Neural Basis for Motor Learning in the Vestibuloocular Reflex of Primates. II. Changes in the Responses of Horizontal Gaze Velocity Purkinje Cells in the Cerebellar Flocculus and Ventral Paraflocculus

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SUMMARY AND CONCLUSIONS

1. We made extracellular recordings from Purkinje cells in the flocculus and ventral paraflocculus of awake monkeys before and after motor learning in the vestibuloocular reflex (VOR). Three samples were recorded 1) after miniaturizing spectacles had reduced the gain of the VOR (eye speed divided by head speed) to 0.4; 2) when the gain of the VOR was near 1.0; and 3) after magnifying spectacles had increased the gain of the VOR to 1.6.

2. We studied Purkinje cells that showed stronger modulation of simple-spike firing rate during horizontal than during vertical pursuit. These cells corresponded to the previously identified “horizontal gaze velocity Purkinje cells” or HGVP-cells. During pursuit of smooth target motion with the head stationary, HGVP-cells showed strong modulation of firing rate with increases for ipsiversive eye motion (toward the side of recording). When the monkey canceled his VOR by tracking a target that moved exactly with him during sinusoidal head rotation in the horizontal plane, HGVP-cells again showed strong modulation of firing rate with increases for ipsiversive head motion.

3. The responses of HGVP-cells during pursuit with the head stationary and during cancellation of the VOR reveal separate components of firing rate related to eye and head velocity. We used these two behavioral conditions to test for effects of motor learning on the head and eye velocity components of the simple-spike firing of HGVP-cells. Our data confirm the previous observations that motor learning causes the sensitivity to head velocity to be larger when the gain of the VOR is high and smaller when the gain of the VOR is low. Thus we agree with the previous conclusion that changes in the vestibular sensitivity of HGVP-cells, measured during sinusoidal head motion at low frequencies, are in the wrong direction to cause changes in the gain of the VOR.

4. To determine whether the simple-spike output from the HGVP-cells plays a role in the VOR after motor learning, we recorded simple-spike firing during the VOR evoked by transient, rapid changes in head velocity in darkness. When the gain of the VOR was low, firing rate increased during the VOR evoked by ipsiversive head motion and decreased during the VOR evoked by contraversive head motion. When the gain of the VOR was high, the direction selectivity of the responses was reversed. These data agree with previous recordings of the effect of motor learning on the output from the flocculus and ventral paraflocculus during the VOR and show that changes in the output from HGVP-cells during the VOR are in the correct direction to support learning in the VOR, which has a latency of 19 ms.

5. We assessed possible cause-and-effect relationships between HGVP-cell firing and the gain of the VOR by measuring the latency from the onset of head motion to the onset of the responses of HGVP-cells. The latencies ranged from 6 ms to over 60 ms, with a mean of 27.3 ms. The paucity of HGVP-cells with responses at short latencies implies that their output probably occurs too late to cause the earliest component of motor learning in the VOR, which has a latency of 19 ms.

6. We present a simple model of the brain stem and cerebellar VOR pathways that shows how motor learning can cause the responses of HGVP-cells to undergo changes that are in the correct direction to support learning when measured during the VOR and in the wrong direction when measured during cancellation of the VOR at low frequencies. Analytic solution of the model suggests that changes in the gain of the VOR may require changes in the strength of transmission of vestibular signals in the brain stem as well as changes in the strength and time course of vestibular inputs to IIGVP-cells.

INTRODUCTION

The cerebellum is required for the normal operation of a long-term adaptive mechanism that regulates the performance of the vestibuloocular reflex (VOR) throughout life (Gonshor and Melvill Jones 1976, Robinson 1976). Under normal conditions the adaptive mechanism adjusts the strength of transmission through vestibuloocular pathways to ensure that smooth eye motion is opposite in direction and almost equal in amplitude to rotatory head motion (Fuchs and Kimm 1975; Keller 1978; Miles and Eighmy 1980). As a result, gaze is stabilized in space, and the images from the stationary surroundings remain nearly stable on the retina. In the laboratory we induce adaptive changes in the VOR by allowing monkeys to turn their heads while viewing through spectacles that magnify or miniaturize the visual scene (Miles and Fuller 1974). Over a time course of hours or days, the resulting conjunction of visual and vestibular stimuli causes large increases or decreases in the gain of the VOR, defined as eye speed divided by head speed in darkness. We consider this example of motor adaptation to be a simple form of “motor learning.”

Before providing an introduction to the cerebellar structures that are important for motor learning for the VOR, we must explain the terminology we will use in this paper. Previous studies on the role of the primate cerebellum during motor learning in the VOR (Lisberger et al. 1984; Lisberger and Pavelko 1988; Miles et al. 1980a; Watanabe 1984, 1985) have used the terminology of Madigan and Carpenter (1971) and referred to the relevant structure as the “flocculus.” However, Gerrits and Voogd (1985) have recently pointed out that the terminology of Larsell (1970) is correct and that the cerebellar tissue in question includes...
both the flocculus and the ventral paraflocculus. Detailed histological reconstructions were not always reported in the earlier studies, but sufficient information was usually provided so that we could determine whether the area studied was the flocculus, the ventral paraflocculus, or both. This has allowed us to correct earlier studies and to refer to the ventral paraflocculus when it was studied, even if the original paper referred to the site of study as the flocculus.

Learning is abolished, but the normal VOR is relatively unaffected after bilateral ablation of the flocculus, the dorsal paraflocculus, and ventral paraflocculus in monkeys (Lisberger et al. 1984), bilateral chemical destruction of the flocculus in rabbits (Nagao 1983), and removal of the entire cerebellum in cats (Robinson 1976) and goldfish (Michnovicz and Bennett 1987). Many studies have demonstrated pathways that would allow the flocculus and ventral paraflocculus to participate in motor learning in the VOR. In nonprimates, Purkinje cells (P-cells) in the flocculus inhibit monosynaptically neurons in the vestibular nuclei that are interneurons in the direct brain stem VOR pathways (Baker et al. 1972; Fukuda et al. 1972; Highstein 1973; Ito et al. 1977; Sato et al. 1988). In primates, both the flocculus and the ventral paraflocculus project to the same region of the vestibular nucleus (Balaban et al. 1981; Langer et al. 1985a), where they inhibit neurons that are excellent candidates to be interneurons in the disynaptic VOR pathways (Lisberger et al. 1994a; Scudder and Fuchs 1992).

The exact function of the cerebellar cortex during motor learning in the VOR has remained controversial, and two conflicting hypotheses have postulated two quite different roles. Ito (1972, 1982) developed a specific model (Fig. 1.4) that was based on the general models of Marr (1969) and Albus (1971). He suggested that learning occurs in the flocculus and is guided by the conjunction of vestibular mossy fiber inputs and visual climbing fiber inputs. In contrast, Miles and Lisberger (1981) postulated (Fig. 1B) that the primary site of learning is in the brain stem. They accounted for the effects of cerebellar lesions with the suggestion that learning is guided by an error signal encoded in the simple-spike output of a specific group of Purkinje cells called horizontal gaze velocity Purkinje cells (HGVP-cells). HGVP-cells have been recorded primarily in the ventral paraflocculus (Lisberger and Fuchs 1978a,b; Miles et al. 1980b; Stone and Lisberger 1990a), but also in the flocculus (this study). Miles and Lisberger (1981) postulated that there was also learning in the vestibular inputs to HGVP-cells but suggested that the function of this secondarily site of learning was to adjust the operation of the cerebellum in a way that compensates for the primary changes in the brain stem, rather than to cause changes in the VOR.

The available data did not indicate whether these changes occurred in the cerebellar cortex or in the brain stem neurons that relay vestibular inputs to the cerebellum.

Both the flocculus and the ventral paraflocculus receive multiple input signals that would support the mechanisms postulated by either hypothesis for motor learning. Anatomic and physiological studies have demonstrated that vestibular inputs are transmitted to both of these structures over mossy fiber pathways (Gerrits and Voogd 1989; Langer et al. 1985b; Lisberger and Fuchs 1978b; Miles et al. 1980b; Wilson et al. 1976). Physiological experiments also have shown that visual inputs are transmitted over climbing fiber pathways to the flocculus in rabbits (Maekawa and Simpson 1973) and to the ventral paraflocculus in monkeys (Gillespie et al. 1991; Stone and Lisberger 1990b). Thus the inputs required by Ito's hypothesis of cerebellar learning are present in the ventral paraflocculus and probably also in the flocculus of monkeys. However, additional input signals have been revealed in recordings from monkeys that had been trained to track a moving target. Of the P-cells that appear to be related to horizontal gaze, most receive mossy fiber inputs related both to eye movement and to head movement (Lisberger and Fuchs 1978a,b; Miles et al. 1980b; Stone and Lisberger 1990a). These cells have been called HGVP-cells because their simple-spike firing during smooth tracking is related to ipsiversive gaze velocity, defined as eye velocity with respect to space. Many HGVP-cells also receive visual mossy fiber inputs that, like the climbing fiber inputs, provide information about the direction and speed of retinal image motion (Miles and Fuller 1975; Noda and Warabi 1986, 1987; Stone and Lisberger 1990a). Miles and Lisberger (1981) pointed out that the combination of eye movement, vestibular, and visual mossy fiber inputs would allow the simple-spike output from HGVP-cells to form an error signal that could be used in the brain stem to guide motor learning in the VOR.
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Watanabe (1984, 1985) and Miles et al. (1980a) both attempted to determine the role of the flocculus and ventral paraflocculus in motor learning by recording from P-cells before and after monkeys had undergone adaptive changes in the VOR. However, the two groups did different experiments, recorded from overlapping but nonidentical parts of the flocculus and/or ventral paraflocculus, and came to different conclusions. Watanabe (1984, 1985) recorded from individual P-cells in both the flocculus and the ventral paraflocculus during the VOR in the dark. He adapted the VOR by subjecting the monkey to an hour of passive oscillation with a visual scene that moved either exactly with or exactly opposite the monkey. This induced either decreases or increases in the gain of the VOR and changed the modulation of P-cell firing rate during the VOR in the correct direction to support learning. Watanabe’s experiment demonstrates that the output from the P-cells he studied is appropriate to support the VOR after motor learning. However, it does not reveal whether the changes in the firing of P-cells result from learning in the cerebellum. The same data would result if the changes in P-cell firing resulted from learning that occurred elsewhere and was transmitted to the cerebellum. For example, the changes in P-cell responses during the VOR could have been transmitted to the cerebellum as changes in the firing of mossy fiber inputs that signaled either head motion or eye motion.

