J. Physiol. (1980), **300**, *pp* 539–555
With 9 text-figures
Printed in Great Britain

DISCHARGES OF PURKINJE CELLS AND MOSSY FIBRES IN THE CEREBELLAR VERMIS OF THE MONKEY DURING SACCADIC EYE MOVEMENTS AND FIXATION

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(*Received 3 May 1979*)

SUMMARY

1. Discharges of Purkinje cells and of presumed mossy fibres were extracellularly recorded from vermal lobules VI and VII of two monkeys during saccadic eye movements and fixation. Among the units showing changes in activity in relation to either saccades or eye position, eighty-four units were identified as mossy fibres and ninety-one units were Purkinje cells.

2. Based on the discharge patterns associated with saccades, mossy fibre units were classified into long-lead burst, burst, and burst-tonic units. The long-lead burst units (twenty-eight units) started firing long before the saccades, the discharge consisting of a prelude (average lead time: 160 msec) and a burst (average lead time: 16 msec). In twenty-two units the saccade-related bursts showed a directional preference. The burst units (thirty-seven units) started firing slightly before the saccade onset (average lead time: 7·4 msec) and thirteen units showed directional preference. The bursts in burst-tonic units (thirteen units) had an average lead time of 0·2 msec.

3. Among the ninety-one Purkinje cells, eighty-eight cells showed bursts associated with saccades. Three units paused for all directions of saccades.

4. Seventy-one units out of the eighty-eight burst Purkinje cells showed bursts beginning approximately at the saccade onset (average lead time: 0·6 msec) and lasting throughout the saccade. The durations of bursts and saccades were highly correlated (correlation coefficients ranging from 0·70 to 0·88).

5. In the remaining seventeen burst Purkinje cells, the bursts followed the saccade onset (average delay: 32 msec). The bursts started approximately 40 msec before the end of a saccade and persisted on the average 70 msec after its completion. Peak firing rate occurred with a close temporal relation to the end of the saccade.

6. The tonic activity in nineteen mossy fibres and five Purkinje cells changed with eye positions. In the nineteen mossy fibres, there were thirteen burst-tonic and six tonic units. The activity in the five Purkinje cells was a linear function of horizontal eye position.

INTRODUCTION

Ever since electrical stimulation of the posterior vermis was found to elicit eye movements (Hoshino, 1920) a considerable number of investigations have been undertaken to discern what function this structure performs in connexion with the oculo-

0022-3751/80/7070-0190 $07.50

motor system. Two lines of evidence have implicated the vermis especially in saccadic eye movements. Localized stimulation with well controlled current induced ipsilateral saccadic eye movements (Cohen, Goto, Shanzer & Weis, 1965; Ron & Robinson, 1973) and vermal ablation impaired the frequency or accuracy of saccadic eye movements (Aschoff & Cohen, 1971; Ritchie, 1976).

Recent studies have revealed the rich anatomical connexions of the posterior vermis which receives mossy fibre inputs from the pontine nuclei and reticular tegmental pontine nucleus (Hoddevik, Brodal, Kawamura & Hashikawa, 1977) as well as climbing fibre inputs from the inferior olive (Hoddevik, Brodal & Walberg, 1976). All of these structures, in turn, receive substantial inputs from the superior colliculus (Kawamura & Brodal, 1973; Kawamura, Brodal & Hoddevik, 1974). The posterior vermis also receives inputs from the vestibular nuclei (Brown-Gould & Graybiel, 1976; Precht, Volkind & Blanks, 1977; Batini, Buisseret-Delmas, Corvisier, Hardy & Jassik-Gerschenfeld, 1978) and from the prepositus hypoglossal nucleus (Brodal, 1952; Batini *et al.* 1978). These nuclei have additional projections directly to the oculomotor and abducens nuclei (Precht, 1977). The same region of the vermis also receives proprioceptive inputs from the extraocular muscles (Fuchs & Kornhuber, 1969; Baker, Precht & Llinás, 1972; Schwartz & Tomlinson, 1977). The output of the posterior vermis is directed to the vestibular nuclei and reticular formation either directly or via fastigial nuclei (Haines, 1975; Batton, Jayaraman, Ruggiero & Carpenter, 1978). Such anatomical connexions implicate a close functional relationship between the posterior vermis and saccade-related structures in the brain stem.

Physiological studies on the structures involved with saccadic eye movements in alert monkeys have been remarkably extensive. Single unit recording techniques have been used to characterize the patterns of neuronal activity occurring in relation to eye movements in the oculomotor nucleus (Robinson, 1970; Henn & Cohen, 1973), the abducens nucleus (Luschei & Fuchs, 1972), the pontine reticular formation (Luschei & Fuchs, 1972; Keller, 1974), the superior colliculus (Schiller & Koerner, 1971; Wurtz & Goldberg, 1972), the prepositus hypoglossal nucleus (Baker, 1977), the vestibular nuclei (Miles, 1974; Fuchs & Kimm, 1975), and the flocculus (Noda & Suzuki, 1979). A detailed account of discharge patterns of vermal units in regard to saccades is necessary in order to understand what operation the vermis may perform and what role it may play among these structures. This report describes the detailed temporal analysis of activity in individual vermal mossy fibres and Purkinje cells of alert monkeys during saccadic eye movements and fixation. These data are interpreted with reference to the other single unit studies in order to throw light on the possible functions of the vermis in saccadic eye movements. Preliminary reports of these data have already appeared (Kase & Noda, 1977, 1978).

METHODS

(1) *Identification of Purkinje cells and mossy fibres*

A total of 430 units, exhibiting phasic changes in activity associated with saccadic eye movements (saccades), were recorded from the posterior vermis (lobules VI and VII) of two monkeys (*Macaca nemestrina*). From the total, ninety-one units were identified as Purkinje cells and eighty-four units were mossy fibre units. Purkinje cells were identified by the presence of complex spikes interspersed with simple spikes (Thach, 1970), as seen in Fig. 1 *A* where complex spikes are

indicated by small circles. This characteristic discharge pattern is believed to be caused by discrete afferents; mossy fibres maintaining tonic simple spike activity through the excitatory granule cell-parallel fibre system, and climbing fibres directly giving rise to complex spikes (Jansen & Fangel, 1961; Eccles, Llinás & Sasaki, 1966*a*; 1966*b*). A further discussion concerning the identification of Purkinje cell activity has been made in separate papers on floccular units (Noda, Asoh & Shibagaki, 1977; Noda & Suzuki, 1979). All positively identified Purkinje cells were characterized by a high tonic firing rate of simple spikes which averaged 30–150 spikes/sec in the majority of units. In many units the tonic rate of discharge changed with shifts in gaze but was never below 15 spikes/sec for any fixation period longer than one second. Complex spikes occurred at a low frequency, averaging about one per second and showed no discernible temporal relationship with eye movements.

