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Searching for an internal representation of stimulus kinematics in the response of ventral paraflocculus Purkinje cells

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Abstract

Motor control theories propose that the central nervous system builds internal representations of the motion of both our body and external objects. These representations, called *forward models*, are essential for accurate motor control. For instance, to produce a precise reaching movement to catch a flying ball, the central nervous system must build predictions of the current and future states of both the arm and the ball. Accumulating evidence suggests that the cerebellar cortex contains a forward model of an individual's body movement. However, little evidence is yet available to suggest that it also contains a forward model of the movement of external objects. We investigated whether Purkinje cell simple spike responses in a coulometer region of the cerebellar cortex called the ventral paraflocculus contained information related to the kinematics of behaviorally relevant visual stimuli. We used a visual motor task that obliges animals to track moving targets while keeping their eyes fixated on a stationary target to separate signals related to visual tracking from signals related to eye movement. We found that ventral paraflocculus Purkinje cells do not contain information related to the kinematics of behaviorally relevant visual stimuli; they only contain information related to eye movements. Our data stand in contrast with data obtained from cerebellar Crus I, wherein Purkinje cell discharge contains information related to moving visual stimuli. Together, these findings suggest specialization in the cerebellar cortex, with some areas participating in the computation of our movement kinematics and others computing the kinematics of behaviorally relevant stimuli.

Keywords

Cerebellum; forward models; Purkinje cells; motor control

Introduction

To properly interact with a changing environment, our central nervous system must build internal representations of the current and future states of our body and of the external world. In motor control theory, these internal representations are called *forward models* or

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Compliance with Ethical Standards: Conflicts of Interest

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predictive models [1, 2]. Computational work, neuronal recordings, and clinical studies have pointed to the cerebellar cortex as one possible structure in which the forward models of our body movement may be constructed [3-5]. Hewitt and colleagues [6] demonstrated that the responses of Purkinje cells in lobules IV, V, and VI of the intermediate and lateral macaque cerebellum represent the output of a forward model of arm movement during manual tracking tasks. Additional forward models of human body movements have been identified in other areas of the cerebellar cortex (e.g., the flocculus, the coulometer vermin, and the intermediate and lateral cerebellum) [7-10]. Interestingly, very little research has been dedicated to looking for the existence of a forward model of external moving objects in the cerebellar cortex.

In 2006, Miles and collaborators [11] suggested that Purkinje cells in the lateral cerebellar cortex (Crus I) carry information related to the motion of relevant objects during visual reaching tasks. In a follow-up study, the same authors suggested that the responses of these Purkinje cells correlate with a prediction of the inertial motion of these objects [12]. Remarkably, this work on Crus I represents the only single-unit recording study to suggest that the cerebellar cortex contains a forward model of the motion of external objects. It is arguable that the cerebellar cortex (e.g., Crus I) would send this object-related information via the dentate nucleus–thalamus pathway to the frontal cortical areas related to movement planning [13-15].

The goal of our study was to investigate whether the Crus I findings just described could be generalized to other areas of the cerebellar cortex. We investigated a coulometer region of the cerebellar cortex called the ventral paraflocculus (VPFL) to see if it contained information about the kinematics of moving visual stimuli. The VPFL receives efferent copy information through the prepositus hypoglossi nuclei and the nucleus of the paramedian track [16-19]. Modeling work suggests that efferent copy information is transformed by the VPFL into estimates of the kinematics of the eye movement, which are then sent to target neurons in the brainstem and used for pursuit maintenance [17, 20]. However, the VPFL also receives visual sensory information (retinal slip) via the pontine nuclei and the inferior olivary nuclei [21-24]. Thus, the VPFL may receive sufficient information to build a model of the kinematics of behaviorally relevant objects in the visual space.

We recorded VPFL Purkinje cell responses while animals tracked a small visual stimuli that moved through their visual fields using a variant of the visual reaching task described by Cermnara and colleagues [12]. In the task designed for the previous study, the animals were instructed to track a moving object and to generate reaching responses (leg movements) in response to a “Go” signal. In our task, the animals were instructed to track a moving visual stimulus while fixating their gaze on a stationary target. For the current study, the reaching response was defined as a saccade eye movement followed by a smooth pursuit eye movement. The advantages of our task are that it allows for full control of the motor system (eye movement) and that it neatly separates signals related to the visual tracking of the target, the prediction of target movement, and eye movement. Our data indicate that the VPFL contains eye movement information, but it does not contain information related to the movement kinematics of behaviorally relevant objects. Thus, the VPFL does not participate in the building of forward models of the movement of visual stimuli.