Miles et al. (1980a) recorded the responses of identified HGVP-cells before and after magnifying spectacles or left-right reversing prisms had caused either increases or decreases in the gain of the VOR. They studied the simple-spike firing rate of HGVP-cells both during the VOR in the dark and during visual tracking conditions that could be used to estimate separately the strength of the head and eye velocity inputs to P-cells. When Miles et al. (1980a) recorded the responses of HGVP-cells during the VOR after the monkeys had been adapted for at least a week, they found the same effects reported later by Watanabe (1984, 1985), at least for decreases in the gain of the VOR. When they recorded the responses of the same cells during cancellation of the VOR, Miles et al. (1980a) found that both increases and decreases in the gain of the VOR were associated with changes in the strength of the head velocity input to HGVP-cells. However, these changes were in the wrong direction to cause the changes in the VOR. They therefore concluded that the site of learning was not in the vestibular inputs to HGVP-cells.

One of our goals in the present study was to address issues that were left unresolved by Watanabe (1984, 1985) and Miles et al. (1980a). For example, it was not clear whether these two groups of investigators performed somewhat different experiments on the same P-cells or if they drew their samples from different populations of P-cells. A second question concerned the different methods used to cause changes in the gain of the VOR and the very different time courses of the behavioral changes. Our results demonstrate that neither of these considerations can account for the difference in interpretation of the two extant sets of data. Individual HGVP-cells show the effects reported by Miles et al. (1980a) and those reported by Watanabe (1984, 1985).

For the specific case of HGVP-cells, the data of Miles et al. (1980a) disproved Ito’s hypothesis of cerebellar learning. However, important questions remain concerning the role of the HGVP-cells in motor learning in the VOR. First, it remains unclear whether changes in the VOR cause changes in the responses of HGVP-cells during the VOR, or vice versa. Second, it is not known whether it is legitimate to infer the function of HGVP-cells during the VOR in the dark from the measurements made by Miles et al. (1980a), of the vestibular sensitivity of HGVP-cells during cancellation of the VOR. Finally, it is essential to reconcile the very different effects of motor learning on the responses of HGVP-cells under different behavioral conditions: how can the responses of HGVP-cells change in the right direction to support learning when measured during the VOR and in the wrong direction when measured during cancellation of the VOR?

In the preceding paper (Lisberger et al. 1994b) we developed stimuli that should help to answer these questions about the role of HGVP-cells in motor learning. In that paper we used a rapid change in head velocity to study the effect of motor learning on the responses of neurons that are called flocculus target neurons (FTNs) because they are inhibited at monosynaptic latencies after electrical stimulation of the flocculus and the ventral paraflocculus with single pulses (Lisberger et al. 1994a). During the VOR evoked by rapid changes in head velocity, motor learning causes the FTNs to show profound changes in firing that are expressed at a latency that averaged 12.9 ms after the onset of head motion (Lisberger et al. 1994b). In the present paper we found that the latency of HGVP-cell responses during the VOR was too long to cause either the changes in the firing of FTNs or the shortest-latency changes in the eye movements of the VOR (Lisberger 1984). We also demonstrated that measurements made during cancellation of the VOR provide good estimates of the strength of the vestibular input to HGVP-cells during the VOR in the dark. We conclude that the HGVP-cells are not the site of the cellular changes that mediate motor learning in the short-latency components of the VOR. Finally, we have used computational techniques in an effort to reconcile all existing observations about the effect of motor learning in the VOR on the responses of HGVP-cells. Analysis of a simple model shows how changes in the time course and strength of vestibular inputs to HGVP-cells could mediate the longer latency components of learning without contradicting the data reported previously by Miles et al. (1980a) or Watanabe (1984, 1985).

**Methods**

We made extracellular single-unit recordings from P-cells in the flocculus and ventral paraflocculus of four awake, behaving rhesus monkeys. Methods described in an earlier paper (Lisberger et al. 1994a) were used to train the monkeys to track a moveable target spot. We then anesthetized the monkeys with halothane and used sterile procedure to implant devices for restraining the head, for recording horizontal and vertical eye movement, and for introducing microelectrodes into the cerebellum on a daily basis.

**Recording from the cerebellum**

A stainless steel cylinder was positioned stereotaxically on the skull so that it was tilted 26° back from the coronal plane and was aimed at ear bar zero, 11 mm lateral to the midline. Recording electrodes entered the brain through this cylinder and were driven through the cerebral cortex and the tentorium into the cerebellar
cortex, which was recognized by a sharp increase in background activity and by the presence of complex spikes. In the cerebellum, P cells were identified by the typical negative-positive configuration of their simple-spike waveforms, by the presence of complex spikes, and by the ease of maintaining good isolation over up to 100 μm of electrode travel. Arrival of the electrode into the flocculus or ventral paraflocculus was recognized by the modulation of P-cell firing rate in relation to horizontal or vertical pursuit and by the eye movement–related activity of neural elements that were not P-cells. In most of our penetrations, the electrode entered these structures 2–5 mm below the surface of the cerebellum and remained in them until it either entered the vestibular or auditory nerve (Lisberger and Pavelko 1986) or exited the brain. Standard histological procedures (Lisberger et al. 1994a) were used to verify the location of our recordings.

The electrical potentials of P-cells were amplified conventionally (bandpass 100 Hz to 10 kHz) and led through two window discriminators. One discriminator had both time and amplitude windows; whenever possible, it was set to register the occurrence of complex spikes without triggering off the simple spikes. The other discriminator had a simple amplitude window and was used to trigger off the simple spikes. Although the latter discriminator usually did not distinguish between simple spikes and complex spikes, the frequency of complex spikes was so low that it did not have a serious effect on the average firing rate attributed to simple spikes. We were able to see and hear the complex spikes in most of our recordings from P-cells and to trigger on both the simple and the complex spikes in ~25% of the P-cells. A few recordings were included in the sample of P-cells even though they did not show clear complex spikes. These cells had responses that were similar to identified HGVP-cells in all other regards, had electrical potentials of the same shape and duration commonly found in the simple spikes of identified P-cells, and, when injured by advancing the microelectrode, showed the same pattern of electrical potentials seen for recordings that included complex spikes.

**Experimental design and recording protocol**

Motor learning was induced in the VOR by fitting the monkeys with spectacles that magnified or miniaturized the visual scene (Lisberger et al. 1994b). The VOR was studied by subjected the monkey to a series of transient vestibular stimuli in darkness. Each stimulus consisted of a rapid change in head velocity from 0 to 30°/s over 50 ms, a period of head rotation at constant velocity for 200 ms, and a rapid change in head velocity back to 0°/s (see Fig. 1 of Lisberger and Pavelko 1986). Each pulse was presented in darkness, and the monkey was rewarded for fixating a stationary spot that was illuminated only in the interval when the head was stationary between vestibular stimuli. The gain of the VOR was measured as the mean steady-state eye speed divided by the mean head speed, both computed in the interval 100–200 ms after the onset of head motion. Two monkeys were used to obtain 1 sample of Purkinje cells when the gain of the VOR was > 1.5, and 2 were used to obtain another sample when the gain of the VOR was < 0.45. The two monkeys that provided the low-gain sample also were used to record a sample of Purkinje cells when the gain of the VOR was close to 1.0.

The behavioral paradigms we used are outlined in Table 2, which appears later in the paper to summarize our results. Each P-cell we encountered was first studied during pursuit of sinusoidal target motion at 0.5 Hz, ±10° along the horizontal and vertical axis of the visual field. P-cells that showed a stronger modulation of simple-spikes firing rate during horizontal than during vertical pursuit were studied while the monkey tracked a target that moved exactly with him during sinusoidal vestibular rotation about the vertical axis at 0.5 Hz, ± 10° (cancellation of the VOR). Their responses were also recorded during the VOR evoked in darkness by a sequence of ~100 rapid changes in head velocity in each direction. Although pursuit of horizontal or vertical target motion was used as a search stimulus, P-cells were tested during cancellation of the VOR even if they did not respond during pursuit with the head stationary. This ensured that we did not overlook a potential subpopulation of P-cells that would respond during horizontal vestibular stimulation but not during pursuit eye movements. Our data agree with previous reports (e.g., Lisberger and Fuchs 1978a; Miles et al. 1980b; Stone and Lisberger 1990a) that the parts of the cerebellum we sampled contain few P-cells that respond in relation to vestibular stimulation without showing the other properties of HGVP-cells.

**Data acquisition and analysis**

Data were recorded on a laboratory computer (LSI 11/23) and were analyzed after the experiment with the use of the procedures detailed in our previous papers (Lisberger et al. 1994a,b). For sinusoidal stimuli, we calculated the average firing rate and eye velocity for the responses to ~10 consecutive cycles of the stimulus for each P-cell. We then used a fast Fourier transform (FFT) to obtain the amplitude and phase of the fundamental components of average firing rate, eye velocity, and head velocity. The sensitivity to eye or head velocity was estimated as the amplitude of the fundamental component of firing rate divided by the amplitude of the fundamental component of eye or head velocity. The difference in phase between the fundamental components of firing rate and eye or head velocity was used to determine whether firing rate increased for motion toward or away from the side of recording along the horizontal axis and for upward or downward pursuit along the vertical axis. The sign of the sensitivity to eye velocity was based on the phase shift between firing rate and eye velocity. For horizontal pursuit and cancellation of the VOR, sensitivity to eye or head velocity was defined as positive if the phase shift between firing rate and eye or head velocity toward the side of recording was between −90° and +90°. For vertical pursuit, sensitivity to eye velocity was defined as positive if the phase shift between firing rate and upward eye velocity was between −90° and +90°. Most of the cells we encountered had phase shifts close to zero and could be assigned clearly according to the direction of eye motion that caused increased firing (see Fig. 5 of Stone and Lisberger 1990a). For the remainder of the paper, we will use the terms “ipsiversive” and “contraversive” to refer to motion toward and away from the side of recording, respectively.

**RESULTS**

**Identification of P-cells for horizontal eye movement**

Each P-cell was characterized according to physiological criteria established in previous recording studies of Purkinje cell firing in the structure that was called the flocculus (Lisberger and Fuchs 1978a; Miles et al. 1980b; Stone and Lisberger 1990a). First, we used the responses during pursuit eye movements to categorize each P-cell as related to horizontal or vertical eye movement. For each P-cell we encountered, we recorded the simple-spike firing rate during horizontal and vertical pursuit and, at the same time, listened to the audio monitor to determine whether the modulation of simple-spike firing rate sounded larger during horizontal or during vertical pursuit. Cells were selected for further study if the modulation heard over the audio monitor was stronger for horizontal pursuit. After the experiment, we analyzed the responses of each cell during horizontal and vertical pursuit and verified that our selection criteria during the experiments had been appropriate.