In contrast to Purkinje cells, mossy fibres exhibited a single type of action potential and a gaze position could always be found for which firing ceased completely (Fig. 1*C*). Some mossy fibre units, in fact, were silent during all periods of fixation in any gaze position and were characterized by discharges only during saccades (Fig. 1*B*). The eye-movement-related discharge patterns observed in mossy fibre units, therefore, differed markedly from the discharge patterns observed in the identified Purkinje cells. Some other fibre units encountered in white matter between Purkinje cell layers exhibited low frequency discharges which were comparable

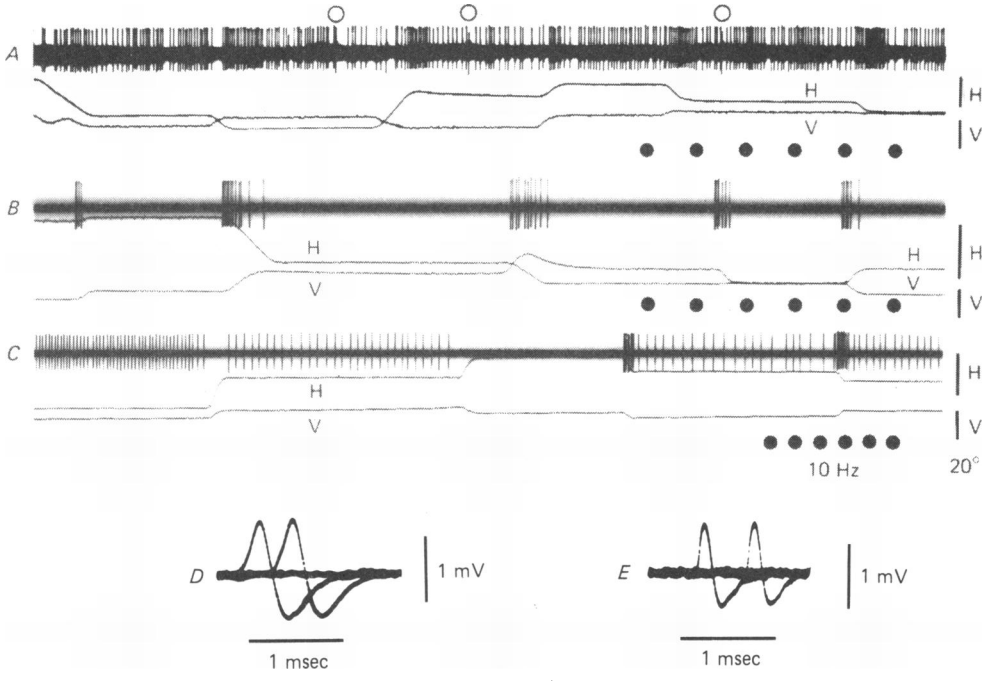

Fig. 1. Examples of discharge patterns of a Purkinje cell (*A*) and of mossy fibres (*B* and *C*). Note that the Purkinje cell exhibited simple and complex (marked with a small circle) spikes. *B*, burst discharge of a mossy fibre. Note the lack of directional preference for the bursts and the absence of activity during fixation. *C*, burst-tonic activity in a mossy fibre. Note that bursts were observed with saccades in the preferred direction and pauses in the non-preferred direction. Beyond a position threshold, tonic activity changed with shifts of fixation points. *D*, examples of cellular spikes. Note the slow rising phase and long spike duration which exceeded 1 msec. *E*, examples of axon spikes. Note the sharp non-inflected rising phase and short spike duration. The spikes were photographed from the data recorded on magnetic tapes with a system having a response frequency ranging from 50 Hz to 10 kHz. In this and succeeding Figures H and V are horizontal and vertical electro-oculograms, respectively.

to complex spikes of the Purkinje cells. They were presumably climbing fibres. Based on these differences, discharges of mossy and climbing fibre units could be distinguished from the firing patterns recorded from axons of Purkinje cells.

Spike configuration was also different between cellular and fibre units. Action potentials of fibre units showed a sharp non-inflected rising phase and short spike duration which never exceeded one millisecond (Fig. 1 *E*) whereas cellular spikes exhibited a slow rising phase which included more than one component of different slope. The latter had long durations which in some units exceeded one millisecond (Fig. 1 *D*).

Other cells recorded in the vermal cortex were classed as interneurones on the basis of spike configuration, absence of complex spikes, and low tonic activity with prolonged silent periods. They are not included in this report.

(2) *Experimental methods*

A detailed account of the methods involved in making single unit and electro-oculogram (e.o.g.) recordings from alert monkeys has been given elsewhere (Noda& Suzuki, 1979). In brief, monkeys were given general anaesthesia to permit implantation of electrodes for recording e.o.g.s bilaterally and above and below the left eye in order to detect eye movements in horizontal and vertical planes, respectively. A stainless-steel recording chamber (bone fixed adaptor, Trent-Wells, Inc.) was also implanted over the occipital bone aiming postero-medially at the posterior vermis, and two transverse tubes for use in immobilizing the head were affixed to the skull with dental acrylic cement.

During recording sessions, the monkey was mounted in a specially designed primate chair which provided painless immobilization of the head and permitted an unimpeded view of a rear projection screen subtending 60° of the visual field horizontally and 45° vertically. Using the procedure described elsewhere (Noda & Suzuki, 1979), the monkeys had been trained to stabilize the image of a fixation target on the fovea and to maintain fixation even if the position of the target was changed. It was possible to induce saccades of known magnitude and direction merely by changing the position of the target. The e.o.g. signals could be calibrated in this manner.

Stainless-steel micro-electrodes (made from Eligiloy 0·25 mm orthodontic wire) insulated with Isonel 31 were introduced into the brain through the bone fixed adaptor. Electrodes were guided to just above the cerebellar tentorium through a cannula made from a 22-gauge spinal needle and were driven from the tip of the cannula into the cerebellum by a hydraulic micro-drive.