Methods

Animal Preparation and Experimental Setup

Two adult male rhesus macaques were used in this study. Animals were prepared for recording using standard procedures [25]. Briefly, animals underwent two surgical procedures to implant a scleral search coil, a titanium head post, and a recording chamber. The recording chambers were implanted stereotactically, with their centers aimed toward the left or right VPFL (13 mm lateral and 1 mm posterior). The VPFL was identified by its stereotaxic location and its characteristic neuronal discharge in response to eye movements during pursuit [25]. Moreover, our recordings were performed in the same location and with the same animals used in two previous studies [25, 26]. After a 3-week recovery period, the animals were trained in coulometer tasks with the use of a standard water restriction protocol. All procedures conformed to the National Institutes of Health Guide for the Care and Use of Laboratory Animals and were approved by the Institutional Animal Care and Use Committee.

During the experiments, the animals were comfortably seated in primate chairs that were placed on top of a rotating table (Kollmorgen Corporation, Radford, VA). The heads of the animals were fixed to the chairs by their head posts to allow for stable neuronal recordings. The visual stimuli consisted of one green laser and one red laser. These lasers were back-projected onto a translucent screen located 50 cm in front of the animals. The green laser position was fixed so that it was projected onto the center of the screen; this coincided with the straight line of sight of the animals. The red laser position could be moved horizontally and vertically by two mirror galvanometers that provided near linear displacement of the laser within the range used in this experiment. Horizontal and vertical eye positions were continuously measured with the use of a three earth-fixed field coil system (CNC Engineering, Enfield, CT) or a video eye-tracking system (ISCAN ETL-200; ISCAN Inc, Woburn, MA). Neuronal data were filtered and amplified using an 0.3 to 8 kHz band-pass filter (Model MDA-41; Bak Electronics Inc, Umatilla, FL). A Power1401 interface and Spike2 software (Cambridge Electronic Design, Milton, and Cambridge, UK) were used to record eye, laser, and rotating table position (0.5 KHz) as well as neuronal data (40 KHz).

Behavioral Protocol

All behavioral tasks were controlled with the use of custom software written in the Spike2 computer language. We employed three behavioral tasks: 1) a standard visually guided saccade task was used to calibrate the eye coil daily. This task consisted of 15 degrees of horizontal and vertical visually guided saccades starting from the center fixation. 2) A sinusoidal pursuit task that consisted of vertical and horizontal pursuit around the center fixation (0.4 Hz, ± 10 degrees of amplitude) was used to determine the preferred response orientation (i.e., vertical or horizontal) and direction (i.e., up, down, ipsilateral, or contralateral) of each Purkinje cell. 3) A specially designed tracking task called “Track-with-gap” task was used to investigate behavioral and neuronal responses related to the tracking of moving objects in the visual field while fixating. This task is described below and in Fig. 1; see also Suppl. Movies 1 and and Suppl. Fig. 1.

For the “Track-with-gap” task (see Fig. 1), animals were trained to fixate their gazes on the green laser while it was on. When the green laser was turned off, animals were trained to immediately orient their gazes toward the moving red laser. A single successful trial consisted of the following steps:

Step 1: A green laser appears at the center of the screen. Animals must maintain their eyes within 3 degrees of the green laser position for 500 msec.

Step 2: A red laser appears at an eccentric position. This laser remains fixed at the same location for 500 msec. During this time, animals must maintain fixation on the green laser.

Step 3: The red laser moves at a constant velocity (5, 7.5, 10, 12, 15, or 20 dig/sec) either horizontally or vertically for a random time. The duration of Step 3 is shorter for high-target velocities as compared with low-target velocities to ensure that the target locates within 8 degrees from the center fixation at the end of Step 3. For example, for target velocities of 7.5 degrees/sec, we selected the duration of Step 3 to take random values between 1000 and 2300 msec. During this step, animals are required to maintain fixation on the green laser. Step 3 represents the tracking phase of this task.