**Figure 2, A and B,** shows the average firing rate and eye velocity during pursuit along the horizontal (A) or vertical
Horizontal and vertical eye velocity were equal. The open circles plotted just above the top diagonal line in Fig. 3 even though they show data from P-cells that were judged, by listening to the audio monitor, to respond more strongly for horizontal pursuit. These cells were slightly more sensitive to vertical than to horizontal eye velocity, but we have included them in our sample of P-cells because we had selected them for study during the experiment and recorded their responses during the VOR in the dark. The P-cells plotted with other symbols were not studied during the VOR in the dark. They included a large group of P-cells (open triangles) that plotted below the horizontal dashed line and at negative values along the abscissa. These cells were more sensitive to vertical than to horizontal eye velocity and showed increased firing for contraversive and downward eye motion. Previous studies have suggested that the cells with strong increases in firing for downward pursuit

\[ \text{(B) axis for a typical P-cell that showed simple-spike firing related to horizontal eye movement. During pursuit of sinusoidal target motion along the horizontal axis (Fig. 2A), the P-cell showed a deep modulation of firing rate with a peak that occurred just before peak ipsiversive eye velocity (vertical dashed line). During pursuit of sinusoidal target motion along the vertical axis (Fig. 2B), the same P-cell showed weak periodic modulation of firing rate that appeared consistently in each cycle of the stimulus. Figure 2, C and D, shows the responses of a P-cell that was related primarily to vertical eye movement. During pursuit of sinusoidal target motion along the horizontal axis (Fig. 2C), this P-cell showed a small periodic modulation of firing rate with a peak (vertical dashed line) that occurred near peak contraversive eye velocity. During vertical pursuit, the same P-cell showed a strong modulation of firing rate with a peak that occurred near peak downward eye velocity (vertical dashed line).}

Figure 3 compares the responses during horizontal and vertical pursuit for our full sample of P-cells recorded when the gain of the VOR was high or low. Each point shows the responses of a single P-cell, and the two oblique dashed lines show where points would plot if the sensitivities to horizontal and vertical eye velocity were equal. The open circles plot the responses of the P-cells that were selected to be studied during the VOR because they were judged, by listening in the audio monitor, to show larger responses during horizontal than during vertical pursuit. Most of these P-cells plotted to the right of the two oblique dashed lines in Fig. 3 and at positive values of sensitivity to horizontal eye velocity. Therefore they were more sensitive to horizontal than to vertical eye velocity, and they showed increased firing during ipsiversive eye motion. A few open circles plotted just above the top diagonal line in Fig. 3 even though they show data from P-cells that were judged, by listening to the audio monitor, to respond more strongly for horizontal pursuit. These cells were slightly more sensitive to vertical than to horizontal eye velocity, but we have included them in our sample of P-cells because we had selected them for study during the experiment and recorded their responses during the VOR in the dark. The P-cells plotted with other symbols were not studied during the VOR in the dark. They included a large group of P-cells (open triangles) that plotted below the horizontal dashed line and at negative values along the abscissa. These cells were more sensitive to vertical than to horizontal eye velocity and showed increased firing for contraversive and downward eye motion. Previous studies have suggested that the cells with strong increases in firing for downward pursuit

\[ \text{FIG. 2. Selection of Purkinje cells (P-cells) that were related to horizontal eye movement, by comparison of the modulation of firing rate during pursuit along the horizontal and vertical axis. A and B: averages from a P-cell that was related primarily to horizontal eye movement. C and D: averages from a P-cell that was related primarily to vertical eye movement. Each quadrant of the graph shows average firing rate, average eye velocity, and average target position for 10 cycles of sinusoidal target motion at 0.5 Hz, ±10°/s. Averages of firing rate were computed by counting the number of spikes in a 100-ms sliding window that was centered at 512 equally spaced times along the sinusoidal cycle. Firing rate traces have been aligned so that the same calibration markers apply to A and B and to C and D. A and C: horizontal eye and target motion. B and D: vertical eye and target motion. A single cycle is repeated in each average to facilitate viewing of the periodic events. The vertical dashed lines show the time of a peak or trough of eye velocity. Upward deflections indicate eye or target motion toward the side of recording or upward.}

\[ \text{FIG. 3. Summary of the preferred axis of eye motion for the full sample of P-cells. Each point shows the responses of a P-cell and plots the sensitivity to horizontal eye velocity during horizontal pursuit as a function of the sensitivity to vertical eye velocity during vertical pursuit. For each axis of motion, the stimulus was sinusoidal target motion at 0.5 Hz, ±10°. The 2 diagonal dashed lines have slopes of +1 and -1, and they divide the population of P-cells according to whether the sensitivity to eye velocity was higher for horizontal or vertical pursuit. As shown by the arrows in the top right corner of the graph, P-cells that showed increased firing during ipsiversive eye motion had positive values of sensitivity during horizontal pursuit, and P-cells that showed increased firing during downward eye motion had negative values of sensitivity during vertical pursuit. Open circles show P-cells that were selected during the experiment for study during the VOR, all of which showed increased firing for ipsiversive eye motion during horizontal pursuit. Open triangles show P-cells that increased their firing for downward eye motion during vertical pursuit and for contraversive eye motion during horizontal pursuit. This graph does not distinguish the P-cells recorded when the gain of the VOR was high and low.} \]
may be down-GVP-cells that subserve vertical gaze in the same way HGVP-cells subserve horizontal gaze (Miles et al. 1980b; Stone and Lisberger 1990a). Two smaller groups of P-cells (filled circles) had stronger responses during vertical than during horizontal pursuit and showed increased firing either for ipsiversive and downward eye motion or for contraversive and upward eye motion. Although these cells had not been found in large numbers in our previous recordings (e.g., Stone and Lisberger 1990a), we do not think their presence in our sample represents an effect of motor learning on the responses of P-cells in the ventral paraflocculus. Rather, we think that minor differences in the sampling procedures can explain why we recorded them more frequently in the present study.

For the P-cells in our sample, complex spikes tended to fire out-of-phase with simple spikes during pursuit with the head stationary. P-cells that showed stronger modulation of simple-spike firing during horizontal pursuit also showed stronger modulation of complex-spike firing during horizontal than during vertical pursuit. This finding shows that the complex-spike responses of the P-cells included in our sample are in good agreement with those of the P-cells included in the sample reported by Watanabe (1984). We have elected not to document the complex-spike responses of HGVP-cells because our new recordings simply confirm our previous data (Stone and Lisberger 1990b).

Identification of HGVP-cells

All but one of the P-cells selected during the experiment for recording during the VOR in the dark (open circles in Fig. 3) showed the response characteristics of HGVP-cells. Earlier studies (Lisberger and Fuchs 1978a; Miles et al. 1980b; Stone and Lisberger 1990a) have demonstrated that the simple-spike firing of HGVP-cells includes two independent components related to eye velocity and head velocity. The relationship between firing rate and eye velocity can be studied in isolation during pursuit of sinusoidal target motion along the horizontal axis with the head stationary (Fig. 4A). As we have shown above, HGVP-cells undergo a periodic modulation of firing rate and reach peak firing near peak ipsiversive eye velocity (vertical dashed line in Fig. 4A). The relationship between the simple-spike firing rate of HGVP-cells and head velocity can be studied in isolation when the monkey cancels his VOR by tracking a target that moves exactly with him during sinusoidal head rotation in the horizontal plane (Fig. 4B). Even though there is very little modulation of eye velocity under these tracking conditions, HGVP-cells show a strong modulation of firing rate, now reaching peak firing near peak contraversive head velocity (vertical dashed line). The HGVP-cell illustrated in Fig. 4 was recorded when the gain of the VOR was low and, as reported by Miles et al. (1980a), showed a smaller modulation of simple-spke firing during cancellation of the VOR (Fig. 4B) than during pursuit with the head stationary (Fig. 4A).

Nonlinear relationships between firing rate and eye or head velocity in HGVP-cells

In the examples that appear in Fig. 4, and in many of the HGVP-cells we studied, firing rate during pursuit or cancellation of the VOR showed a clear asymmetry with strong positive modulation of firing rate for ipsiversive eye or head motion and little or no negative modulation for contraversive motion (see also Miles et al. 1980b; Stone and Lisberger 1990a). In Fig. 4 the asymmetry is revealed by the fine horizontal lines through the firing rate traces, which indicate the resting level of firing rate when eye and head velocity was between -1 and +10°/s. It was possible that this asymmetry would affect our measurements of the strength of the vestibular and eye movement inputs to HGVP-cells. For example, an increase in the strength of a given input could not be reflected completely in the firing of a cell whose response is already limited because it has cut off at zero firing rate. Therefore it was necessary first to analyze the asymmetry to establish the range of eye and head velocities over which measurements of response amplitude would provide reliable estimates of the strength of the eye and head movement inputs to HGVP-cells.

For each recording from an HGVP-cell during pursuit with the head stationary or during cancellation of the VOR, we converted the time-varying averages of firing rate and eye or head velocity into plots like those in Fig. 5. Each graph contains 512 points, 1 for each of the 512 bins in averages like those in Figs. 2 and 4. For the responses during horizontal pursuit with the head stationary (Fig. 5, A, C, and E), each graph plots the measured firing rate as a function of eye velocity. For the responses during cancellation of the VOR (Fig. 5, B, D, and F), the average of firing rate was first corrected for any contribution from the small residual modulation of eye velocity. This was done by the equation

\[ \text{firing rate corrected}(t) = \text{firing rate measured}(t) - r \times E(t) \]

where \( r \) (sensitivity to eye velocity) was estimated as the slope calculated by linear regression on all the points in the
cases, such as Fig. 5, C and D, the asymmetry could not be attributed to cutoff at zero firing rate because firing rate increased for negative values of eye and head velocity even though the minimum firing rate was >100 spikes/s. In many other HGVP-cells, such as Fig. 5, E and F, the asymmetry appeared to be related to the low spontaneous firing rate and the high sensitivity of the HGVP-cell to eye velocity, which caused firing rate to cut off at or just above zero during the half-cycle that contained eye motion away from the side of the recording. Many of the graphs in Fig. 5 show hysteresis so that the firing rate has different values for a given eye velocity depending on whether the eye was accelerating or decelerating. Hysteresis is expected in graphs like this whenever the phase shift between firing rate and eye or head velocity is not exactly 0°.