Extracellular action potentials were led through an FET pre-amplifier to a conventional amplifier with a band pass of 35 Hz–10 kHz and displayed on an oscilloscope. After transformation by a Schmitt trigger which changed spikes into pulses of 0·5 msec in duration, the signals were fed into one channel of a polygraph. Simultaneously, instantaneous discharge rate, horizontal and vertical e.o.g.s, and horizontal eye velocity signals were also recorded on the other channels. The data were continuously monitored on the polygraph and when the unit activity was related either to saccades or to eye position, all signals were recorded on a 14-channel magnetic tape recorder (Ampex FR 1300) for later detailed analysis. Unit activity and voice annotations were directly recorded on channels with band pass of 50 Hz–10 kHz, while the other signals were recorded on separate FM channels (band pass DC to 628 Hz) at a tape speed of 1·88 in./sec.

The tape-recorded data were later photographed at film speeds of 5 or 10 cm/sec. Lead times were determined by enlarging the photographed records with a modified slide projector which projected images from below on a rear-projection screen-plate installed on the top of a table. The images were magnified 10 times. With the horizontal e.o.g. so magnified, a tiny positive or positive-negative spike could be recognized immediately preceding the deflexions of saccades. This represented electromyographic (e.m.g.) activity due to contraction of the lateral rectus muscle. Measuring from the peak of the unit action potential to the peak of the e.m.g. spike, it was possible to evaluate lead times with an accuracy of half a millisecond. In each unit the average lead time was evaluated from at least 20 saccades. Statistical computations were performed by utilizing the Campus Computing Network of the University of California, at Los Angeles.

(3) *Recording sites*

Recording sites were anatomically reconstructed with reference to a micro-electrode track in the centre of an active zone where Purkinje cells exhibiting saccade-related activity were located.

The centre of the active zone was identified histologically by finding the spot resulting from the Prussian blue reaction to deposited iron ions.

In Fig. 2, anatomical locations of seven reaction spots in the vermal lobules VI and VII, identified in different sagittal sections, are superimposed on a near midsagittal plane. Three spots were found in the first monkey and the remaining four spots were found in the second monkey. All spots were located within three millimeters of the midsagittal plane. Vermal lobules were identified by referring to the atlas of Madigan & Carpenter (1971).

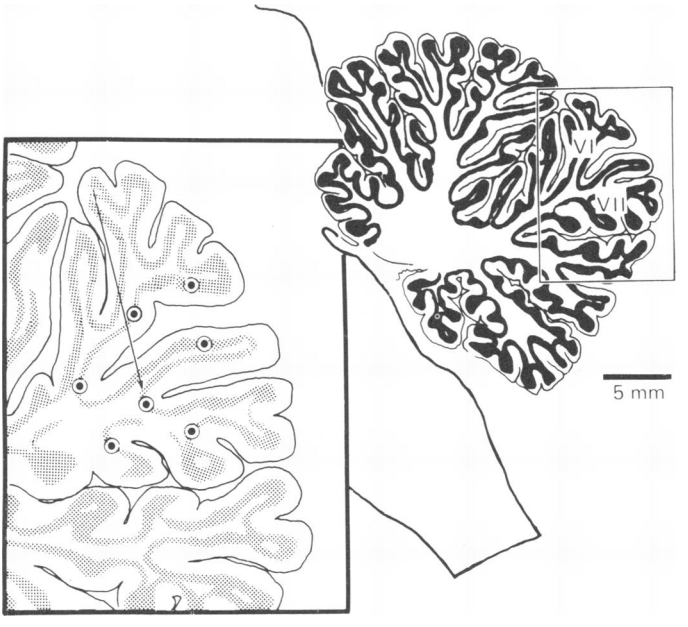

Fig. 2. Anatomical location of recording sites in lobules VI and VII of the posterior vermis of the monkey. Centres of saccade-related Purkinje cell activity were identified from Prussian blue reaction to deposited iron ions. The arrow direction indicates the course of advancing electrodes to the active sites. Anatomical figures were constructed with reference to the atlas of the cerebellum of the rhesus monkey by Madigan & Carpenter (1971).

RESULTS

I. *Activity in vermal units during saccadic eye movements*

(1) *Mossy fibre activity*

Among the units recorded from the posterior vermis and showing changes in activity with saccades, seventy-eight units were identified as mossy fibres (see Methods). On the basis of their firing pattern, they were classified into one of three groups: long-lead burst, burst, or burst-tonic units.

Long-lead burst units ($n = 28$) were characterized by relatively long 'preludes' of irregular activity followed by high frequency bursts. With the exception of an occasional discharge, there was no activity during periods of steady fixation. In Fig. 3, the original record (*A*), raster (*B*), and peri-saccadic time histogram (*C*) of a typical long-lead burst unit are shown. The raster and histogram were constructed from the activity associated with twenty saccades, occurring in the preferred direction. The onset of the prelude varied from saccade to saccade in individual units. The lead times

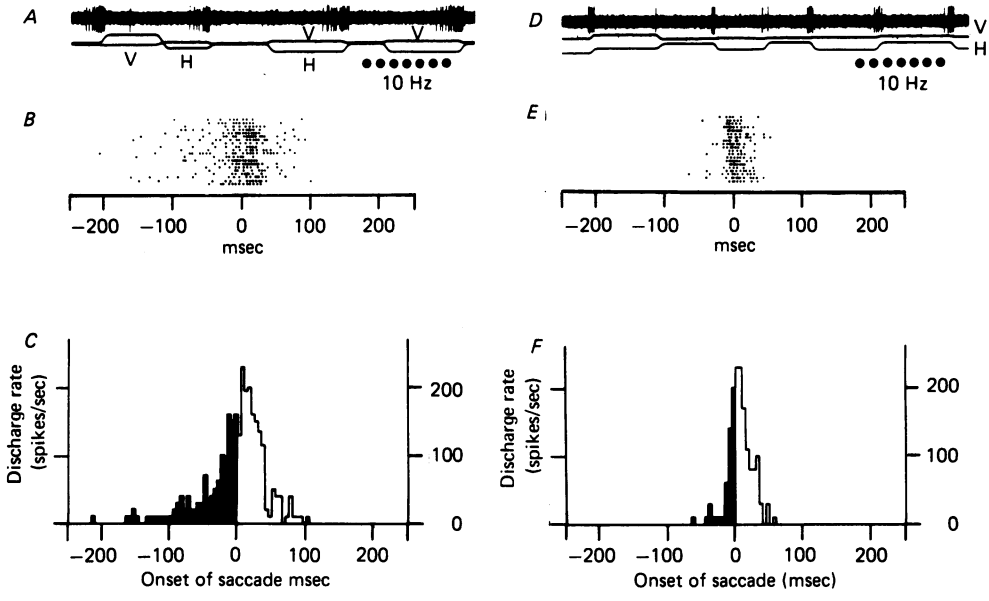

Fig. 3. Time relationship between unit activity and saccade onset for a mossy fibre long-lead burst unit (*A*, *B* and *C*) and a mossy fibre burst unit (*D*, *E* and *F*). *A*, original record of a mossy fibre long-lead burst unit. *B*, raster for the same unit as in *A* generated from twenty saccades in the preferred direction. Spike trains were sampled from 200 msec before to 300 msec after the saccade onset. *C*, peri-saccadic time histogram, constructed from the raster in *B*, which demonstrates discharge rate in relation to the saccade onset. *D*, original record of a mossy fibre unit. *E*, raster generated by sampling spike trains 200 msec before to 300 msec after the saccade onset. *F*, peri-saccadic time histogram showing the temporal relationship between discharges and the saccade onset. Bin width 5 msec.

of the preludes, measured from the onset of saccades varied from unit to unit and the average lead times ranged from 66 to 480 msec (with an average of 160 msec). The lead times of the bursts for individual units ranged from 2 to 36 msec (with a group mean of 16 msec).