Step 4: The green and red lasers are turned off simultaneously. This is the “Go” signal. In response to this “Go” signal, animals are to make eye movements to catch and follow the “phantom” of the red laser; this is an imaginary red laser with the same inertial speed and trajectory that the red laser had before it was turned off. The minimum and maximum reaction times are set to 100 sec and 400 sec, respectively. Step 4 is the “post-tracking/movement preparatory” phase. A successful Step 4 indicates that the animal has been tracking the target during the tracking phase (at least during the last portion of Step 3).

Step 5: The red laser is turned on between 350 and 400 sec after the “Go” signal. Trials are invalid if the animals' eyes are not within 3 degrees of the red laser position when the red laser is turned on again. Animals must maintain their eye position near the position of the red laser as it moves across the projecting screen. The window size used in Step 5 was 4 degrees during neuronal recordings, but it was increased to up to 6.5 degrees during behavioral experiments to allow us to quantify a larger spectrum of eye position and eye velocity errors when using high-target velocities (Fig. 2).

Step 6: The red laser is turned off. Animals receive a water reward 10 sec later.

The “Track-with-gap” task was usually delivered in blocks of 20 trials with the same tracking orientation (i.e., the red laser moves either horizontally or vertically). Opposite directions of target movement were mixed pseudo randomly within each block. For instance, during the 20 trials included in each horizontal block, the target moved 10 times toward the right and 10 times toward the left. We used an initial horizontal position offset of 15 degrees opposite of the movement direction during horizontal tracking and an initial vertical position offset of 15 degrees opposite of the movement direction during vertical tracking (see Fig. 1 and Suppl. Movies 1 and 2). In addition, to ensure that the animals generated a detectable response (saccade), the red laser also had an offset position that was perpendicular to the

target movement. During horizontal tracking trials, we used vertical position offsets of 7.5 degrees; during vertical tracking trials, we used horizontal position offsets of 7.5 degrees.

After 2 weeks of training, animals reached asymptotic performance in the “Track-with-gap” task with a 90% rate of successful trials. It is important to clarify that the animals had to track the target (i.e., red laser) before the “Go” signal was given to complete the “Track-with-gap” task.

Neuronal Recordings

We recorded single units from the VPFL using epoxy-coated tungsten microelectrodes with 8 to 10 Mega ohms of impedance (FHC Inc, Bowdoin, ME). We identified the VPFL by its characteristic eye-related activity. We identified the three layers of the cerebellar cortex using a standard procedure [25, 26]. Briefly, the molecular layer was identified by the presence of complex spikes and the absence of simple spikes. The Purkinje cell layer was identified by the presence of both complex and simple spikes. The granular layer was identified by its characteristic saccade-related hashing activity and the absence of complex spikes.

When possible, Purkinje cells were identified by the presence of a pause of at least 10 sec in their simple spike discharges after a complex spike. Alternatively, Purkinje cells may have been identified by their location in the Purkinje cell layer. Fourteen Purkinje cells of the 20 included in this study were identified by the existence of a pause in simple spikes after a complex spike. Six Purkinje cells were identified by their location.

Data Analysis

All data analysis was performed offline using custom MATLAB software (Math Works, Natick, MA). Animals responded to the “Go” signal with saccade eye movements of their gaze from the center of the screen to the target position (i.e., the red laser); we called this the “intersecting saccade.” After each intersecting saccade, there was a period of about 80 to 120 sec of smooth eye movement, and this was followed by a second saccade that we called the “corrective saccade.” We used the intersecting saccade to calculate behavioral response latency with respect to the “Go” signal (velocity threshold, 40 degrees/sec). We used the eye movement data between the end of the intersecting saccade and the beginning of the corrective saccade to calculate how good the animals were at estimating target position and velocity. The time between the intersecting saccade and the corrective saccade can be considered to be the open-loop period of our tracking task [27]. During the open-loop period, eye movements were not influenced by sensory feedback signals [27]. Eye position estimation error was calculated offline for each correct trial as the difference between the eye position and the target position at the end of the intersecting saccade. Eye velocity estimation error was calculated offline as the difference between the median absolute eye velocity during the open-loop period and the absolute target velocity (see Fig. 2). Thus, regardless of the direction of the target movement, negative eye velocity errors indicated that the eye was moving more slowly than the laser.

Purkinje cells were classified as horizontal or vertical on the basis of the pursuit orientation that generated the largest amplitude of simple spike modulation during sinusoidal pursuit.

