Relationship of Cerebellar Purkinje Cell Simple Spike Discharge to Movement Kinematics in the Monkey

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Fu, Q.-G., D. Flament, J. D. Coltz, and T. J. Ebner. Relationship of cerebellar Purkinje cell simple spike discharge to movement kinematics in the monkey. J. Neurophysiol. 78: 478–491, 1997. The simple spike discharge of 231 cerebellar Purkinje cells in ipsilateral lobules V and VI was recorded in three monkeys trained to perform a visually guided reaching task requiring movements of different directions and distances. The discharge of 179 cells was significantly modulated during movement to one or more targets. Mean simple spike rate was fitted to a cosine function for direction tuning, a simple linear function for distance modulation, and a multiple linear regression model that included terms for direction, distance, and target position. On the basis of the fit to the direction and distance models, there were more distance-related than direction-related Purkinje cells. The simple spike discharge of most direction-related cells modulated at only one target distance. The preferred directions for the simple spike tuning were not uniformly distributed across the workspace. The discharge of most distance-related cells modulated along only one movement direction. On the basis of the multiple linear regression model, simple spike discharge was also correlated with target position, in addition to direction and distance. Approximately half of the Purkinje cells had simple spike activity associated with only a single parameter, and only a small fraction of the cells with all three. The multiple regression model was extended to evaluate the correlations as a function of time. Considerable overlap occurred in the timing of the simple spike correlations with the parameters. The latency for correlation with movement direction occurred mainly in a 500-msec interval centered on movement onset. The correlations with target position also occurred around movement onset, in the range of 200–500 ms. Distance correlations were more variable, with onset latencies from 500 to 1,000 ms. These results demonstrate that the simple spike discharge of cerebellar Purkinje cells is correlated with movement direction, distance, and target position. Comparing these results to motor cortical discharge shows that the correlations with these parameters were weaker in Purkinje cell simple spike discharge, and that, for the majority of Purkinje cells, the simple spike discharge was significantly related to only a single movement parameter. Other differences between simple spike responses and those of motor cortical cells include the nonuniform distribution of preferred directions and the extensive overlap in the timing of the correlations. These differences suggest that Purkinje cells process, encode, and use kinematic information differently than motor cortical neurons.

INTRODUCTION

One step in understanding how a neural structure contributes to movement control is to define the relationship between the neuronal discharge and the relevant movement parameters (Georgopoulos 1986; Kalaska 1991). This approach has been successful in relating the firing of primary, premotor, and parietal cortical neurons to the kinematics of reaching movements (Caminiti et al. 1991; Fu et al. 1993, 1995; Georgopoulos et al. 1982, 1988; Kalaska et al. 1983; Lacquaniti et al. 1995; Schwartz et al. 1988). Unfortunately, the motor parameters encoded or controlled by the cerebellum during voluntary limb movements remain only partially defined. Movement direction may be the parameter most commonly studied in relation to the firing of cerebellar neurons. Purkinje cell simple spike discharge as well as dentate and interposed neuronal discharge display directionally sensitive discharge in single-joint movements (Frysinger et al. 1984; Thach 1970a, 1978; Wetts et al. 1985) and multijoint movements (Foreman et al. 1989, 1993). However, some investigators observed only minimal (Chapman et al. 1986; MacKay 1988) or no directional coding in the discharge of dentate neurons (Robertson and Grimm 1975), whereas others reported a large population of bidirectional cerebellar neurons during single-joint movements (Schieber and Thach 1985). Two recent studies of multijoint movements showed that the modulation with direction is not necessarily reciprocal, but instead graded, and can be modeled by a cosine tuning function (Foreman et al. 1989, 1993). This illustrates the need to evaluate systematically the discharge properties of cerebellar neurons over not only a large range of values for the parameter of interest, but also over the physical workspace.