If a cell has an excitatory response that is larger than its resting firing rate, then cutoff at zero firing rate would restrict the magnitude of its inhibitory response and would cause asymmetries like those shown in Fig. 5. We evaluated this possibility in Fig. 6 by plotting the amplitude of the excitatory response during pursuit or cancellation of the VOR as a function of the resting firing rate for each HGVP-cell. We estimated the resting firing rate by computing the firing rate at zero velocity as the average firing rate over the bins when eye or head velocity was between −1 and +1°/s. We estimated the amplitude of the excitatory response as the peak firing rate during the sinusoidal cycle minus the firing rate at zero velocity. During both pursuit with the head stationary (Fig. 6A) and cancellation of the VOR (Fig. 6C), there was wide variation in the relationship between the amplitude of the response and the firing rate at zero velocity. About 40% of the HGVP-cells (filled symbols) plotted above the line of slope 1. For these HGVP-cells, the amplitude of the excitatory response was larger than the firing rate at zero velocity. Therefore symmetrical excitatory and inhibitory responses were impossible because of cutoff at zero firing rate.

For the same HGVP-cells, we next used linear regression to analyze the slope of the relationship between firing rate and head or eye velocity separately for velocities between −40 and +1°/s and between −1 and +40°/s. We used overlapping ranges for this analysis to ensure that the two regression lines would meet at zero velocity. Figure 6, B and D, plots the sensitivity to eye or head velocity for contraversive motion as a function of that for ipsiversive motion. The open and filled symbols show data from the same HGVP-cells that are plotted as open and filled symbols in Fig. 6, A and C. In agreement with Stone and Lisberger (1990b), some cells showed marked asymmetries even though their excitatory response was smaller than the resting rate (open symbols from Fig. 6, A and C). However, the most pronounced asymmetries were seen when the excitatory response was larger than the resting rate (cells plotted as filled symbols). We conclude that cutoff at or near zero firing rate often prevents the simple-spike firing of an HGVP-cell from expressing the full magnitude of its inputs during head or eye motion away from the side of recording. Therefore the sensitivity to ipsiversive (on-direction) eye or head velocity provides the most accurate estimate of the strength of the incoming eye movement and vestibular signals, and we have used only this on-direction sensitivity in subsequent graphs. Two of the HGVP-cells in our sample had unusu-

![Figure 5](image-url)

**Fig. 5.** Inflections in the relationships between firing rate and eye or head velocity for 3 representative HGVP-cells. A, C, and E: responses during horizontal pursuit with the head stationary. B, D, and F: responses during cancellation of the VOR. The 3 rows of graphs were taken from 3 HGVP-cells. Each graph contains 512 points that were obtained from 1 periodic average of firing rate and eye or head velocity during sinusoidal stimulation. Each point plots the values of firing rate and eye or head velocity in 1 bin of the periodic average. Each graph contains two lines obtained by separate linear regression for velocities between −40 and +1°/s and between −1 and +40°/s. Positive values of eye or head velocity indicate ipsiversive motion.

plots of firing rate as a function of eye velocity during pursuit. Even for cells with highly nonlinear relationships between firing rate and eye velocity, we used the slope provided by linear regression over the range of eye velocity as an average of the sensitivity to eye velocity over the entire range of eye velocities. We do not think that this linearization affected our conclusions materially; the excursion of eye velocity was small during cancellation of the VOR so that the correction had only a small effect on the modulation of simple-spike firing rate. After the small eye velocity component had been removed, the corrected firing rate was plotted as a function of head velocity for each of the 512 bins in the time-varying averages.

In Fig. 5, cell 1 is an example of a small group of HGVP-cells that showed an approximately linear relationship between firing rate and eye or head velocity with little evidence for an inflection near zero velocity. However, many HGVP-cells (e.g., cells 2 and 3) showed clear asymmetries in the relationships between firing rate and eye or head velocity. For the three cells shown in Fig. 5 and most of the HGVP-cells in our sample, the two tracking conditions yielded relationships with similar asymmetries. In some
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FIG. 6. Quantitative comparison of the sensitivity to eye and head velocity for motion toward and away from the side of recording. A and B: responses during horizontal pursuit with the head stationary. C and D: responses during cancellation of the horizontal VOR. Each point shows the responses of a single HGVP-cell. A and C plot the difference between the peak firing rate and the firing rate at 0 velocity as a function of the firing rate at 0 velocity. The diagonal lines have slopes of 1. The values of sensitivity in B and D were calculated from graphs of firing rate as a function of eye or head velocity like those in Fig. 5. Each point plots the slope of the regression line for negative values of head or eye velocity as a function of that for positive values of head or eye velocity. Positive and negative values of sensitivity indicate that firing rate increased for motion toward or away from the side of recording, respectively. Filled symbols in all 4 panels show the cells that plotted above the diagonal line in A and C. Circles, triangles, and squares show data obtained when the gain of the VOR was high, normal, and low, respectively.

FIG. 7. Changes in the relationship between sensitivity to eye velocity and head velocity during pursuit and cancellation of the VOR. A and B: pursuit with the head stationary. C and D: cancellation of the horizontal VOR. Each point shows a single HGVP-cell. A and C plot the difference between the peak firing rate and the firing rate at 0 velocity as a function of the firing rate at 0 velocity. The diagonal line has a slope of 1. The values of sensitivity were calculated from graphs of firing rate as a function of eye or head velocity like those in Fig. 5. Each point plots the slope of the regression line for negative values of head or eye velocity as a function of that for positive values of head or eye velocity. Positive and negative values of sensitivity indicate that firing rate increased for motion toward or away from the side of recording, respectively. Filled symbols in all 4 panels show the cells that plotted above the diagonal line in A and C. Circles, triangles, and squares show data obtained when the gain of the VOR was high, normal, and low, respectively.

Effect of changes in the gain of the VOR on sensitivity of HGVP-cells to head and eye velocity

In an earlier study of HGVP-cells, Miles et al. (1980a) demonstrated that the sensitivity to eye velocity during pursuit is the same when the gain of the VOR is high or low, although it is slightly higher in both cases than when the gain of the VOR is normal. Several studies have also demonstrated that the sensitivity to head and eye velocity are nearly equal in individual HGVP-cells when the gain of the VOR is normal (Lisberger and Fuchs 1978a; Miles et al. 1980b; Stone and Lisberger 1990a). These two observations, taken together, allow the firing of each HGVP-cell during pursuit with the head stationary to serve as an internal control. For an HGVP-cell recorded when the gain of the VOR is high or low, its sensitivity to eye velocity during pursuit with the head stationary estimates how it would have responded during cancellation of the VOR if the gain of the VOR were normal. Therefore the best method that was available to document any effect of changes in the gain of the VOR on the strength of vestibular inputs to HGVP-cells was to plot the sensitivity to head velocity during cancellation of the VOR as a function of the sensitivity to eye velocity during pursuit with the head stationary (e.g., Fig. 7). When the data are plotted in this way, each graph normalizes the data for the inherent variation among HGVP-cells in the baseline strengths of their vestibular and eye movement inputs.

Figure 7 shows that changes in the gain of the VOR affected the slope of the relationship between sensitivity to head velocity and sensitivity to eye velocity. Regression analysis (solid lines) revealed that the slope of the relationship was 0.65 when the gain of the VOR was low (Fig. 7A), 0.86 when the gain of the VOR was normal (Fig. 7B), and 1.05 when the gain of the VOR was high (Fig. 7C). For these three graphs, the y-intercepts were 0.56, 0.31, and 0.33 spikes/s per deg/s, and the gain of the VOR averaged 0.40, 1.01, and 1.62 when the data were recorded. Therefore changes in the gain of the VOR were associated with changes in the slope of this relationship that were in the same direction as reported by Miles et al. (1980a) but were slightly smaller. The smaller changes may reflect the smaller range of VOR gains in our data, our methods for estimating sensitivity to head or eye velocity from the responses to ipsiversive motion only, or our use of vestibular stimuli at higher frequencies. We measured the head velocity component of firing rate during cancellation of the VOR with sinusoidal head rotation at 0.5 Hz, ±10°, and they used sinusoidal rotation at 0.2 Hz, ±20°.

Our samples are smaller than those reported by Miles et al. (1980a) and are therefore potentially subject to more bias than were theirs. For example, a comparison of Fig. 7B with Fig. 7, A and C, makes it clear that we did not record as many HGVP-cells with high values of sensitivity to eye velocity when the gain of the VOR was normal as we did when the gain of the VOR was high or low. The larger sample of Miles et al. (1980a) demonstrated that motor learning does not have a profound effect on the sensitivity of HGVP-cells...
to eye velocity. Because our sample is clearly not as large as theirs, we have not attempted to do an extensive statistical analysis of the effect of changes in the gain of the VOR on the absolute values of sensitivity to head and eye velocity. In addition, to avoid biasing the results because our three samples of HGVP-cells had different numbers of cells that were not well related to head or eye velocity, data were plotted in our graphs but excluded from the regression analysis if the sensitivity to eye velocity was < 0.5. In practice, excluding these cells had only tiny effects on the numbers provided by the statistical analysis and did not alter our conclusions. We also excluded the point in Fig. 7A that plots at a sensitivity to head velocity of 4.2 and a sensitivity to eye velocity of 0.6 because it was one of the rare cells we encountered that was not an HGVP-cell but showed increased firing for ipsiversive eye or head motion.

**Effect of changes in the gain of the VOR on the responses of HGVP-cells during the VOR**

Figure 8 illustrates the responses during the VOR evoked by rapid changes in head velocity for two HGVP-cells, one recorded when the gain of the VOR was low (Fig. 8, A and B) and the other when the gain of the VOR was high (Fig. 8, C and D). Each panel shows the average simple-spike firing rate, eye velocity, and head velocity during a pulse of head velocity from 0 to 30°/s and back to 0. The target was extinguished just before each pulse of head velocity (Fig. 8, E and F) so that the recordings described in this section document the responses of HGVP-cells during the VOR in the dark (see Lisberger et al. 1994b). For the HGVP-cell recorded when the gain of the VOR was low, a pulse of ipsiversive head motion evoked a sharp increase in firing rate (Fig. 8A), and a pulse of contraversive head motion evoked a sharp decrease in firing rate (Fig. 8B). For this cell the response showed an initial transient increase or decrease in firing rate (arrows in Fig. 8, A and B) followed by a sustained change in firing. The HGVP-cell recorded when the gain of the VOR was high (Fig. 8, C and D) showed responses with the opposite direction selectivity. Ipsiversive head motion evoked a small decrease in firing rate (Fig. 8C), and contraversive head motion evoked an increase in firing rate (Fig. 8D).