The distinction between the prelude and burst was sometimes ambiguous, but differences in the character of the discharges could be used to aid in the separation of the two components. The frequency of prelude activity was always lower than the frequency of burst discharges and the interspike interval within preludes often appeared to be more variable than for bursts. Within the prelude, discharge frequency increased gradually, while within the burst discharge rate increased more rapidly and attained a peak prior to the onset of saccades.

The distribution of the burst lead times is shown as filled columns in Fig. 4*A*. In twenty-two out of twenty-eight units, saccade-related activity showed a directional preference. The directional preference was rightward for fourteen units, leftward for seven units, and upward for one unit. No consistent correlation between recording site and directional preference was observed although it was difficult to determine whether some recording sites were to right or left of the midline.

Burst units ($n = 37$) showed bursts which slightly preceded the onset of saccades

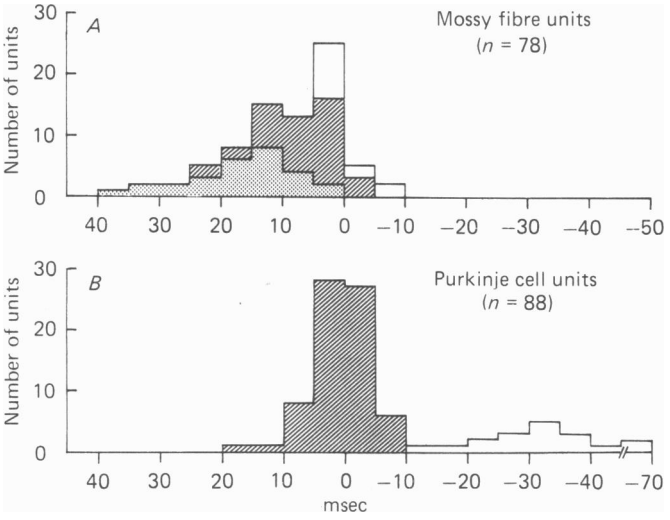

Fig. 4. Distributions of the lead times in mossy fibre units (*A*) and Purkinje cell units (*B*). The lead time was measured in individual units from the first spike of the burst to the saccade onset for twenty-five saccades. For the purpose of comparison, only the onset of the burst is used for long-lead burst units and the prelude onset (which generally began much earlier) is not indicated in this Figure. Stippled columns represent the number of long-lead burst units, cross-hatched columns represent burst units, and open columns represent burst-tonic. *B*, distribution of the lead times for two classes of Purkinje cells: Purkinje cells showing bursts associated with the saccade onset (cross-hatched columns) and Purkinje cells showing bursts associated with the end of saccades (open columns).

(Fig. 3 *D*, *E* and *F*). The lead times, which varied markedly also in this class, ranged from +22 to −1·25 msec (a positive value indicates lead and a negative value indicates lag), as can be seen in the distribution of burst onsets in Fig. 4 *A* (cross-hatched columns). The average lead time was 7·4 msec.

Eye movement-related bursts usually terminated before the end of saccades. The duration of each burst was highly correlated with the duration of the corresponding saccade (Fig. 5 *B*). The correlation coefficients of the five best units ranged from 0·93 to 0·96 (Fig. 5 *D*) and were greater than 0·80 in most units. The burst duration tended to be slightly shorter than the saccade duration. In contrast to long-lead burst units, the majority of burst units (twenty-four out of thirty-seven units) showed no directional preference. In the thirteen units demonstrating a directional preference, rightward was preferred in six units, leftward in five units, upward in one unit, and downward in one unit.

Burst-tonic units ($n = 13$) exhibited bursts only for saccades in a preferred direction, while eye movements in the opposite direction were associated with pauses in activity. These units exhibited tonic discharge during fixations in preferred directions and ceased firing during fixations in non-preferred directions (Fig. 1 *C*). The burst lead times ranged from +4·9 msec to −6·7 msec (with an average of 0·2 msec). The mean lead time for burst-tonic units was significantly shorter than the means for the other two classes of mossy fibre units (open columns in Fig. 4 *A*).