Similarly, we set the preferred direction for each Purkinje cell to correspond with the movement direction that generated the largest increases in the simple spike firing rate. In our case, it corresponded to either ipsilateral or downward movement (see Results).

After the preferred orientation of a Purkinje cell was determined online, we recorded the neuronal response to the “Track-with-gap” task along that orientation. Simple spike responses of individual Purkinje cells were obtained by averaging identical trials with the use of per stimulus time histograms, with bin sizes of 40 msec. Trials in which animals showed slow, drifting eye movements (>2 degrees/sec) along the target movement direction or had small saccades (>2 degrees) were eliminated from the per stimulus time histograms. We used two analysis methods to search for neuronal responses:

1. We compared the firing rate during each task period (see Steps 1-6 above) using Wilcoxon rank-sum testing (significance level of 0.01 with Bonferoni corrections).
2. We used a moving window of 120 sec (in 40-msec steps) over the average data to search for significant changes in neuronal responses throughout the task (Wilcoxon rank-sum test, $p < 0.01$ over four consecutive steps). The initial period of the trial (see Step 1 of Fig. 1; this is the period during which the green laser was on) was used as the control period.

These two analysis methods were applied to individual neurons and to the average population data.

Results

Behavioral Response

We investigated the effect of target velocity on eye position and eye velocity errors during the “Track-with-gap” task. Figure 2 shows data obtained from Monkey A (Fig. 2a, b) and Monkey B (Fig. 2c, d). For both animals, changes in target velocity had no effect on eye position errors, regardless of tracking direction. The maximum r^2 of the linear fit of the average eye position error versus the target velocity was 0.27, the median was 0.13, and the mean was 0.14 (see Fig. 2b, d).

By contrast, changes in target velocity did affect eye velocity error. Larger target velocities resulted in larger eye velocity errors. This was true for both animals and for all movement directions. The minimum r^2 of the linear fit of the average eye velocity error versus the target velocity was 0.51, the median was 0.93, and the mean was 0.89. The effect of target velocity on eye velocity error was most evident for upward movements. Upward target velocities of 10 degrees/sec and above significantly increased eye velocity error ($p < 0.01$ for analysis of variance using the eye velocity error data at 5 degrees/sec target velocity as the control data; see Fig. 2b, d, top right). This prominent effect on upward movements can be explained by the inherent asymmetries of the coulometer system. Thus, upward eye movements normally saturate at lower velocities [28]. In our animals, this saturation corresponded to about 7 to 10 degrees/sec during the open-loop period (i.e., the first 80-100 sec after the intersecting saccade). Notice that the black traces in the right panels of Fig. 2a,

b, barely show any change in eye velocity during the open-loop period. For downward and horizontal target velocities, increases in the absolute values of eye velocity errors became significant for target velocities of 12.5 degrees/sec and above ($p < 0.01$ for analysis of variance using the eye velocity error data at 5 degrees/sec target velocity as the control data; see Fig. 2c, d). Eye velocity errors during horizontal and downward movements cannot be attributed only to difficulties in the generation of eye velocities above 10 degrees/sec, because, as shown in the raw data (see Fig. 2a, b), animals could generate eye velocities well above 10 degrees/sec during the open-loop period. Hence, these increases in eye velocity error may be the result of increases in target velocity estimation errors. Overall, our data indicate that coulometer performance during the “Track-with-gap” task deteriorated for target velocities of more than 10 degrees/sec. We do not know whether this effect was due to failures related to tracking the target, generating the correct eye movement, or both.

As described previously, animals could correctly track targets and generate appropriate intercepting saccades and pursuit eye movements when target velocities were 10 degrees/sec or less. Thus, we used tracking velocities of 7.5 degrees/sec during neuronal recordings, as described below.

Purkinje Cell Simple Spike Responses During the Tracking Phase

We recorded simple spike responses from 11 horizontal VPFL Purkinje cells, all with ipsilateral preferred direction, and from 9 vertical VPFL Purkinje cells, all with downward preferred direction. The average Purkinje cell gain during sinusoidal pursuit was 2.11 spikes/sec per degrees/sec (standard deviation [STD], 1.11) and 1.55 spikes/sec per degrees/sec (STD, 0.67) for horizontal and vertical Purkinje cells, respectively. The response of vertical and horizontal Purkinje cells during the “Track-with-gap” task was normalized on the basis of their preferred direction. These responses are described below.