Changes in the gain of the VOR were associated with large changes in the responses of HGVP-cells during the VOR evoked by rapid changes in head velocity. We analyzed these responses by measuring the amplitude and direction of both the initial change in firing evoked by rapid head acceleration and the sustained change in firing recorded during head motion at constant velocity. We thought it was important to measure the initial and sustained responses separately, because many HGVP-cells showed an initial
HGVP-cells had sustained firing rate during ipsiversive head motion that was below the resting firing (Fig. 10B) and sustained firing during contraversive head motion that was above the resting firing (Fig. 10D). Therefore both the transient and the sustained responses of HGVP-cells during the VOR were in phase with the afferents from the ipsilateral horizontal canal when the gain of the VOR was low and out-of-phase when the gain of the VOR was high. In contrast to the data in Figs. 8–10 of this paper, Fig. 10 of Stone and Lisberger (1990a) demonstrated that HGVP-cells show little or no response during the VOR evoked by rapid changes in head velocity when the gain of the VOR is close to one.

**Latency of HGVP-cell responses during the VOR**

For each HGVP-cell that showed a clear modulation of simple-spike firing rate during the VOR evoked by rapid changes in head velocity, we estimated the latency from the onset of head motion to the onset of the change in firing separately for each direction of head motion. Latencies were estimated by hand with the use of the methods and criteria described in the preceding paper of this series (Lisberger et al. 1994b). The histograms in Fig. 11 include two measurements for each HGVP-cell recorded when the gain of the VOR was high or low; the latencies for ipsiversive and contraversive head turns are shown as solid bars and open bars, respectively. Open bars are stacked on top of solid bars so that the tops of the solid bars give the baseline for the open bars and the tops of the open bars summarize the distribution of latency for both directions of head motion. A few HGVP-cells responded at latencies <10 ms during the VOR, but the majority responded only after much
As described in the previous sections, changes in the gain of the VOR are associated with changes in the strength of one or more inputs to HGVP-cells. For example, the effect of motor learning on the responses of HGVP-cells during the VOR in the dark (Figs. 8–10) does not provide any information about changes in the individual strengths of either vestibular or eye movement inputs to HGVP-cells. HGVP-cell firing during the VOR reflects a balance between opposing head and eye velocity inputs. Therefore, the change in the amplitude of the eye velocity of the VOR after motor learning would be sufficient to cause changes in the responses of HGVP-cells, even without any change in the strength of their vestibular inputs. The experiments of Miles et al. (1980a), which we confirmed in Fig. 7, provide one way to estimate the strength of the vestibular inputs to HGVP-cells. However, that approach used the vestibular signals recorded during cancellation of the VOR as an estimate of the strength of the vestibular input during the VOR.

Our goal in the present section is to use data recorded during the VOR in the dark to derive an estimate of the strength of the vestibular input to HGVP-cells. To describe this analysis we distinguish between the sensitivities to head and eye velocity, which are in units of spikes/s per deg/s, and the head and eye velocity components of firing rate, which are in units of spikes/s and refer to the parts of firing rate caused by ongoing eye and head velocity. Our estimate of the head velocity component of firing rate \( f_{\text{head}}(t) \) was based on the conclusion of earlier studies (Lisberger and Fuchs 1978a; Milis et al. 1980b; Stone and Lisberger 1990a) that HGVP-cell firing during the VOR can be described by the equation

\[
 f_{\text{VOR}}(t) = f_{\text{eye}}(t) + f_{\text{head}}(t)
\]

where \( f_{\text{eye}}(t) = r \times \dot{E}(t) \), \( r \) is the sensitivity to eye velocity measured during pursuit with the head stationary, and \( \dot{E}(t) \) is the eye velocity at time \( t \) during the VOR evoked by rapid changes in head velocity. Substituting \( r \times \dot{E}(t) \) for \( f_{\text{eye}}(t) \) allows us to estimate the head velocity component of firing during the VOR as

\[
 f_{\text{head}}(t) = f_{\text{VOR}}(t) - r \times \dot{E}(t)
\]

When the gain of the VOR is normal, the eye and head velocity components of firing rate are both large, but they are opposite in direction and nearly equal in amplitude during the VOR. The two components cancel, and HGVP-cells show little modulation of firing rate. For the data shown in Figs. 12–14, we represented the sensitivity to eye velocity \( r \) by the slope of the regression line that relates the firing rate during pursuit to ipsiversive eye velocity. We will show later that the conclusions from this analysis did not depend on whether we estimated \( r \) as the slope for contraversive eye motion, the slope for contraversive eye motion, their maximum, or their mean.

Figure 12 shows how we estimated the head velocity component of firing rate for one HGVP-cell recorded during the VOR evoked by rapid changes in head velocity when the gain of the VOR was high. In agreement with the data presented in Figs. 8–10, this HGVP-cell showed a decrease in firing during the VOR evoked by ipsiversive head motion.
we recorded when the gain of the VOR was high, normal, or low. We then calculated the amplitude of the sustained part of the head velocity component as the mean value of its firing rate in the interval 100–200 ms after the onset of head motion minus the mean firing rate in the last 100 ms before the onset of head motion. To convert these measurements to estimates of the sensitivity to head velocity during the VOR, we divided the amplitude of each response by the magnitude of the change in head velocity (30°/s).

For the reasons outlined in reference to Fig. 7, we have again focused on the slope of the relationship between the sensitivity to head velocity during the VOR and the sensitivity to eye velocity during pursuit. For the sustained sensitivity to head velocity (Fig. 13), the slope of the relationship was clearly related to the gain of the VOR and was larger than normal when the gain of the VOR was high and smaller than normal when the gain of the VOR was low. For ipsiversive head motion (filled symbols), the slopes of the regression lines (solid lines) were 0.51 when the gain of the VOR was low (Fig. 13A), 0.96 when the gain of the VOR was normal (Fig. 13B), and 1.16 when the gain of the VOR was high (Fig. 13C). For contraversive head motion (open symbols), the slopes of the regression lines were 0.28, 0.62, and 1.03 when the gain of the VOR was low, normal, and high, respectively. Statistical comparison of the slopes when the gain of the VOR was high and low revealed that the differences were significant for both ipsiversive and contraversive head motion (t test, P < 0.02).

Table 1 shows that the effect of motor learning on vestibular sensitivity calculated during the VOR was in the same direction as that measured during cancellation of the VOR. Although the exact slope of the relationship between sensitivity to head and eye velocity depended somewhat on which of the two behavioral conditions was used, the slope was generally small when the gain of the VOR was low, intermediate when the gain of the VOR was normal, and large when the gain of the VOR was high. In the data obtained during cancellation of the VOR for ipsiversive head motion (Fig. 7), the slope of the relationship was 0.65 and 1.05 when the gain of the VOR was low or high. Changes in the gain of the VOR had somewhat larger effects on the slope of the relationship between estimated sensitivity to head velocity during the VOR and sensitivity to eye velocity during pursuit. When the gain of the VOR was low and high, the slope of the relationship was 0.51 and 1.16 for ipsiversive head motion and −0.28 and −1.03 for contraversive head motion. We conclude that the data obtained during cancellation of the VOR may underestimate somewhat the effect of motor learning on the strength of the sustained head velocity input to HGVP-cells during the VOR. However, the effect of motor learning on the head velocity component of HGVP-cell firing rate estimated during the VOR was in the same direction as the effects on the sensitivity to head velocity measured during cancellation of the VOR.

The calculation of sustained sensitivity to head velocity during the VOR should depend on how we estimated the sensitivity to eye velocity 1) to calculate the head velocity component of firing rate during the VOR and 2) as the value plotted on the abscissa. Therefore we repeated the analysis in Figs. 11 and 12 with the use of the sensitivity to contraversive eye velocity, the mean sensitivity to eye velocity, and the maximum of the sensitivities for ipsiversive and contraversive eye motion. This confirmed that the values of sensitivity to head velocity and the slopes of the relationships depended strongly on how we estimated the sensitiv-
Sensitivity to eye velocity. However, the effect of changes in the gain of the VOR on the sensitivity to head velocity did not depend on how we estimated sensitivity to eye velocity. For each set of assumptions, the analysis illustrated in Fig. 13 revealed that the slopes of the regression lines when the gain of the VOR was high were two to three times larger than the slope when the gain of the VOR was low. In addition, the slopes were always intermediate for the HGVP-cells sampled when the gain of the VOR was close to 1.0.

TABLE 1. Effect of motor learning and behavioral conditions on the slope of the relationship between sensitivity to head velocity and sensitivity to eye velocity of HGVP-cells

<table>
<thead>
<tr>
<th>Gain of VOR</th>
<th>Low (0.4)</th>
<th>Normal (1.0)</th>
<th>High (1.6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cancellation of VOR, ipsiversive head motion</td>
<td>0.65</td>
<td>0.86</td>
<td>1.05</td>
</tr>
<tr>
<td>VOR, ipsiversive head motion</td>
<td>0.51</td>
<td>0.96</td>
<td>1.16</td>
</tr>
<tr>
<td>VOR, contraversive head motion</td>
<td>-0.28</td>
<td>-0.62</td>
<td>-1.03</td>
</tr>
</tbody>
</table>

Data obtained during cancellation of the VOR were taken from Fig. 7, and data obtained during the VOR in the dark were taken from Fig. 13. For the data obtained during the VOR, sensitivity to head velocity was obtained by removing the eye velocity component from the measured firing rate. HGVP-cells, horizontal gaze velocity Purkinje cells; VOR, vestibuloocular reflex.

Stone (1987) showed that the sensitivity to eye velocity during pursuit of sinusoidal target motion at 0.5 Hz provides a good estimate of the sensitivity to eye velocity for sustained eye motion at constant speed. Therefore it was valid to use data obtained during pursuit of sinusoidal target motion as part of the calculation of the amplitude of the sustained eye velocity component of HGVP-cell firing during the VOR. However, we have no way to estimate the initial time course of the eye velocity input to HGVP-cells. During the rapid change in eye velocity at the onset of pursuit, for example, the eye velocity component of HGVP-cell firing rate is obscured by a pulse of firing related to the motion of the image from the tracking target (Stone and Lisberger 1990a). Therefore our calculation of the first 100 ms of the head velocity component of firing rate could not take into account possible dynamics in the eye velocity input, and it might have introduced a consistent error in our estimates of the initial sensitivity of HGVP-cells to head velocity during the VOR. Because of this potential problem, we have elected to not to report the values of initial sensitivity to head velocity during the VOR.