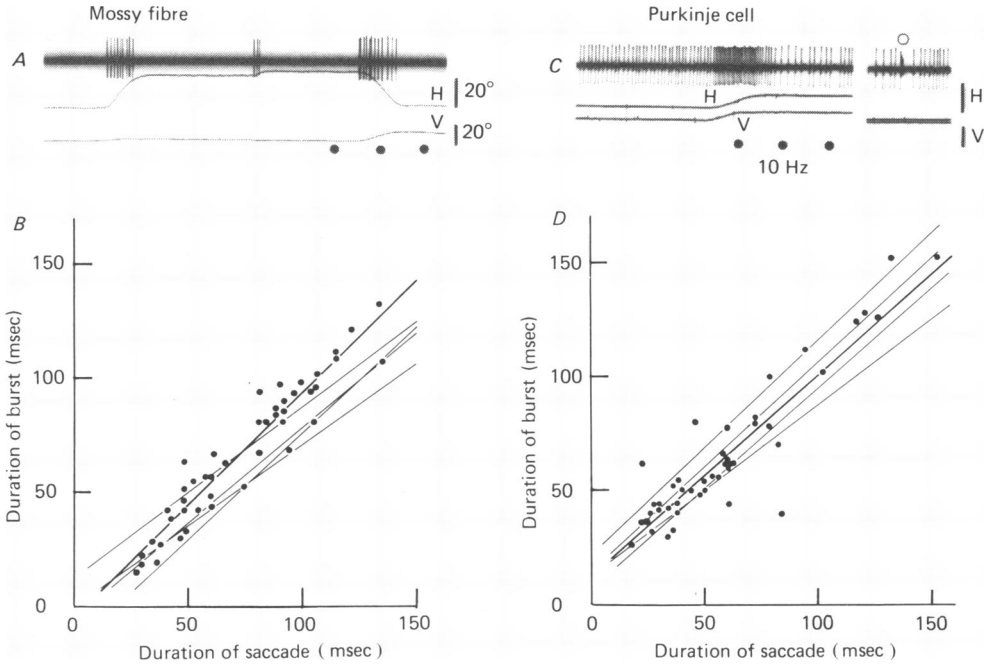

Fig. 5. Saccade duration as a function of burst duration for mossy fibres (*A* and *B*) and Purkinje cells (*C* and *D*). *A*, original record of a typical mossy fibre burst unit. *B*, the time representing the duration of saccade was plotted as a function of the time corresponding to the duration of the unit burst. Points on the graph represent the values which were determined for forty-five saccades from the unit in *A* and the darkest line is the calculated regression line ($r = 0{\cdot}96$). The regression lines shown for four other mossy fibre units had correlation coefficients ranging from 0·93 to 0·95 *C*, original record of a representative Purkinje cell. The small circle above the spike train signifies the appearance of a complex spike. *D*, points in the graph represent the values which were determined for 45 saccades from the unit in *C* and the darkest line is the calculated regression line ($r = 0{\cdot}88$). The regression lines for the other four Purkinje cells shown in *D* had correlation coefficients ranging from 0·79 to 0·86.

(2) *Purkinje cell activity*

All of the ninety-one Purkinje cells were spontaneously active during fixation. Simple spikes were discharged at rates ranging from 30 to 150 spikes/sec. The frequency of complex spike discharges was invariably low in all Purkinje cells, appearing on the average once every second. Because of such a low frequency, complex spikes did not contribute significantly to quantitative analyses and they were excluded Saccade-related modulation in activity was observed only in simple spike discharges and these phasic changes in activity persisted in complete darkness. Most Purkinje cells ($n = 88$) showed bursts associated with saccades. Three Purkinje cells paused in relation to all saccades.

Purkinje cells showing bursts associated with saccade onsets. This class of Purkinje cells showed a burst of activity time-locked to the onset of saccades. Seventy-one out of the eighty-eight burst Purkinje cells were of this type. Their bursts started with saccade onset, having lead times ranging from $+18{\cdot}2$ msec to -10 msec (Fig. 4 *B*, cross-hatched columns). The burst onset of Purkinje cells preceded the saccade onset

by an average of only 0·6 msec. The latency between the average burst onset of burst mossy fibre units and that of Purkinje cells was 6·7 msec. Whereas, the latency between the long-lead burst mossy fibre units and bursts of Purkinje cells was 15·4 msec. In contrast to this, the burst onset in burst-tonic mossy fibre units slightly followed bursts of the Purkinje cells (Fig. 4). Two examples of burst Purkinje cells are shown in Fig. 6.

The unit on the left (Fig. 6*A*, *B* and *C*) showed bursts associated with all saccades and had an average lead time of 5 msec. Peak firing rates appeared approximately at the middle of the saccade excursions. This type of saccade-related burst was observed in the great majority of the Purkinje cells. A different pattern of saccade-related bursts is exemplified by the Purkinje cell in Fig. 6*D*, *E*, *F*. In this and some other units, bursts started around the onset of saccades and reached peak activity at an earlier stage of the saccade excursions. The burst durations in the majority of Purkinje cells were correlated with saccade durations, although the correlation was somewhat less than that seen in mossy fibres. The correlation coefficients ranged from 0·79 to 0·88 in the five best Purkinje cells (Fig. 5*D*) and were larger than 0·70 in most units. Burst durations tended to be longer than saccade durations. The directional preference was rightward for nine units, leftward for six units, and upward for one unit, but the majority of Purkinje cells ($n = 55$) showed no directional preference.

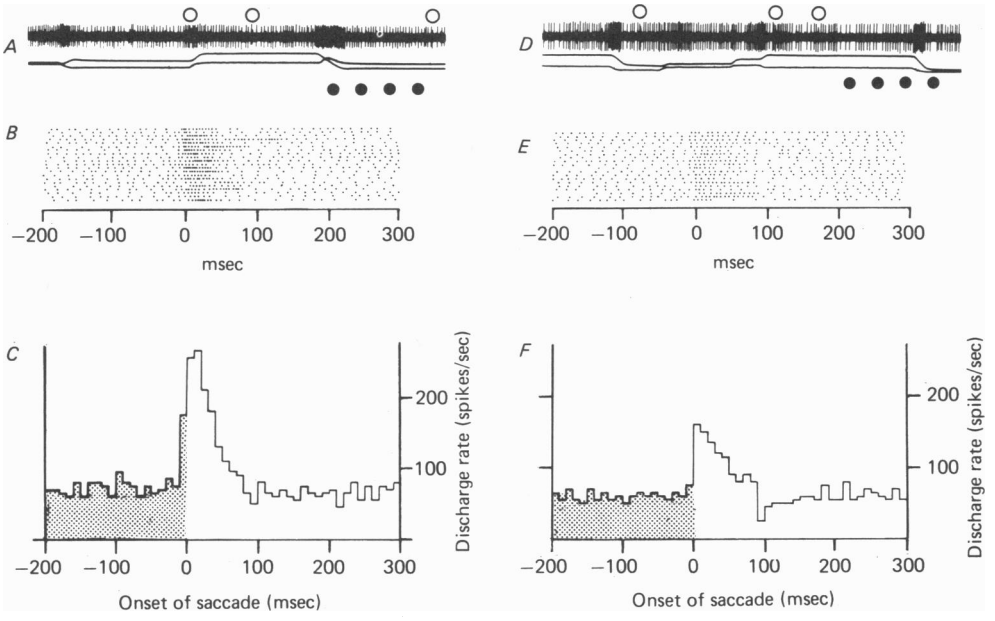

Fig. 6. Two examples of Purkinje cells exhibiting bursts in relation to saccade onset. Small circles above the spike train represent the appearance of complex spikes. Time calibration dots at 5 Hz. *A*, original record of a burst Purkinje cell which demonstrates peak firing rates approximately at the middle of saccade. *B*, raster generated from 20 saccades. *C*, peri-saccadic time histogram of the same unit. *D*, original record of a burst Purkinje cell showing bursts near saccade onset which reached peak activity at an earlier stage of saccade. *E*, raster generated from 20 saccades. *F*, peri-saccadic time histogram of the same unit. Bin width in histograms 10 msec.

