

Discussion

Comparison of the models for retinal slip and eye movement using Local and Global Fitting

Our results provide insight as to how the primate oculomotor system accomplishes the transformation of sensory information (retinal slip) to a motor command. There are clear differences between the temporal firing patterns in the VPFL and the upstream structures (MST and DLPN). The boxes in Fig. 8 summarize the results of the present study. The model for retinal slip data accurately described the temporal firing patterns of MST and DLPN neurons and of VPFL P cells under the single stimulus condition (Local Fitting, the left sides of Figs. 8A, C, and E), but not under the multiple stimulus conditions (Global Fitting, the right sides of Figs. 8B, D, and F). The differences in the distributions of C.D.s under Local and Global Fitting were significant at the $P < 0.0001$ level in all three areas (the Mann-Whitney U-Tests of non-parametric tests). The acceleration signal of retinal slip made a large positive contribution to the reconstructed firing patterns of the MST and DLPN neurons, and had a small effect on the reconstructed firing patterns of the VPFL P cells. On the other hand, the model for eye movement accurately described the temporal firing patterns of the VPFL P cells under both single and multiple stimulus conditions (Fig. 8F). However, the model for eye movement accurately described only for a portion of the temporal firing patterns of the MST and DLPN neurons

under the single stimulus condition (Local Fitting, the left sides of Figs. 8B and D) and did not describe most of them under multiple stimulus conditions (Global Fitting, the right sides of Figs. 8B and D). The differences in the distributions of C.D.s between Local and Global Fitting were significant at the $P < 0.001$ and $P < 0.004$ levels for the MST and DLPN neurons, respectively.

As shown in the left box in each of the panels in Fig. 8 (Local Fitting), under single stimulus conditions, the model for retinal slip more accurately described the temporal firing patterns of the MST and DLPN neurons better than did the model for eye movement (left boxes in A vs. B and C vs. D). The differences were significant at the $P < 0.008$ and $P < 0.005$ levels for the MST and DLPN neurons, respectively; the difference was not significant for the VPFL P cells ($P = 0.32$, left boxes in B vs. F). Furthermore, the contribution of the acceleration components of retinal slip to the firing patterns was more evident in MST and DLPN neurons than in VPFL P cells. These results indicate the following two points: (1) The MST and DLPN neuron firing represents the information of retinal slip under single stimulus conditions; (2) To get the proper temporal firing patterns of the P cells, the information of retinal slip might be integrated. On the other hand, as shown in the right box in each of the panels in Fig. 8 (Global Fitting), under multiple stimulus conditions, only the model for eye movement accurately described the temporal firing patterns of the VPFL P cells (right boxes in C vs. F); this difference was significant at $P < 0.0005$. Neither model

satisfactorily described the temporal firing patterns of the MST and DLPN neurons. The acceleration and velocity coefficients described in the present study indicate the following three points: (1) P cell firing encodes the dynamic component of the motor command for ocular following under multiple stimulus conditions; (2) The MST and DLPN neuron firing does not yet represent the dynamic component of the motor command; And (3) the information encoded in the temporal firing patterns of the MST and DLPN neurons is likely transformed into the dynamic component of the motor command prior to the VPFL P cell firing pattern.

Visual properties of the MST and DLPN neurons and VPFL P cells

The response properties of the MST and DLPN neurons and the VPFL P cells during ocular following have been studied in previous experiments (Kawano et al. 1992, 1994; Shidara et al. 1991, 1993). Most of the MST and DLPN neurons responded to movements of a large-field visual stimulus with directional selectivity. Regarding the distribution of the preferred direction of movement of the MST and DLPN neurons, no significant differences were observed between preferences for ipsiversive or contraversive (or for up vs. down) movement (Kawano et al. 1992, 1994). Further, using the best direction for each neuron, the responses to a visual scene moving at different speeds were studied (10, 20, 40, 80 and 160 deg/s). Most of the direction-selective MST and DLPN neurons showed their

strongest responses at high stimulus speeds, but the remainder showed their strongest responses at low stimulus speeds. Thus, it appears that the preferred speed for each neuron in the MST and DLPN is distributed among various stimulus speeds.

In the present study, our analysis of MST and DLPN neurons describes how the temporal firing patterns encode the retinal slip sensory information associated with ocular following. The model used to interpret retinal slip data accurately describes the firing of MST and DLPN neurons during the ocular following responses under a single stimulus condition. In particular, the strongest responses of neurons at their optimal stimulus were reconstructed very well by the model for retinal slip data (Fig. 9). Figure 9 shows the relationship between the preferred stimulus speed and the C.D. of the model for retinal slip data under single stimulus conditions. The open squares, triangles, and filled circles represent MST neurons, DLPN neurons, and VPFL P cells, respectively, and are plotted in the square of the optimal speed for the neural response (x axis) and in the square of the speed at which the neural response was fitted with the best C.D. (y axis). For the preferred speed, we averaged the firing rate of a neuron over the time interval applied by the linear regression analysis. Some neurons in the MST (4/13) and DLPN (8/25), the neural responses of which preferred 160 deg/s, showed saturation in their C.D.s at high stimulus speeds. Because these neurons that preferred 160 deg/s responses increased their discharge rate in response to the slower stimulus speed, resulting in a sufficient S:N

ratio and better fit to the model, a statistical index, their C.D.s were high. Despite this, it is clear that the two different components of the neural responses and the C.D.s have an equivalent relationship to stimulus speed in most cases. In other words, when a neuron preferred faster speeds, its C.D. tended to be higher at faster speeds, and when a neuron preferred slower speeds, its C.D. tended to be higher at slower speeds.