Site of recordings in vestibulocerebellum

Analysis of histological sections revealed that we recorded HGVP cells both in the ventral paraflocculus and in the flocculus. Figure 14 contains drawings of sagittal sec-

FIG. 13. Effect of motor learning on the sustained response in the head velocity component of HGVP-cells during the VOR. A: measurements from HGVP-cells recorded when the gain of the VOR was low. B: measurements from HGVP-cells recorded when the gain of the VOR was normal. C: measurement from HGVP-cells recorded when the gain of the VOR was high. For each HGVP-cell the head velocity component of firing rate during the VOR was estimated by the subtraction procedure outlined in Fig. 12. Here, the ordinate plots the average head velocity component of firing rate in the interval 100-200 ms after the onset of head motion minus the mean firing rate before the onset of the stimulus, all divided by the amplitude of the change in head velocity (30°/s). The abscissa plots the sensitivity to eye velocity during pursuit toward the side of recording. Each HGVP-cell is represented by 2 symbols: a filled symbol for head motion toward the side of recording and an open symbol for head motion away from the side of recording. The horizontal dashed line shows a response of 0 spikes/s, and the diagonal dashed lines have slopes +1 and -1. The solid lines were obtained by linear regression on the filled or open symbols, separately.
tions through the lateral part of the cerebellum in two of our monkeys. Only the rostral part of the cerebellum is shown, and the folia that correspond to flocculus and ventral paraflocculus have been numbered as well as shaded to show the white matter, granule cell layer, and molecular layer. The posterolateral fissure (PLF) defines the boundary between the flocculus (folia 1–4) and the ventral paraflocculus (folia 5–10). In monkey N we found electrode penetrations into both the flocculus and the ventral paraflocculus, ranging from folium 2 to the caudal parts of folia 6–8. The two black dots in folia 2 and 5 indicate the sites of marking lesions made at the sites of recording of HGVP-cells in monkey N. In monkey J we found electrode penetrations only into the ventral paraflocculus, including parts of folia 5–9. Our positive finding, that HGVP-cells are found as far caudal as folium 2 of the flocculus, contradicts the conclusion of Nagao (1992) that HGVP-cells are not found in the flocculus. However, we emphasize that our recordings have sampled extensively only in the ventral paraflocculus, and we think that future experiments must sample in the flocculus more thoroughly. This will reveal whether HGVP-cells are the principle class of Purkinje cells in the flocculus, as they are in the ventral paraflocculus.

Comparison of the sections from monkeys N and J contradicts our prior assumptions that the incoming eighth nerve is always rostral to the PLF and underneath the most caudal two folia of the ventral paraflocculus (5 and 6 in our diagrams). Both in these sections and in our reconstructions of the sites of stimulating electrodes in the ventral paraflocculus and flocculus (Lisberger et al. 1994a), we have found that the eighth nerve is under folia 5 and 6 (ventral paraflocculus) in some monkeys, such as monkey J, and that it is under folium 4 (floculus) in other monkeys, such as monkey N.

DISCUSSION

We have recorded from HGVP-cells in the flocculus and ventral paraflocculus after motor learning had caused either increases or decreases in the gain of the VOR. Although previous studies conducted similar experiments (Miles et al. 1980a; Watanabe 1984, 1985), the interpretation of their data has been controversial, and the role of these cerebellar structures in changing the gain of the VOR is not yet resolved. One problem with the previous studies was the absence of substantial overlap in experimental procedure. Miles et al. (1980a,b) concentrated on the responses of HGVP-cells in the ventral paraflocculus during pursuit with the head stationary and during cancellation of the VOR. Watanabe (1984, 1985) recorded from P-cells in the flocculus and ventral paraflocculus during the VOR in the dark and made no attempt to identify them as HGVP-cells. A second problem was that data were obtained only for sinusoidal target motion at low frequencies so that no information was available on the latencies of P-cell responses during the VOR. The final problem was that the interpretation of the data was based on models that were not suitable for analyzing responses to vestibular inputs that varied as a function of time.

Identification of P-cells that participate in the horizontal VOR

Our data argue that the previous recordings of Watanabe (1984, 1985) and Miles et al. (1980a) were drawn from the same populations of P-cells and that this population is involved in the horizontal VOR. We limited our attention to P-cells that showed deeper modulation of simple-spike firing rate during horizontal pursuit than during vertical pursuit with the head stationary. Almost all of these P-cells fell into the well-known category of HGVP-cells that were studied by Miles et al. (1980a,b). Stone and Lisberger (1990b) demonstrated that the complex-spike activity of HGVP-cells is modulated in relation to horizontal eye motion and is driven by horizontal image motion, thereby satisfying one of the important criteria for recordings from the part of the flocculus and ventral paraflocculus that is involved in horizontal eye movements (called the "H-zone" by Watanabe 1984, 1985). Table 2 summarizes the effect of changes in the gain of the VOR on the responses of HGVP-cells under a variety of conditions. As found by both Watanabe (1984, 1985) and Miles et al. (1980a), motor learning...

<table>
<thead>
<tr>
<th>TABLE 2. Effect of motor learning on the responses of HGVP-cells in different behavioral conditions</th>
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<tbody>
<tr>
<td>Smooth pursuit</td>
</tr>
<tr>
<td>E-i</td>
</tr>
<tr>
<td>V-i</td>
</tr>
<tr>
<td>V-i</td>
</tr>
<tr>
<td>V-i</td>
</tr>
<tr>
<td>V-c</td>
</tr>
<tr>
<td>Stronger V-i</td>
</tr>
</tbody>
</table>

When the gain of the VOR was low or high, the responses during VOR cancellation and the head velocity component during the VOR were referred to those recorded when the gain of the VOR was normal. V-i, V-c, E-i, and E-c indicate that firing rate increased for ipsiversive (i) or contraversive (c) eye movement (E) or vestibular stimulation (V); for other abbreviations, see Table 1.
causes the responses of HGVP-cells during the VOR to change in a direction that is appropriate to support the associated changes in the gain of the VOR. As found by Miles et al. (1980a), motor learning causes the responses of HGVP-cells during cancellation of the VOR to change in the wrong direction to support changes in the gain of the VOR. Any model of the VOR must account for the fact that these apparently contradictory data are true for individual cells.

The nomenclature used to refer to the flocculus and ventral paraflocculus has changed in the past 5 years, complicating the question of whether we have failed to record from a class of P-cells that is relevant for motor learning in the VOR. Most previous research on these parts of the cerebellum has used the term flocculus to describe a structure that has 10 or 11 folia and extends across 6 or 7 folia rostral to the PLF and 4 folia caudal to the PLF (Madigan and Carpenter 1971). Recent anatomic studies (Gerrits and Voogd 1989) have pointed out that the terminology of LarSELL (1970) is more accurate and that the PLF divides this structure into the ventral paraflocculus rostrally and the flocculus caudally. We encountered HGVP-cells in both the flocculus and the ventral paraflocculus, but the overwhelming majority of our sample was drawn from the ventral paraflocculus. Therefore we do not know if there is another population of P-cells that resides primarily in the flocculus, that discharges selectively in relation to horizontal eye movements and/or vestibular stimulation, and that might play a role in motor learning different from that of HGVP-cells.

Available data do not persuade us that there is any evidence for differences in the physiological functions of the flocculus and the ventral paraflocculus during the VOR. The primary claim for differences in the physiological function of these two structures comes from a short report by Nagao (1992). However, the data presented in that paper fail to support its claims. First, Nagao (1992) claims that there are large differences between the flocculus and the ventral paraflocculus in the amplitude of the modulation of P-cell simple-spike firing rate during pursuit with the head stationary. In fact, the data show that the amplitude of modulation of P-cells recorded in the flocculus was, on average, 71% of that for P-cells recorded in the ventral paraflocculus. In addition, the sampling procedures used by Nagao (1992) were flawed. He did not record the firing of P-cells during vertical pursuit and therefore cannot exclude the likely possibility that his samples were contaminated with P-cells that discharged weakly in relation to horizontal pursuit and much more strongly in relation to vertical pursuit (Stone and Lisberger 1990a; this paper). Second, Nagao (1992) claims that P-cells in the flocculus and ventral paraflocculus differed in their responses during cancellation of the VOR. However, the raw data shown in Fig. 4 of Nagao (1992) fail to support this claim and show approximately equal modulation of firing for the example P-cells recorded in the flocculus and ventral paraflocculus. In addition, the distributions of response amplitudes for the populations of P-cells are not summarized in sufficient detail to allow any conclusions.

Anatomic evidence also provides some information about possible differences in the functions of the flocculus and ventral paraflocculus. For example, Gerrits and Voogd (1989) have shown that these two cerebellar structures receive mossy fiber inputs from different visual nuclei of the brain stem (Gerrits and Voogd 1989). The input to the flocculus arises from the nucleus reticularis tegmenti pontis, whereas that to the ventral paraflocculus arises from the dorsolateral pontine nucleus. However, other studies have demonstrated strong similarities in the other anatomic projections to and from the flocculus and ventral paraflocculus. Although most of the other studies were performed before the recent change in nomenclature, they provided enough histological information to allow reinterpretation of their data. These anatomic studies show that the flocculus and the ventral paraflocculus receive mossy fiber inputs from overlapping areas of the vestibular nuclei (Langer et al. 1985b) and the nucleus prepositus (Belknap and McCrea 1988) and that P-cells in the two structures project to the same parts of the vestibular nuclei (Langer et al. 1985a; Balaban et al. 1981). Finally, the climbing fiber projection from the inferior olive terminates in a rostral-caudal strip that appears to be continuous across all 11 folia of the flocculus and ventral paraflocculus (Gerrits and Voogd 1989). Thus the majority of the anatomic data emphasize similarities between the flocculus and the ventral paraflocculus, and only the different origin of the visual mossy fiber inputs suggests a difference. It is clearly important to determine the functional correlates of the differences in the anatomic sources of the visual inputs to the flocculus and the ventral paraflocculus. However, we do not think this single anatomic difference provides enough evidence to conclude that the two structures have completely different functions during a behavior, the VOR, that is studied in the dark.