In addition to direction, movement velocity may play a significant role in modulating cerebellar neuronal discharge. The phasic character of simple spike discharge during movements (Harvey et al. 1977; Mano and Yamamoto 1980; Marple-Horvat and Stein 1987) suggests that the time derivatives of movements are encoded. The discharge of cerebellar interposed neurons is correlated significantly with elbow angular velocity during forearm movements in the primate (Robertson and Grimm 1975) and during limb movements in the cat (Soechting et al. 1978). In the primate, Purkinje cell simple spike discharge varies with wrist velocity during manual tracking (Mano and Yamamoto 1980) and with hand velocity during the operation of a joystick (Marple-Horvat and Stein 1987). In the latter report, simple spike correlations with velocity were stronger than the correlations with acceleration. Some mossy fiber afferents, in addition to interpositus neurons, discharge in relation to movement velocity in the primate (van Kan et al. 1993a, b).

There has been no systematic study of Purkinje cell discharge modulation in relation to movement amplitude or position for either single- or multijoint limb movements. Position-related activity may be limited in the discharge of
cerebellar nuclear cells (Chapman et al. 1986; Harvey et al. 1977; Thach 1978) and in the simple spike firing of Purkinje cells (Bauswein et al. 1983; Mano and Yamamoto 1980). However, some position-related simple spike discharge occurs in Purkinje cells (Marple-Horvat and Stein 1987). Simple spike firing is also related to the maintenance of a fixed wrist position against a torque load (Gilbert and Thach 1977; Thach 1970b).

In the present study, we examine the relationship between the simple spike discharge of Purkinje cells and target direction, distance, and location. We used a whole arm, two-dimensional reaching task in which direction and distance were systematically varied, a task effective in revealing correlations between unit discharge in the motor cortical areas and movement parameters (Fu et al. 1993, 1995). We used the same simple and multiple linear regression analyses to identify statistically the prevalence and strength of the simple spike correlation with the parameters. Therefore, in addition to defining characteristics of Purkinje cell simple spike discharge during reaching movements throughout a two-dimensional workspace, the task design and analysis permitted a detailed comparison with previous premotor and primary motor cortical findings. A preliminary account of these results has been presented in abstract form (Fu et al. 1994).

**METHODS**

**Behavioral paradigm**

The behavioral paradigm is similar to that used previously (Fu et al. 1993, 1995). Three female rhesus monkeys (Macaca mulatta) weighing 5.0, 5.2, and 5.3 kg performed visually guided, multijoint arm movements in the horizontal plane with the use of a two-joint manipulandum. The animals sat in a primate chair and faced a vertically positioned color monitor (23.5 x 32 cm) placed ~45 cm from the animal’s chest. Using the manipulandum, the animals superimposed a cross-hair cursor (0.75 cm) onto brightly colored squares (1 cm²) displayed on the screen. In each trial, the animals first superimposed the cursor onto a centrally positioned start box for a randomized period of time ranging from 0.5 to 1.5 s. The start box was then extinguished and 1 of 48 targets appeared. The targets were arranged circumferentially around the start box at 45º intervals (8 directions) and at six distances ranging from 1.0 to 6.0 cm, in 1.0-cm increments. To complete the trial successfully, the animals were required to move the cursor to the target within 2 s of its appearance and to maintain the cursor in the target for an additional 1.5 s. The successful completion of a trial was rewarded with the delivery of fruit juice.

