of the resumed movement. This reduction by a factor of almost four in eye position noise is exactly the effect that is predicted in a saccadic system controlled by internal negative feedback.

The resettable neural integrator and the spatial location of collicular activity

Several findings/assumptions can help explain the saccade metrics and collicular activity observed during resumed saccades reported by Keller and Edelman, 1994. First, the presentation of the target creates an initial motor error equivalent to the retinal error while setting the resettable neural integrator to zero. Second, the motor error must decrease and the resettable neural integrator must increase as the eyes move toward the target. Third, the resettable neural integrator and motor error must stay constant during the period between the end of the initial saccade and the onset of the resumed movement (when the eyes are still); this result has been demonstrated in this report. Fourth, at the end of the resumed movement the motor error and the resettable neural integrator are set to zero, either exponentially or *via* other mechanisms.

In the Keller and Edelman (1994) report, saccades were interrupted in midflight while activity in the superior colliculus burst neurons during the resumed saccades was recorded. If the resettable neural integrator and the motor error signals were held constant during the interruption duration, the desired displacement signal necessary to drive the motor error to zero would be equivalent to the initial motor error. Therefore, the superior colliculus neurons that burst for the initial saccade must also burst for the resumed saccade, as observed by the authors. However, neurons which encode a constant motor error during the pause period have not yet been reported.

Superior colliculus stimulation induced interrupted saccades

Finally, we wish to make some comparisons between the interrupted saccades that we have produced by stimulation of the OPN region in the present study and the interrupted saccades that can be produced by stimulation of the rostral region of the superior colliculus in monkey (Munoz & Wurtz, 1993; Gandhi & Keller, 1995). Similar compensatory interrupted gaze shifts have been reported in the cat following collicular stimulation (Paré & Guitton, 1994; Pélisson et al., 1995). Munoz and Wurtz (1993) initially showed and we (Gandhi & Keller, 1995) have confirmed that the interrupted saccades produced by electrical stimulation of the rostral region of the superior colliculus in monkey tend to be hypometric, but neither study reported quantitative data on this effect. Even though the mechanism of interrupted saccades produced by superior colliculus stimulation is unclear and controversial (Gandhi & Keller, 1995), the undershoot effect is in direct contrast to the resettable neural integrator theory prediction. A possible explanation for the hypometricity is that stimulation of the superior colliculus leads to the creation of two active loci on the collicular motor map, one at the rostral site of the stimulation and one at the caudal collicular site associated with the initial ongoing saccade. Because the creation of two separate loci of collicular activity has been shown to lead to a spatial averaging phenomenon in which the resulting saccade is made to a location representing the spatial average of the two active sites (Robinson, 1972; Van Opstal & Van Gisbergen, 1990), it might be expected that rostral stimulation during an ongoing saccade would lead to an overall movement that would be hypometric at the completion of the interrupted movement.

Acknowledgments

This work was supported by National Institutes of Health Grants EY-06860 and EY-06883 and the Smith-Kettlewell Eye Research Foundation.

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