One additional fact demonstrates that the ventral paraflocculus plays an important role in changes in the gain of the VOR. Lisberger et al. (1984) studied the effect of bilateral ablations of the flocculus and ventral paraflocculus on motor learning in the VOR in monkeys. They fitted the monkeys with spectacles that doubled the size of the visual scene or that caused the visual scene to move exactly with the monkey, and they used continuous sinusoidal oscillation as a vestibular stimulus for motor learning. This allowed them to document accurately the amount of visual-vestibular stimulation received by the monkey and to follow the time course of changes in the gain of the VOR. Again, this paper used the wrong terminology to describe the ablations, but it provided diagrams that allow reinterpretation of the data with the correct terminology. Of the two monkeys used by Lisberger et al. (1984), one had a complete bilateral ablation of the flocculus and ventral paraflocculus and showed no changes in the gain of the VOR over several days of appropriate stimulation. The other monkey had a complete bilateral ablation of the flocculus but retained the most rostral three folia of the ventral paraflocculus on both sides. He showed some residual capacity to increase and decrease the gain of the VOR, albeit with a time course that was slower than before the ablation. We conclude that the cerebellar cortex of the ventral paraflocculus may be able to mediate some motor learning in the VOR, even in the complete absence of the flocculus.

Although we do not think that available evidence provides much support for differences in the function of the flocculus and ventral paraflocculus, we recognize that there is a gap in our understanding of the function of the flocculus. The present study was designed not to reveal whether
the flocculus and ventral paraflocculus perform similar functions, but rather to provide information about the role of HGVP cells in motor learning in the VOR. We turn, therefore, to positive findings concerning the function of HGVP-cells.

**Role of HGVP-cells in motor learning**

The question of the function of HGVP cells during changes in the gain of the VOR has two separate components. One, addressed in this section, is the question of whether learning is associated with changes the simple-spike discharge of HGVP-cells that are appropriate to drive or support the changes in the eye movements evoked by head turns. We have addressed this issue by recording the firing of HGVP-cells during the VOR in the dark when the gain of the VOR was low, normal, or high. The second component, addressed later in the discussion, is whether learning is caused by cellular changes that occur in the cerebellar cortex.

Both previous models for motor learning in the VOR include two vestibular pathways to extraocular motoneurons, one through the brain stem and one through HGVP-cells. When the gain of the VOR is normal, the discharge of HGVP-cells is nearly unmodulated during the VOR (Lisberger and Fuchs 1974; Stone and Lisberger 1990a), and eye velocity is driven principally by vestibular pathways through the brain stem. Ito (1972) pointed out that the vestibular pathway through P-cells has an inhibitory effect on the VOR. Thus the gain of the horizontal component of the VOR would be reduced if the discharge of HGVP-cells became modulated during the VOR and if it were in phase with the vestibular inputs from the ipsilateral horizontal canal. This would reduce the vestibular drive to motoneurons by providing cerebellar inhibition to counteract the excitatory inputs from the ipsilateral vestibular nerve to the FTNs (Broussard and Lisberger 1992), which are targets of inhibition from the flocculus and ventral paraflocculus (Lisberger et al. 1994a). Previous studies in monkeys have demonstrated (Miles et al. 1980a; Watanabe 1984, 1985) and our data have confirmed that the output from HGVP-cells satisfies this expectation. When the gain of the VOR is low, the firing rate of HGVP-cells during the VOR in the dark is in phase with discharge of the afferent fibers from the horizontal canal in the ipsilateral vestibular nerve (V-i in Table 2). In addition, when the gain of the VOR is high, the firing of HGVP-cells is out-of-phase with the firing in afferents from the ipsilateral horizontal canal (V-c in Table 2) and so will increase the modulation of FTN firing and increase the vestibular drive to motoneurons. The latter finding disagrees slightly with Miles et al. (1980a), who did not find that increases in the gain of the VOR caused changes in the responses of HGVP-cells during the VOR. This minor difference could result either from the fact that Miles et al. (1980a) were able to study only a small fraction of their sample during the VOR in the dark, especially when the gain of the VOR was high, or from the different stimuli used in the two studies to evoke the VOR. We used a pulse of head velocity that had total duration of only 300 ms, whereas Miles et al. (1980a) used sinusoidal head rotation at 0.2 Hz. We conclude that the output of HGVP-cells provides at least some of the signals that drive the VOR after changes in the gain of the VOR.

Our recent studies have established an additional criterion for identifying signals that help drive the VOR after learning. Recordings of the eye movements evoked by transient natural vestibular stimuli have demonstrated that the earliest components of the VOR are not modified by learning, whereas later components of the VOR are modified. For rapid head turns like those used in this paper, the onset of the VOR occurs after a latency of 14 ms (Lisberger 1984). However, the first 5 ms of the evoked eye velocity follows the same trajectory when the gain of the VOR is low, normal, and high, and the traces diverge first at a latency of 19 ms after the onset of head motion. Therefore the modified VOR pathways have latencies of at least 19 ms (Lisberger 1984). We demonstrated in the preceding paper (Lisberger et al. 1994b) that FTNs in the vestibular nucleus respond during the VOR with latencies that average just under 13 ms, which is consistent with the suggestion that the output from FTNs drives the earliest modified component of the VOR. Because the latency from electrical stimulation of the flocculus to the onset of the evoked eye movement is at least 9 ms (Lisberger 1994), HGVP-cells can contribute to the earliest modified component of the VOR only if they respond within 10 ms of the onset of head motion. Fewer than 5% of the HGVP-cells in our sample had latencies that were this short (see Fig. 11).

Conclusions about the latencies at which HGVP-cells contribute to the VOR depend on the accuracy of our measurements of latency. We elected to measure latency by manual selection of the onset of the response because objective methods are biased consistently by factors such as the standard deviation of the resting firing rate and the initial rate of rise or fall in the response. The resting firing rate of HGVP-cells was quite irregular and the initial rate of rise or fall was sometimes quite slow, an objective measure of latency would have provided longer latencies than we found. Thus objective methods would have biased our results in favor of the conclusion that HGVP-cells respond to a rapid head turn too late to drive the earliest components of the modified VOR. Further, our methods would have to overestimate latency by an average of 13 ms before the actual latency of HGVP-cell responses could average 10 ms, which would be required if HGVP-cells drive the earliest modified component of the VOR. Therefore it seems unlikely that the change in the simple-spike firing of HGVP-cells is a primary cause of the changes in the gain of the VOR that can be recorded at a latency of 19 ms after the onset of the head turn. Instead, we propose that the output of HGVP-cells helps to drive changes in the VOR that are expressed only at longer latencies after the onset of head motion. For example, Snyder and King (1992) have recently provided evidence for separable components of the VOR that are expressed at latencies of ~20 and 30 ms after the onset of head motion. In addition, our recent experiments with electrical stimulation of the vestibular apparatus (Bronte-Stewart and Lisberger 1994; Broussard et al. 1992) have suggested that the VOR has multiple modified components, some of which may not affect eye velocity until 30 ms or longer after the onset of the vestibular stimulus.
Sites of learning that would cause changes in the responses of HGVP-cells during the VOR

We have measured the effect of changes in the gain of the VOR on the firing of identified neurons in the cerebellum. However, electrical recordings can establish only the consequences of learning and, used alone, cannot measure the physiological and anatomic locus of the mechanisms that are actually modified to cause learning. Instead, we must use quantitative models to assist in making the link from observations of neural firing to possible sites for learning.

Previous studies (Lisberger 1976; Miles et al. 1980a,b; Miles and Lisberger 1981) developed the model outlined in Fig. 15 A to account for the signal processing in the brain stem and cerebellar pathways for the VOR. The model also provided a conceptual starting point for interpreting the effect of changes in the gain of the VOR on the responses recorded from HGVP-cells. In Fig.15 A the circle labeled P is a summing junction that represents the HGVP-cells, and the circle labeled V is a summing junction that represents the FTNs in the brain stem. One of the main elements of Fig. 15 A is based on the previous suggestion that the firing of HGVP-cells during the VOR in the dark is composed of two different components related to head velocity and eye velocity (Lisberger and Fuchs 1978a; Miles et al. 1980b).

These studies demonstrated that the firing of HGVP-cells (P) during the VOR can be described by the equation

\[ P = a \cdot \dot{H}(t) + b \cdot \dot{E}(t) \]

where \( \dot{H}(t) \) and \( \dot{E}(t) \) are head and eye velocity at time \( t \), \( a \) is the sensitivity to head velocity, and \( b \) is the sensitivity to eye velocity. In Fig. 15 A, \( a \) and \( b \) are two of the three possible sites at which changes in the strength of transmission of neural signals could cause learning.

Miles et al. (1980a) demonstrated, and we have confirmed, that changes in the gain of the VOR are associated with changes in the strength of the vestibular signal \([a \cdot H(t)]\) recorded on HGVP-cells during cancellation of the VOR. Because the head motion \([\dot{H}(t)]\) was the same when the gain of the VOR was high or low, Miles et al. (1980a) concluded that motor learning was associated with changes in the value of \( a \). They also pointed out that the anatomic locus of \( a \) could be either in the cerebellar cortex or in the brain stem sites that project vestibular inputs to HGVP-cells. Miles et al. (1980a) then used a model like that in Fig. 15 A to interpret the changes in \( a \). First, they made arguments based on the anatomic organization of the vestibular pathways through HGVP-cells, which dictates that the sensitivity to head velocity \( a \) must increase to cause decreases in the gain of the VOR (Ito 1972). If changes in the vestibular inputs to HGVP-cells cause learning, then the strength of the vestibular input to HGVP-cells should vary inversely with the gain of the VOR. Because the strength of the vestibular inputs to HGVP-cells varied in parallel with the gain of the VOR, Miles et al. (1980a) concluded that Ito’s hypothesis is contradicted for HGVP-cells.

We agree. Second, Miles et al. (1980a) deduced that, if changes in the value of \( a \) did not cause motor learning, then changes in the gain of the VOR must be mediated by changes in the value of \( d \), which is intended to represent the strength of transmission from vestibular inputs directly to the brain stem VOR pathways.¹

One criticism of the data of Miles et al. (1980a) was that their estimates of the strength of vestibular transmission to HGVP-cells were based on recordings made during cancellation of the VOR and not during the VOR itself. The convergence of head and eye velocity inputs onto HGVP-cells makes it impossible to measure the strength of the head velocity input to HGVP-cells directly during the VOR. Instead, we have estimated the size of the head velocity input to HGVP-cells during the VOR by taking advantage of the fact that the head and eye velocity inputs to HGVP-cells add linearly (Lisberger and Fuchs 1978a; Stone 1987). We derived the head velocity component of firing rate during the VOR by computing the eye velocity component and subtracting it from the measured firing rate. Changes in the gain of the VOR altered the size of the head velocity component of firing measured during the VOR in the same direc-

¹ Miles et al. (1980a) also include a multiplication factor \( e \) in the connection from the HGVP-cells to the FTNs. Because of evidence that this variable is not modified in association with motor learning (Lisberger 1994), we have replaced it with \( a - 1 \) that represents the inhibitory action of HGVP-cells on FTNs.
tion as the head velocity component measured during cancellation of the VOR. This increases our confidence in the validity of using data obtained during cancellation of the VOR to estimate directly the strength of vestibular transmission to HGVP-cells.