**Chamber implantation and electrophysiological recording**

On demonstrating proficiency at the behavioral task, the animals were anesthetized with xylazine (1.0 mg·kg⁻¹·h⁻¹) and ketamine (20 mg·kg⁻¹·h⁻¹) and implanted with stainless steel chronic recording chambers. The chambers were positioned stereotaxically on the animal’s right side (monkey MA: posterior 6 mm, lateral 10 mm; monkey LI: posterior 6 mm, lateral 10 mm; monkey BE: posterior 6 mm, lateral 13 mm) and attached to the skull with screws and acrylic cement. In the immediate postoperative period the animals received an analgesic (Nubain, 0.05 mg/kg), and for several days they received prophylactic doses of antibiotics (Amoxicillin, 250 mg·kg⁻¹·day⁻¹). After recovery, extracellular single-unit recordings were made with the use of paralyne-coated tungsten microelectrodes (3–10 MΩ). Purkinje cells were identified by the presence of spontaneous simple and complex spikes, which were discriminated with the use of time and amplitude techniques (Ojakangas and Ebner 1992). A description of the complex spike activity during this task will be included in a future report. Discriminator signals were converted to transistor-transistor logic pulses before being digitized and stored to computer at 1 kHz. Signals from potentiometers located at the manipulandum’s joints were sampled and stored at 1 kHz for calculation of hand position and tangential velocity. Palpation and passive limb manipulation were used to determine whether a cell had a somatosensory receptive field of the hand, wrist, elbow, or shoulder girdle. Cells were also examined for modulation during active, spontaneous reaching movements with the manipulandum. Cells that did not respond to either active movements or passive manipulation were not studied further.

**Data and statistical analyses**

Neuronal discharge and kinematic data were aligned on movement onset, defined as the time at which tangential velocity exceeded 1.0 cm/s; correspondingly, we defined movement end as the time at which tangential velocity fell below this threshold. Averages of simple spike activity and kinematics were constructed from 5–10 movements for each of the 48 targets. We analyzed three time periods for each cell: (1) premovement time (PT), defined as the 200-ms interval before movement onset; (2) movement time (MT), defined as the period from movement onset to movement end; and (3) total time (TT), defined as the sum of PT and MT. To determine the presence of significant simple spike modulation, we used a one-way analysis of variance (ANOVA) for movements to all 48 targets, comparing firing rate with background activity (measured as the average simple spike discharge in the interval 1,200–500 ms before movement onset) for each time period. Cells whose modulation was not statistically significant for all three time periods were not included in the subsequent regression analyses.

To quantify the relationship between simple spike discharge and the kinematic parameters, we used the same linear regression analyses as described previously (Fu et al. 1993, 1995) to fit the simple spike firing to movement direction, distance, and target position. We used both simple and multiple linear regression analyses to identify correlations between simple spike discharge and movement parameters for two reasons. First, the multiple regression analysis requires that either direction or distance modulation in the discharge occur over a range of the workspace. This model could potentially fail to detect correlations that occur over a limited range of directions or distances. Use of the simple linear models was necessary to examine specifically for directional tuning along a single distance and distance modulation along a single direction. Second, use of both simple and multiple regression analysis permitted a full comparison with previously published motor cortical discharge studied with the use of the same paradigm (Fu et al. 1993, 1995).

For direction, the average simple spike discharge above baseline firing was fitted (in PT, MT, and TT) to a cosine function as described by Georgopoulos et al. (1982) as follows

\[ f = b_0 + b_1 \sin (\theta) + b_2 \cos (\theta) \]  

(1)

where \( b_0 \) represents the intercept of the regression equation, \( b_1 \) and \( b_2 \) the regression coefficients, \( c_1 \) the change in firing rate of the cell as a function of direction (\( \theta \)), and \( \theta_p \) the preferred direction. On the basis of the model, \( F \) ratio (\( P < 0.05 \)) an \( R^2 \) greater than ~0.7 was required for a significant fit of the model to the data. An index of the depth of directional modulation (\( L_m = c_1/b_0 \)) was used to assess the proportional increase or decrease over the mean.
level of activity (Georgopoulos et al. 1982). To test the hypothesis of uniformity of the cells’ preferred directions, we used Watson’s $T^2$ method (Mardia 1972).

To determine the relationship between simple spike firing rate above background and the six movement distances for each Purkinje cell, we used a simple linear regression model of firing as a function of distance. A cell’s firing rate was significantly correlated with distance if $R^2 > 0.66$ ($P < 0.05$). It should be pointed out that the $R^2$ for significant distance modulation was lower than that for directional tuning because the model for direction (Eq. 1) has two predictors. For each of the three time periods (PT, MT, and TT), firing ($f$) was fitted to movement distance ($d$) as

$$f = a_0 + a_1 d$$

(2)

where $a_0$ is the intercept and $a_1$ is the slope.