On the other hand, previous studies have demonstrated that the P cells which related with ocular following also responded to movements of a large-field visual stimulus with directional selectivity. The distribution of their preferred directions has clearly divided the VPFL P cells into two classes: horizontal P cells, which preferred ipsilateral movement, and vertical P cells, which preferred downward movement (Shidara and Kawano 1993). Further, by changing the stimulus speed in the preferred direction, the P cells increased their firing rate as the stimulus speed increased, reaching a peak with stimuli of 40-80 deg/s (Shidara and Kawano 1993). A similar pattern was observed in eye velocity profiles and eye acceleration profiles (Miles et al. 1986; Shidara and Kawano 1993).

In the present study, our analysis of VPFL P cell firing describes how the cerebellar ventral paraflocculus converts visual motion signals into commands for ocular following. The firing of VPFL P cells during ocular following can be described either by the model for retinal slip data under single stimulus conditions or by the model for eye movement under multiple stimulus conditions. Our success in fitting the firing rate of VPFL

P cells to both models demonstrates that the output of the VPFL of the cerebellum encodes all the visual motion in a local condition, while it encodes the appropriate dynamic drive signals to the ocular motor neurons needed for ocular following under a wide range of conditions.

Previous studies have demonstrated that MST and DLPN neurons have abrupt rising and falling phases in the initial neural responses with short-latencies (Kawano et al. 1992, 1994). The falling phase of the initial neural response was different from neuron to neuron, however; some neurons decreased their firing rate almost to the spontaneous firing level after the initial peak, while others halted their firing rate at a level far above that of spontaneous firing after the initial peak. In either case, the MST and DLPN neurons demonstrated vigorous initial responses with more abrupt rising phases than those of the initial responses of VPFL P cells. In addition, it has been reported that the visual response properties of visual mossy fibers in the VPFL are similar to those of DLPN and MST neurons (Shidara and Kawano 1993). This suggests that the visual information related with ocular following of the visual mossy fibers are already represented in the firing patterns of MST neurons. In the present study, we quantitatively evaluated the temporal firing patterns of MST and DLPN neurons and VPFL P cells using the temporal profiles of eye movement and retinal slip during ocular following. No clear differences were observed in the characteristics of the temporal firing patterns between MST and DLPN neurons. These results suggest a role for MST neurons in detecting visual

motion, a role for DLPN neurons in the mediation of the visual information, and a role for the VPFL P cells in the actual sensorimotor transformation of ocular following.

We examined the neuronal responses for the periods of 10-248 (or 10-298) ms after stimulus onset, which include two portions of the responses (open-loop and closed -loop) together. In the present study, we were unable to determine whether the brain pathways from the retina to the extraocular muscles process information differently in driving the initial (open-loop) and late (closed -loop) components of ocular following. Specifically, because our visual stimulus was a simple ramp movement in one direction, the temporal patterns of retinal slip were insufficient in the initial period. As a result, we could not estimate the details of the information processing that guides the initial components of the neuronal and ocular responses. How does the visual motion drive the initial components of the neuronal firing patterns and ocular following? And how are the visual information for ocular following and the information from eye movement processed to drive the late components of the neuronal firing patterns and ocular following? Further experiments are needed to answer these questions.

Transformation of visual input into commands for eye motion

By systematically analyzing, in the three areas studied (MST, DLPN, and VPFL), the neural activity of the main neural circuit for generating ocular following, we were able to study the transformations accomplished by

the neural substrates of ocular following. Figure 10 schematically summarizes the spatiotemporal sequence of neural activity between the three areas and shows how we believe these neural activities may shape the activity of motor neurons. Our interpretation is that the target motion in a particular direction and speed (the preferred stimulus) is encoded in the activity of the individual cells in the MST by the combination of acceleration, velocity, and position components of retinal slip, and the visual motion signals extracted by the cortex are mediated by the DLPN neurons and are sent to the VPFL via visual mossy fibers. The neuronal activities of MST and DLPN neurons, which represent the information of visual motion, with the large acceleration component of retinal slip signals converge and are summed together in the cerebellum where they are integrated into the motor command. As a result, the temporal firing patterns of the P cells represent the dynamic motor command signals independent of the stimulus speeds, and are different from the temporal firing patterns of the MST and DLPN neurons. Our results suggest that VPFL P cells are a major site of sensory-to-motor transformation for ocular following.