The analysis done by Miles et al. (1980a,b) was correct for the model they used and was valid in ruling out Ito's (1972) hypothesis of cerebellar learning for the specific case of the vestibular inputs to HGVP-cells. However, the papers of Miles et al. (1980a,b) fail to account for complexities that arise if the model is simulated in a dynamic environment. In their model, all the internal elements were either static multiplication factors or summing junctions, and the model computed the gain of the VOR as a simple scalar value that was the same at all times. In a dynamic model, inputs and outputs can vary as a function of time, and the internal elements may perform dynamic transformations such as filtering, so that a step change in input would cause a response that varies as a function of time. To add these necessary complexities to the analysis of Miles et al. (1980a,b), we have developed the model in Fig. 15B (Lisberger and Sejnowski 1992a,b). The flow of signals in our model is the same as in the earlier model, and the primary modification was to add dynamics to a and b with the use of filters in which the response to a step increase in input is an exponential increase in output. We have assumed that the value of b is one (Lisberger et al. 1987) and is not modified in conjunction with motor learning (Lisberger and Sejnowski 1992a,b). The performance of the model in Fig. 15B is an accurate representation of the basic organization of the brain stem and cerebellar VOR pathways, we conclude that both previous proposals for the site of learning require some revision.

The APPENDIX provides the analytic solution for the model in Fig. 15B. It shows that the model is stable only if the values of a and d are equal. If this stability condition is not met, then a constant input will cause the eye velocity output from the model to increase or decrease inexorably toward positive or negative infinity. If a = d, then the steady-state gain of the model will be

$$G_{\text{VOR}} = \frac{d}{a} \frac{T_\text{b}}{T_a} \quad (1)$$

In addition, the steady-state output of node P during the VOR will be

$$P = a \cdot \dot{H} = (T_a - T_a) \frac{d}{T_\text{b}} \quad (2)$$

Comparison of the predictions made by the model in Fig. 15B with the effect of changes in the gain of the VOR on the responses of HGVP-cells suggests a number of revisions in previous thought about possible sites of learning. First, the stability conditions of the model contradict the hypothesis of Ito (1972), who proposed that learning would be mediated by changes in the value of a. In particular, the positive feedback pathway on the right side of Fig. 15B acts as a mathematical integrator that will cause the eye velocity of the VOR to be unstable if the value of a (or d) is changed in isolation. Second, comparison of the predictions of the model in Fig. 15B with the recordings from HGVP-cells shows a number of shortcomings in the proposal of Miles and Lisberger (1981), who suggested that learning was mediated by parallel changes in the values of a and d. In the model of Fig. 15B, the gain of the VOR will be equal to the value of a and d. Although we and Miles et al. (1980a) found that changes in the gain of the VOR are associated with changes in the value of a that are in the direction suggested by Miles and Lisberger (1981), the magnitude of the changes in a are smaller than the changes in the gain of the VOR (Table 1). The model in Fig. 15B also predicts that the output of HGVP-cells (node P) will always be unmodulated during the VOR if $T_a = T_\text{b}$. Even if these two time constants have different fixed values, changes in the values of a and d alone cannot cause the output of node P during the VOR to have opposite polarities when the gain of the VOR is high and low. Under the assumption that the architecture of the model in Fig. 15B is an accurate representation of the behavior of the brain stem and cerebellar VOR pathways, we conclude that both previous proposals for the site of learning require some revision.

The analytic solution of Fig. 15B shows that the steady-state gain of the model can be controlled by varying the values of $T_a$ or $T_\text{b}$ as well as by changes in a or d. Application of this property of the model to the VOR (Table 3) suggests a way to account for our data as well as those of Miles et al. (1980a) and Watanabe (1984, 1985). First, we selected values for a that were consistent with the available data. Because of the assumptions involved in calculating the strength of the head velocity input to HGVP-cells during the VOR, we place the greatest confidence in the quantitative effects of motor learning on the responses of HGVP-cells during cancellation of the VOR. To obtain the value that was assigned to a in Table 3, we expressed the sensitivity to head velocity during cancellation of the VOR when the gain of the VOR was low or high as a fraction of that when the gain of the VOR was normal. Second, we adjusted the value of d according to the stability criteria for the model. This required that the values of a and d be equal. Third, we used Eq. 1 to predict that $T_\text{a} / T_\text{b}$ will be 0.53, 1.0, and 1.63 when the gain of the VOR is 0.4, 1.0, and 1.62. Finally, we used Eq. 2 to reveal that the steady-state output of node P in the model (Table 3) will be in phase with ipsiversive or contraversive head velocity when the gain of the VOR is low or high, respectively.

The values of the parameters in Table 3 allow the model in Fig. 15B to reproduce qualitatively the results of all records of the effect of motor learning on the responses of Purkinje cells in the flocculus and ventral paraflocculus (Miles et al. 1980a; Watanabe 1984, 1985; this paper). The model reproduces the apparently contradictory effects of motor learning on the responses of HGVP-cells during the VOR and during cancellation of the VOR. Further, the model in Fig. 15B suggests that regulation of the time course of the vestibular and/or oculomotor inputs to HGVP-cells may be one mechanism by which the mossy fiber pathways through the flocculus and ventral paraflocculus could play a role in causing changes in the gain of the VOR. The model in Fig. 15B generates testable predictions.

### Table 3. Performance of the model in Fig. 15B

<table>
<thead>
<tr>
<th>Gain of the VOR</th>
<th>Low Gain</th>
<th>Normal Gain</th>
<th>High Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values of a and d</td>
<td>0.76</td>
<td>1.0</td>
<td>1.77</td>
</tr>
<tr>
<td>$T_a / T_\text{b}$</td>
<td>0.53</td>
<td>1.0</td>
<td>1.33</td>
</tr>
<tr>
<td>$P$ as a fraction of head velocity</td>
<td>0.47</td>
<td>0.0</td>
<td>-0.33</td>
</tr>
</tbody>
</table>

The table gives the gain of the VOR and the steady-state output from node P as well as the values for the parameters that allow the model to reproduce available data on the effect of changes in the gain of the VOR on the responses of HGVP-cells. For abbreviations, see Table 1.
for the effect of motor learning on the responses of HGVP-cells. Further experiments will be needed to determine whether these predictions are accurate. However, even verification of the changes we suggest in the vestibular inputs to HGVP-cells will not provide evidence that learning occurs in the cerebellar cortex. For example, available information does not exclude the possibility that these hypothetical changes in the values of \( a \) and \( T_a \) are implemented in the brain stem cells that provide the vestibular inputs to HGVP-cells (Highstein et al. 1987; Langer et al. 1985a; Wilson et al. 1976).

**APPENDIX**

Equations A1 and A2 define the firing rate of the HGVP-cells, \( P \), and the firing rate of the FTNs in the brain stem, \( V \), where \( H \) is head velocity and \( \dot{E} \) is eye velocity

\[
P = \frac{aH}{s T_a + 1} + \frac{E}{s T_b + 1} \quad (A1)
\]

\[
V = dH - P \quad (A7)
\]

The output from the model (\( \dot{E} \)) is defined as \( \dot{E} = -V \), and the gain of the VOR is defined as \( G_{\text{VOR}} = \frac{\dot{E}}{H} \). Combining these definitions with Eqs. A1 and A2 and rearranging yields

\[
G_{\text{VOR}} = \frac{(sT_a + 1)(dST_b + (a - d))}{sT_b (sT_a + 1)} \quad (A3)
\]

We consider first the case where \( a = d \). Then, the gain of the VOR is defined as

\[
G_{\text{VOR}} = \frac{T_a(d)(sT_b + 1)}{T_b (sT_a + 1)} \quad (A4)
\]

Then, the gain of the VOR is determined by the values of \( d \), \( T_a \), and \( T_b \). It is possible to reduce the gain of the VOR by decreasing the value of \( T_a \). Under this assumption, the dynamics of the VOR show lead-lag properties determined by the values of \( T_a \) and \( T_b \). If these two time constants are equal, then eye velocity follows the same trajectory as head velocity.

We consider next the case where \( a \) is not equal to \( d \). If \( T' = T_a \), then the gain of the VOR is defined as

\[
G_{\text{VOR}} = \frac{(a - d)(sT_a + 1)}{sT_b} \quad (A5)
\]

If \( T_a = T_b \), then this reduces to

\[
G_{\text{VOR}} = \frac{(a - d)(sT + 1)}{sT_b} \quad (A6)
\]

Equation A6 describes a system that will integrate steady (DC) inputs toward positive infinity if \( a > d \) and toward negative infinity if \( a < d \) at a rate defined by \( (a - d)/T_b \). The system will pass frequencies above the cutoff defined by \( T_b \). The more complicated system described by Eq. A5 will have the same properties with the added effect of the lead-lag element defined by \( T_a \) and \( T_b \).

We now begin again from Eqs. A1 and A2 but instead derive an expression for \( P \) in terms of the other variables

\[
P = \frac{aH}{s T_a + 1} - \frac{dH}{s T_b + 1} \quad (A7)
\]

If \( T_a = T_b \), then Eq. A7 reduces to

\[
P = H \frac{(a - d)}{s T_a} \quad (A8)
\]

Therefore \( P \) is always zero during the VOR if \( a = d \) and \( T_a = T_b \). Finally, if \( T_a \) is not equal to \( T_b \), but \( a = d \) to preserve stability, then Eq. A7 reduces to

\[
P = \frac{aH}{s T_a + 1} \quad (A9)
\]

Equation A9 shows that the output of \( P \) will be in phase with \( \dot{H} \) if \( T_a > T_b \), a situation that will cause the gain of the VOR to be reduced (Eq. A4). The output of \( P \) will be out of phase with \( \dot{H} \) if \( T_a < T_b \), which will cause an increase in the gain of the VOR (Eq. A4).

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