Figure 3, a and b (top), shows the response of one representative Purkinje cell while the animal was tracking a target that moved along the preferred direction of the neuron (see also Suppl. Fig. 1). The mean neuronal firing rate during the control period (Step 1: Green ON) and during the presentation of the red laser at a fixed location (Step 2: Red ON) were not significantly different (mean [STD], 81.1 [8.8] and 84.7 [8.2] spikes/sec, respectively; Wilcoxon signed-rank test, $p > 0.34$). Similarly, the mean neuronal firing rate during the early and late tracking periods (which correspond to the first and last 0.5 sec of Step 3, respectively) were not significantly different than control values (mean [STD], 85.6 [7] and 84.8 [6.1] spikes/sec during early and late tracking, respectively Wilcoxon signed-rank test, $p > 0.22$). These results suggest that the baseline discharge of VPFL Purkinje cells does not contain information related to the tracking of the red laser. Similar results were obtained for the anti-preferred direction (Wilcoxon signed-rank test, $p > 0.13$; see Fig. 3b [bottom]). We used a 120 sec moving window during Steps 2 and 3 to search for short-lasting changes in firing rate. We found no significant changes in firing rate while the animals fixated on the green laser (comparison of Step 1 to Steps 2 and 3 [early and late tracking, respectively], Wilcoxon signed-rank test, $p > 0.14$).

These results were found to be true for all 20 Purkinje cells. Figure 3c plots the mean firing rate during different tracking periods versus the mean firing rate during the control period

for each Purkinje cell. Notice that the majority of the data points are located closely to the diagonal, which indicates that there were no significant changes in the mean firing rate during the tracking period (see Steps 1, 2, and 3 of Fig. 1; *t*-test of two paired samples for means, $p>0.15$). Moreover, analysis of the population average built from the average response of each single neuron also suggests that Purkinje cell responses do not carry information related to the tracking a moving visual target (Fig. 4). We found no significant differences in the mean firing rate during Step 2 and Step 3 as compared with the control period (Wilcoxon signed-rank test, $p>0.34$). Moreover, there were no significant changes in firing rate during Steps 2 and 3 with the use of a 120 sec moving window (Wilcoxon signed-rank test, $p>0.23$).

Purkinje Cell Simple Spike Responses During the Post-tracking/Movement Preparatory Phase

We analyzed the firing rate of VPFL Purkinje cells just before the onset of the intersecting saccade to investigate whether the VPFL Purkinje cell firing rate contains anticipatory or preparatory information. Figure 5a, shows the average neuronal discharge during this period for the example Purkinje cell shown in Fig. 3b. The pre-saccadic neuronal discharge was not significantly different than the neuronal discharge found during the control period (Wilcoxon signed-rank test, $p>0.28$). In addition, the average firing rate during the pre-saccadic period was not significantly different than the average firing rate found during the control period for all 20 Purkinje cells (see Fig. 5b, left column; *t*-test of paired two sample for means, $p>0.08$). Moreover, there were no significant changes in firing rate preceding the intercepting saccade for both the preferred and anti-preferred directions in the population average (Fig. 6; Wilcoxon signed-rank test, $p>0.12$).

All Purkinje cells showed significant changes in firing rate after the onset of the intersecting saccade (Wilcoxon signed-rank test, $p\gg0.05$). This change in firing rate was evident when comparing the mean firing rate during the eye movement period (see the end of Steps 4 and 5 in Fig. 1) with the control period. Notice how most data points fell out of the diagonal in the Fig. 5c (right column). Purkinje cell responses to the “Go” signal can consist of increases or decreases in firing rate associated with the intersecting saccade eye movement, as described in other studies [26]. These responses are often lagging eye movement responses, as it has been described by others [29].

We also searched for differences between the neuronal response latency to the intersecting saccade versus the neuronal response latency to spontaneous saccades. Changes in neuronal response latency could suggest that the VPFL engages in anticipatory or preparatory processes during the “Track-with-gap” task. We found no differences between the neuronal response latency to the saccade eye movement that direct the eyes toward the predicted position of the target during the “Track-with-gap” task or the neuronal response latency to spontaneous saccades toward the same direction (mean [STD], 32 sec [51 sec] and 20 sec [35 sec], respectively; paired *t*-test, $p=0.16$, see Suppl. Fig. 2).