Purkinje cells showing bursts associated with the end of saccades. Seventeen Purkinje cells were classified in this group. In sharp contrast to all other units recorded in the vermis, these Purkinje cells showed bursts beginning substantially after the onset of saccades (late bursts) as seen in Fig. 7. Additionally, these bursts were preceded by a slight depression of activity (Fig. 7 *B* and *C*). The delay from saccade onset to the beginning of the burst varied greatly from saccade to saccade, ranging from 15 to 65 msec. An intimate temporal relationship between burst onset and saccade end became apparent when the peri-saccadic activity was re-aligned on the end of the saccade, as in Fig. 7 *D* and *E*. Analysed in this manner, bursts started approximately 40 msec

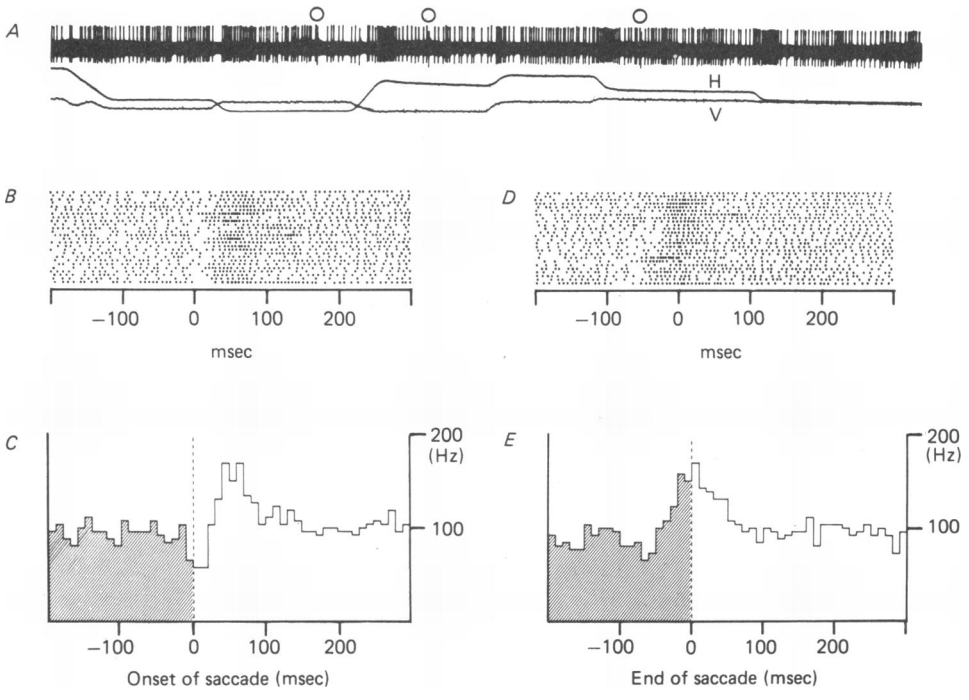

Fig. 7. An example of Purkinje cells which exhibited late bursts. *A*, original record. Small circles signify the appearance of complex spikes. *B*, raster generated from the unit in *A* when the unit activity is aligned on the saccade onset. Notice the consistent depression of activity before the burst. *C*, peri-saccadic time histogram constructed from the raster in *B* demonstrating the delay between peak unit activity with respect to the saccade onset. *D*, raster generated from the same unit when the unit activity was re-aligned on the end of saccades. *E*, peri-saccadic time histogram constructed from the raster in *D* showing peak unit activity in relation to the end of saccades. Bin width in histograms 10 msec.

before the end of saccades and persisted until up to 70 msec after the completion of saccades. Fig. 8 illustrates the temporal relationships between saccades and late bursts for 20 saccades in each of two late burst Purkinje cells. Each open bar represents the duration of a saccade and the accompanying cross-hatched bar represents the duration of the associated late burst. Several points are of particular importance. First, because the bursts started with a close temporal relation to the end of saccades,

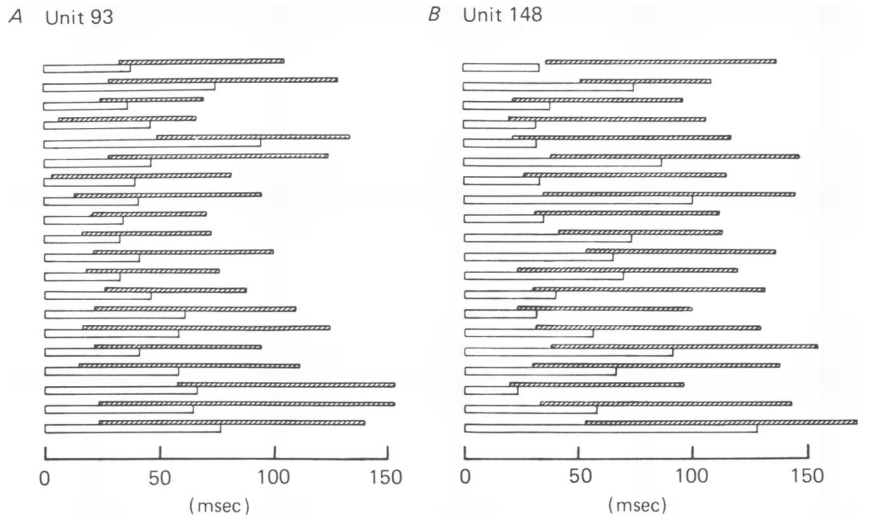

Fig. 8. Two examples of Purkinje cells showing temporal relationships of their late bursts with durations of accompanying saccades. In both *A* and *B*, open bars represent the durations of saccades which are aligned on their onset and the cross-hatched bars immediately above represent durations of the late bursts. Twenty saccades are shown for each unit. Notice that the burst activity begins with a variable latency from the saccade onset and that the burst duration is not correlated with the saccade duration. In general, a longer burst latency is associated with a longer saccadic duration.

the burst latencies were proportional to the durations of the saccades. Secondly, there was no precise correspondence between the duration of the burst and the duration of the associated saccade. This indicates that the duration of the late burst does not correspond with the duration of activity in the extraocular muscles. Together, these points suggest that it is unlikely that the late bursts are evoked by input from proprioceptive afferents in the extraocular muscles. Finally, since the late bursts persisted even in complete darkness, they are not produced by visual inputs.

II. *Activity in vermal units during fixation*

(1) *Mossy fibre activity*

In seventeen mossy fibre units, tonic discharge rates varied with static eye position. Position related discharges were exhibited by two distinct classes of units: burst-tonic and tonic units.