To account for direction and distance together with possible interactions between these two parameters, we fitted firing rate to the following multiple linear regression model

$$f = k_0 + k_1 \sin(\theta) + k_2 \cos(\theta) + k_3 d + k_4 d^2$$

$$+ k_5 \sin(\theta) \cdot d + k_6 \cos(\theta) \cdot d$$

(3)

Here, the interaction terms, $\sin(\theta) \cdot d$ and $\cos(\theta) \cdot d$, are the $X$ and $Y$ coordinates, respectively, of target position. The regression model used is the same as that described in Fu et al. (1993, 1995). Briefly, the development of this final model consisted of testing three preliminary models of increasing complexity. The first was the direction model described above (Eq. 1). The second model combined direction and distance terms as follows

$$f = b_0 + b_1 \sin(\theta) + b_2 \cos(\theta) + b_3 d + b_4 d^2$$

(4)

The third model tested was given in Eq. 3 above, which included terms for direction, distance, and their interaction, target position. A proportional reduction in error (PRE) approach was used to compare the extent to which each of the three models accounted for the variability in firing rate (Judd and McClelland 1989).

An additional analysis was used to determine the relationship between simple spike discharge and each of the movement parameters in time. Cell firing rate, $f(t)$, at time $t$ was fitted to a linear quadratic polynomial function, as follows

$$f(t) = k_0(t) + k_1(t) \sin(\theta) + k_2(t) \cos(\theta) + k_3(t) d$$

$$+ k_4(t) d^2 + k_5(t) \sin(\theta) \cdot d + k_6(t) \cos(\theta) \cdot d$$

(5)

where $d$ is movement distance, $k_n$ are the least-squares estimates, and $\theta$ represents movement direction. The time increments were 20-ms bins. Before fitting the time regression model, the data were smoothed with the use of a three-point moving average.

Model fitting yielded three partial $R^2$ values, each representing the degree to which a given parameter accounted for the variability in cell discharge: one for direction ($\sin$ and $\cos$ terms), a second for distance ($d$ and $d^2$ terms), and a third for position ($\sin \cdot d$ and $\cos \cdot d$ terms). The total $R^2$ gives the proportion of overall discharge variability accounted for by all three parameters. Statistical significance of the total and partial $R^2$s was determined by the F ratio ($P < 0.05$). The significance of the partial $R^2$ value takes into account the sample size ($n$) and the number of predictors, as well as the partitioning of the sums of squares into model, error, and total components. It should be stressed that in similar previous studies (Fortier et al. 1989; Georgopoulos et al. 1982; Schwartz et al. 1988), usually eight directions of movement were used ($n = 8$), whereas in our task eight directions and six distances were used ($n = 48$), increasing the likelihood of finding significant relationships with a smaller partial $R^2$. For the temporal regression (Eq. 5), the criterion for the existence of a correlation was arbitrarily set to three consecutive time bins with a significant partial $R^2$ to reduce the number of spurious correlations. Onset latency of a given parameter correlation was defined as the time at which the first of three consecutive bins had a significant partial $R^2$ value.

**RESULTS**

**Data base and location of Purkinje cells**

We recorded the simple spike activity of 231 movement-related cerebellar Purkinje cells in three monkeys (27 cells in *monkey LI*, 31 in *monkey BE*, and 173 in *monkey MA*). Of the 192 Purkinje cells with receptive fields as tested during reaching movements, 179 (77.5%) had significant increases or decreases in firing rate relative to background discharge for one or more targets (ANOVA, $P < 0.05$) during one or more of the three time periods (125 in PT, 153 in MT, and 151 in TT). The remainder of the analysis was performed on the simple spike data obtained from this group of 179 cells.