Discussion

In this study, we searched for forward models of the motion of behaviorally relevant visual stimuli in the response of VPFL Purkinje cells. We used a new visual tracking task, the “Track-with-gap” task, which has two important features: 1) The moving target disappeared for a short period immediately after the “Go” signal. Thus, to correctly estimate target location and velocity at the time of the intersecting saccade, animals must be tracking the target before the “Go” signal. 2) We imposed fixation during tracking to eliminate any contamination of the response of the Purkinje cells due to signals related to eye movement. These are important advantages over previous reaching tasks [11, 12]. We found that VPFL Purkinje cells do not contain a forward model of moving visual stimuli during steady fixation. Therefore, we suggest that the VPFL is mostly involved in the control of eye movements.

Our behavioral study indicates that animals can reliably predict the position, velocity, and direction of a relevant moving visual stimulus following the Go“signal”. Because our “Track-with-gap” task involves random time periods, random movement directions, and a blind time period that follows the “Go” signal, animals must track a moving target during fixation to generate correct intercepting saccades and subsequent pursuit eye velocities. We used target velocities of 7.5 degrees/sec to study Purkinje cell responses. At that speed, animals are capable of generating accurate predictions of the target position and speed, as suggested by our behavioral data (see Fig. 2). To solve the “Track-with-gap” task, animals must build an internal representation of the movement of the visual target and then use this representation to predict the position, direction, and speed of the target at the end of the intercepting saccade.

Most studies that have investigated the role of the cerebellum in the tracking of moving targets have employed visual manual tracking tasks or pursuit tasks that require continuous eye or arm movements while tracking targets. Such and collaborators [30] demonstrated that Purkinje cell simple spikes in the floccule lobe of macaque monkeys change their discharge in anticipation of predicted changes in targets trajectories (i.e., sum-of-sins tasks) [31]. However, these studies cannot disambiguate whether these changes in Purkinje cell discharge represent predicted eye movements or predicted target movements. In other words, it is unclear whether these neuronal signals represent the current or future state of the eye or the current or future state of the target. Our study was designed to disambiguate these signals by imposing fixation during the tracking phase. Our results indicate that individual VPFL Purkinje cells do not carry information related to the kinematics of relevant visual stimuli. Our population analysis, which should enhance small neuronal responses not detected at the single-cell level, also supports our results by failing to detect any significant response.

Miles and colleagues [11, 12] provided the strongest evidence we have today for the existence of a forward model of external object kinematics in the cerebellar cortex (Crus I Purkinje cell responses). We were unable to find an equivalent signal in the response of VPFL Purkinje cells. There are two possible explanations for the difference between their results and ours. First, Miles and colleagues did not monitor smooth eye movements during the tracking phase of the tasks. In fact, animals were free to move their eyes in pursuit of the

moving target. Therefore, the neuronal responses attributed to object kinematics could represent actual smooth eye movement kinematics. Note that smooth eye movement-related information is present in the pontine nuclei, which is an important input nucleus to Crus I [32, 33]. In addition, the different results can be explained by the differentiated roles of Crus I and VPFL in behavior. Within this framework, the main role of the VPFL would be the control of eye movements, although Crus I also play a role in the non-motor aspects of the tasks. We favor this second explanation due to functional magnetic resonance imaging and anatomical evidence. O'Reilly and colleagues [15], using fMRI, demonstrated the activation of human Crus I during a visual prediction task and thus suggested a role of this area of the cerebellar cortex in temporal prediction aspects of the task (e.g., object velocity). The differential roles of Crus I and VPFL in coulometer tasks may also be explained by differences in their anatomical connectivity. VPFL Purkinje cells do not have direct connections to the deep cerebellar nuclei [21]. Instead, they contact premotor neurons in the brainstem and neurons in the prepositus hypoglossi. By contrast, Purkinje cells in Crus I have direct connection to the dentate nucleus, which in turn connects to cortical areas that are known to contain stimulus kinematic information [11, 14]. Cope and collaborators [34] found that patients with damage to their frontal cortical regions have problems predicting the timing and speed of a reappeared moving target when performing target blanking tasks. Thus, Crus I—but not VPFL—could be a source of forward model information in the frontal cortical area [11, 14].