Burst-tonic units ($n = 13$) were characterized by high frequency bursts preceding saccades in preferred directions and during the subsequent fixation periods by a tonic discharge at a frequency which varied with eye position (Fig. 9). Following saccades in the preferred direction tonic discharge rates increased. Saccades in the non-preferred direction resulted in a pause during the saccade and a decrease in tonic activity during the subsequent period of fixation.

Tonic units ($n = 6$) similarly discharged at rates related to eye position but did not have a saccade-related burst. When tonic firing rate is plotted as a function of horizontal eye position (Fig. 9), a characteristic eye position threshold can be identified for each unit. Saccades in the non-preferred direction, beyond the position

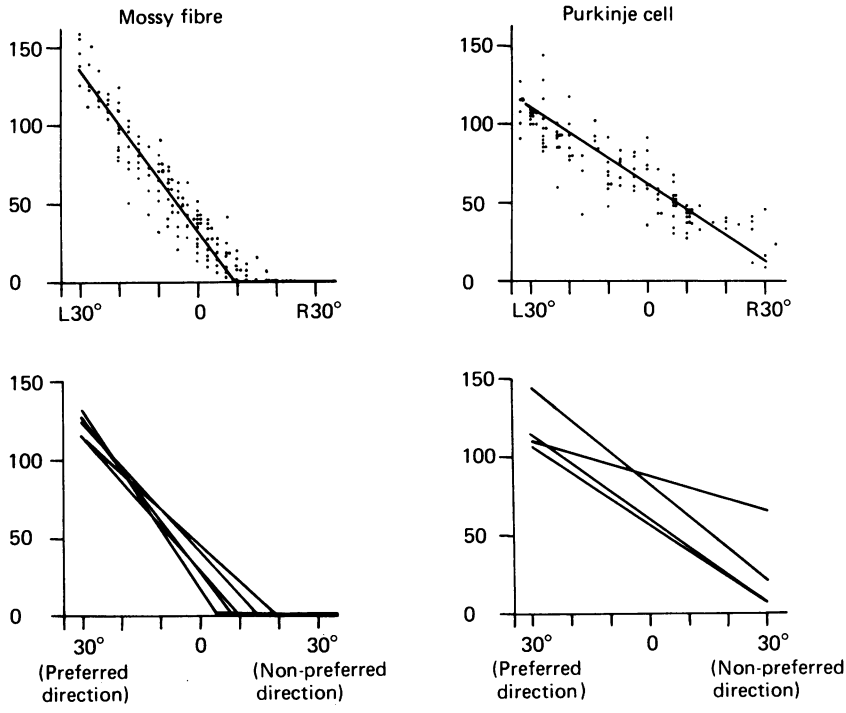

Fig. 9. Unit discharge rates plotted as a function of eye position for position-related mossy-fibres (left side) and position-related Purkinje cells (right side). Points in the two upper graphs represent the values for inter-saccadic discharge frequencies plotted as a function of the fixation position along the horizontal axis. Notice that for the mossy fibre, any gaze position beyond about 10° to the right of the primary eye position was associated with no activity, whereas Purkinje cells exhibited discharge rates proportional to all positions. In the lower graphs, regression lines for other representative position-related Purkinje cell and mossy fibre units are shown.

threshold, resulted in fixation positions associated with zero activity. The position thresholds ranged roughly within $\pm 10°$ of the primary eye position. Fixations in preferred regions demonstrated a nearly linear correlation between tonic firing rates and eye positions, with a steeper increase in firing rate occurring with extreme horizontal excursions of the eye (25–30°). For position-related mossy fibres, the preferred direction was rightward for seven units, leftward for six units, upward for two units, and downward for two units.

(2) *Purkinje cell activity*

Position-related Purkinje cells ($n = 5$) discharged tonically at rates linearly related to horizontal eye position (Fig. 9). Four of these units displayed bursts with saccades in the preferred direction and pauses with saccades in the opposite direction. One position-related cell exhibited pauses with saccades in all directions. Saccades in the preferred directions were followed by an increased tonic firing rate during the next inter-saccadic period. In contrast to mossy fibres, there were no fixation positions associated with zero activity for any Purkinje cell. The position-related discharge

frequencies ranged from 10 to 150 spikes/sec. For position-related Purkinje cells, the preferred direction was rightward for three units and leftward in two units. The relationship between tonic discharge and eye position was maintained even in complete darkness.

DISCUSSION

The present experiment has shown that Purkinje cells in vermal lobules VI and VII exhibit transient changes in activity associated with saccades. Single units showing bursts in relation to saccades have been recorded from the same lobules in monkeys (Llinás & Wolfe, 1977) and cats (Waterhouse, Mays & McElligott, 1976). Stimulation of the region with small amounts of electrical current yields saccades (Ron & Robinson, 1973). However, while causing saccadic dysmetria, ablation of the same vermal region does not interfere with the initiation of saccades (Ritchie, 1976). Whereas the posterior vermis has been implicated in a variety of roles in the control of eye movements, attempts at explicitly identifying its function in neurophysiological terms have been relatively unsuccessful.

An important finding in the present study was that the vermal Purkinje cells started saccade-related bursts with a surprisingly close temporal relationship to the onset of saccades. In the great majority of Purkinje cells (71·5 %), burst onset occurred within ± 5 msec of the onset of saccades. Partially due to the substantial number of units in which the bursts tended to start after the onset of saccades, the average lead time was only 0·6 msec. This is a striking contrast with the previous report by Llinás & Wolfe (1977). According to their results, lead times of the bursts ranged from 11 to 24 msec. Out of the eighty-eight Purkinje cells, we found only one which showed an average lead time longer than 11 msec. The discrepancy between the two sets of data have arisen from the difference in the criteria used in the identification of Purkinje cells. The Purkinje cell units recorded by Llinás & Wolfe (1977) exhibited minimal background activity and the saccade-related burst activity frequently exceeded background levels by the factor of twenty. In contrast to this, all our Purkinje cells, which were identified by the presence of the characteristic climbing fibre response, maintained high levels of tonic discharges during inter-saccadic periods. Since saccade-related bursts were superimposed upon the high levels of tonic background activity, burst spike frequencies rarely exceeded five times the tonic background activity. We have no convincing explanation for the difference in background activity between the two sets of Purkinje cell units.