Conclusion

We propose that the VPFL does not contain a representation of the kinematics of behaviorally relevant moving visual stimuli. Thus, the primary role of the VPFL would be the control of ongoing eye movements, likely through the generation of a forward model of eye movement. Our results, together with those of Miles and colleagues [11, 12], may have important implications for the understanding of cerebellar function. Specifically, these data suggest specialization within the cerebellar cortex, with separate areas participating in the building of internal representations of our body (i.e., kinematics of our movement) and internal representations of the external world (i.e., kinematics of behaviorally relevant stimuli).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Schematic representation of the “Track-with-gap” task. The example trial shows the tracking and interception of a moving target as it moves rightward. Steps 1 through 5 are shown from bottom up. The large squares represent the projecting screen, and the “x” represents the eye position. The green and red dots represent the position of the green and red lasers, respectively. The gray and red arrows represent the movement direction of the eye and the red laser, respectively. The squared with the dashed outline represent the range of eye positions allowed in good trials.

Figure 2.

Changes in eye position and eye velocity errors with task parameters for the “Track-with-gap” task in Monkeys A and B. **a**, Average eye velocity traces obtained using 5, 12, and 20 degrees/sec target velocities for Monkey A (data is overlapped). The black traces indicate trials with rightward and upward tracking directions. The gray traces indicate trials with leftward and downward tracking directions. The shaded areas indicate the open-loop period. **b**, Same as in **a** but for Monkey B. **c**, The four panels represent the eye position and eye velocity errors (average and standard deviation) versus target velocity for rightward (upper left), leftward (bottom left), upward (top right), and downward (bottom right) target movements. The asterisks indicate significant differences (analysis of variance, $p < .01$) between data obtained at a particular target velocity versus data obtained at 5 degrees/sec target velocity. **d**, Same as **c** for Monkey B.

Figure 3.

Purkinje cell response during the “Track-with-gap” task. **a**, Timeline for the different task events. The green and red horizontal bars represent periods when the green and red lasers, respectively, are ON. The dashed vertical lines separate different task steps: green laser ON, red laser ON, red laser moving, and red and green laser OFF (this is the “Go” signal). **b**, Response of a Purkinje cell recorded in Monkey B while the animal tracked a target moving along the preferred (ipsilateral, top) and anti-preferred (contralateral, bottom) directions of the neuron. The black and gray traces represent horizontal and vertical eye velocity, respectively. Data are aligned with the beginning of the tasks and the “Go” signal (left and right, respectively). **c**, Data from individual Purkinje cells showing the average firing rate during Step 2 (Red ON), during the early tracking period, and during the late tracking period of

Step 3 (see Fig. 3a) versus the average firing rate during the control period (Green ON). The top and bottom rows show the data collected during tracking along the preferred and anti-preferred directions, respectively.

Figure 4.

Population average of the simple spike response of all 20 Purkinje cells normalized with respect to each Purkinje cell's preferred direction and baseline firing rate. **a**, Timeline for the different task events. The green and red horizontal bars represent periods when the green and red lasers, respectively, are ON. The dashed vertical lines separate different task steps: green laser ON, red laser ON, red laser moving, and red and green laser OFF (this is the "Go" signal). **b**, The average population response is shown by the thick black lines, and the standard errors are shown by the shaded areas.

Figure 5.

Response of the example Purkinje cell shown in Fig. 3b during the "Track-with-gap" task aligned with the response onset (i.e., the saccade onset). **a**, The average response during tracking along the preferred and anti-preferred directions (left and right panel, respectively). The black and gray traces at the top represent horizontal and vertical eye velocity, respectively. The bottom shows the average neuronal responses. **b**, Data from individual Purkinje cells comparing the pre-saccadic and post-saccadic periods to the control period (green ON). The top and bottom rows show the data collected during tracking along the preferred and anti-preferred directions, respectively.

Figure 6.

Average response of the population of Purkinje cells during the “Track-with-gap” task aligned with the response onset (i.e., the saccade onset). **a** and **b**, The average population responses during tracking along the preferred and anti-preferred directions, respectively, are shown. The black and gray traces at the top represent horizontal and vertical eye velocity, respectively. The black traces at the bottom show the average population responses, and the gray areas represent the standard errors.