In spite of the fact that Purkinje cells exhibit bursts of activity with a close temporal relationship to saccades, the values of the burst lead times in Purkinje cells do not strongly support the notion that the posterior vermis participates either in the initiation or the preprogramming of saccades. The lead time of the vermal output activity, at least for the majority of Purkinje cells, appears to be too short to drive neurones of the oculomotor complex. The average lead time of bursts in the oculomotor neurones was 7·5 msec with a range of 4–10 msec (Robinson, 1970), and that of the abducens neurones, evaluated from the histogram of Luschei & Fuchs (1972, Fig. 1), was 6·0 msec with a range 3–11 msec. In other structures in which saccade-related activity is observed, such as the posterior association cortex (Lynch, Yin,

Talbot & Mountcastle, 1976), the internal medullary lamina of the thalamus (Schlag, Lehtinen & Schlag-Rey, 1974) and the superior colliculus (Schiller & Koerner, 1971; Wurtz & Goldberg, 1972) discharges begin well before (50–150 msec) the saccade onset and may participate more directly in its initiation.

In the present study, the values of the burst lead times from mossy fibres have provided a piece of evidence suggesting that the posterior vermis receives a barrage of information concerning impending eye movements from various sources within the brain stem. In one group of mossy fibre units (long-lead burst units), the 'preludes' started an average of 160 msec before eye movements occurred. Furthermore, in the great majority of the vermal mossy fibre units bursts preceded the saccade onsets by up to 20 msec (average 7·4 msec). Burst lead times in vermal mossy fibres correspond well to burst activity recorded from several brain stem structures. The lead times of the burst units in the pontine reticular formation ranged from 3 to 13 msec with a mode between 8 and 9 msec (Luschei & Fuchs, 1972) or ranged from 7 msec to 12 msec with an average of 9 msec (Keller, 1974). These times also match the range observed for burst units of the mesencephalic reticular formation (Büttner, Hepp & Henn, 1977). The lead times of burst units in the medial and superior vestibular nuclei ranged from 5 to 15 msec (Miles, 1974) and ranged from 6 to 10 msec in the prepositus hypoglossal nucleus of cats (Baker, 1977). If allowance is made for the conduction time for the saccade-related bursts to travel from the brain stem to the vermis, then our value of 7·4 msec is consistent with an origin for the saccade-related mossy fibres in one, some or all of the structures considered above. Although saccade-related activity has not yet been recorded, anatomical connexions suggest that other brain stem nuclei such as the pontine nuclei and reticular tegmental pontine nucleus are also potential origins of such mossy fibres. Whilst the average lead time for saccade-related bursts in the mossy fibre units (input) was 7·4 msec, that for the Purkinje cell units (cortical output neurones) was only 0·6 msec. This delay might be caused by the characteristic circuit of the cerebellar cortex involving parallel fibres, which are among the longest very thin fibres known in the central nervous system. The posterior vermis, therefore, after receiving saccade-related information from the brain stem saccadic centres, may send feed-forward control signals to the oculomotor complex and possibly feed-back signals to the brain stem saccadic centres immediately prior to the initiation of saccades.

Although the posterior vermis may neither initiate nor preprogram saccades, the intimate temporal relationships demonstrated in the present study between Purkinje cell activity and various aspects of saccadic eye movement suggest that this region must play a role in the control of ongoing saccades. A close temporal relationship has been found also between the end of saccades and bursts in a second group of Purkinje cells. That the Purkinje cells exhibited high rates of discharge during fixation implies that the vermis exerts tonic inhibitory influences upon eye movement centres which may serve to ensure a steady eye position during inter-saccadic periods. Bursts of Purkinje cells temporally aligned with the end of saccades will produce a powerful inhibitory influence upon the target cells. The late bursts may thus play a significant role in the initiation of steady fixation. Furthermore, in some units the tonic levels of discharge during fixation periods were proportional to eye position in a certain plane. This relationship may be important when fixation has to be maintained in the

absence of visual cues. Since ablation of the posterior vermis induced position-dependent dysmetria in monkeys (Ritchie, 1976), it is possible that position information from vermal Purkinje cells contributes to the proper adjustment of saccadic magnitudes with reference to the starting eye position.

The data of the present study indicate that position information may be an important component of output of the posterior vermis. The fact that position-related activity was also observed in mossy fibre units indicates that the position information was brought to the vermis by the burst-tonic and tonic fibre channels. This information, however, has to be integrated by the processing circuitry of the vermal cortex. The position related signals in Purkinje cells differ markedly from those of mossy fibres. Purkinje cell activity encompassed the entire range of the central eye positions, whereas in mossy fibres, the tonic level of activity was proportional to eye positions only within a limited range. All mossy fibre units exhibited a zone of eye positions associated with zero activity and position information was coded only in the range above the 'position threshold'. Convergence of such seemingly limited eye position information, conveyed by individual mossy fibres, may result in the full range of position related activity observed in the Purkinje cells. It is known that afferent projections from the extraocular muscles terminate in the posterior vermis (Fuchs & Kornhuber, 1969; Baker *et al.* 1972). There is no evidence to eliminate the possibility that the position information represents the input from the proprioceptors. However, it is unlikely that all burst-tonic mossy fibre units originate in the extraocular muscles. The firing pattern of extraocular proprioceptive afferent fibres during fixation is as yet unknown.

For movements of the extremities, a hypothesis that the cerebellum may play a role in initiating motor cortex activity is by no means new. Herrick (1924) and Holmes (1939) hypothesized that the cerebellum would participate in three successive phases of movement: initiation of the corticospinal output; regulation of motoneural responses to this corticospinal discharge; and adjustment and correction of the motor output following its initiation. The original hypotheses which were based on clinical observations have now been supported neurophysiologically. Direct evidence that cerebellar activity occurs before movement has been obtained from recording of Purkinje and nuclear cells in association with the performance of learned arm movements in monkeys (Thach, 1968; Harvey, Porter and Rawson, 1977; Meyer-Lohman, Hore & Brooks, 1977). Eccles (1967) discussed the participation of the cerebellum in both the ongoing and the correction of movements, while Houk & Henneman (1967) described the cerebellar contribution following emission of the cortical output.

For eye movements, however, the results of this study indicate that the posterior vermis probably does not participate in the initiation of saccades. This conclusion is consistent with that for the flocculus which was studied under identical conditions (Noda & Suzuki, 1979). Saccadic eye movements are in many aspects different from extremity movements. In extremity movements, cerebellar output ascends via the red nuclei and ventrolateral thalamic nuclei to the forebrain which in turn influences the movements. The oculomotor cerebellum, on the other hand, operates somewhat independently of the cerebral cortex. It has a more direct influence upon the oculomotor complex and maintains a close interrelationship with oculomotor centres in the brain stem. The patterns of the Purkinje cell activity demonstrated in this study

implicate the posterior vermis in the fine control of the oculomotor system, particularly in ensuring the accuracy of eye movements.

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