The recording areas based on a dorsal surface view of the cerebellar cortex are shown in Fig. 1A. For each animal the center of the recording area was located near the primary fissure, 8–10 mm from the midline. In all three animals most recordings were either anterior to the primary fissure in lobule V or posterior in lobule VI, extending mediolaterally from the intermediate region well into the hemisphere (HV and HVI). Some of the recordings were more lateral and posterior into the crus region, particularly in *animal BE*, in which the chamber was placed more laterally. Some cells were located in lobule IV. Also shown are examples of several recording/lesion tracts recovered in *animal MA* (Fig. 1B) and *animal BE* (Fig. 1C). In *animal MA* (Fig. 1B) recording tracts from the center of the chamber were located in lobule V. In *animal BE* (Fig. 1C), a lesion tract made at the time of sacrifice shows the center of the chamber to be in lobule VI, just posterior to the primary fissure. The high degree of overlap suggests that we sampled relatively similar groups of cells from all three animals.

**Directional tuning of simple spike activity**

For about half of the Purkinje cells, the simple spike activity significantly fitted a cosine function [69 cells (45.7%) in TT; 52 cells (41.6%) in PT; 75 cells (49.0%) in MT; see Table 1, ‘Direction’ plus ‘Both’]. Figure 2 shows discharge histograms for a Purkinje cell whose simple spike activity in TT was strongly modulated with movement direction at distances of 3–6 cm. This cell’s preferred directions...
I differ greatly among the four individual distances (aftermentioned distances. The degree of modulation did not the peak velocity. For a given distance, peak velocity did yield a significant partial
cement distance (Fig. 3 A kinje cells was significantly cosine tuned at only one move-
Distance-related simple spike activity (Fig. 3 B) and of
dir among the three analysis
Fig. 4 A. A The distribution of the cells' preferred directions expressed as vectors of length $l_{uw}$ with origin at the start position is shown in Fig. 4 A. The distribution was not uniform across the two-dimensional workspace (Fig. 4 A. Watson's test, $V^2 = 50.8, P < 0.01, n = 116$). To visualize better the clustering of the preferred directions, the workspace was divided into 16 segments of 22.5° each and the number of cells with a preferred direction in each segment was determined. As shown in Fig. 4 B, the majority of cells had preferred directions in the segments spanning 45–135° and 225–315°. These segments were diametrically opposed, one pointing away from the body with a large number of preferred directions directed across the midline, the other toward the body with a large number of preferred directions directed ipsilaterally (cf. Fortier et al. 1989).

Purkinje cell discharge has been shown to be correlated with movement velocity (Mano and Yamamoto 1980; Marple-Horvat and Stein 1987). In this reaching task peak velocity is tightly correlated with movement amplitude (Fu et al. 1993); this speed-distance relationship has been extensively documented (Fitts 1954; see Georgopoulos 1986). Therefore one possibility is that the nonuniform directional tuning was related to variation in movement velocity as a function of direction. We evaluated this possibility on the basis of the peak velocity. For a given distance, peak velocity did not vary with direction (ANOVA, $P > 0.05$). Furthermore, the depth of modulation with direction, $l_{uw}$, was not correlated with the peak velocity ($r = 0.04, P > 0.05$). Therefore the simple spike directional tuning was independent of the peak velocity.

**Distance-related simple spike activity**

The relationship of simple spike activity to movement distance was evaluated with the use of a simple linear regression model (Eq. 2). Of 151 Purkinje cells studied during TT, 55% (45 “Distance” plus 38 “Both”) had simple spike activity that significantly correlated ($R^2 > 0.67$) with movement distance (Table 1). During PT, 45% of the cells had simple spike activity that significantly correlated with dis-

![FIG. 1. A: regions where majority of recordings was obtained for each animal. ---, monkey BE; --, monkey MA; · · ·, monkey LI. B and C: examples of recovered recording tracts in monkey MA (B) and a lesion tract in monkey BE (C). Pt, primary fissure. Anterior is to the right in the parasagittal sections in B and C. Calibration bar: 1.3 mm.](image)

**TABLE 1. Parameter Coding**

<table>
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<th>Analysis Period</th>
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<th>Total Significant</th>
<th>Grand Total</th>
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<tr>
<td></td>
<td>n</td>
<td>%</td>
<td>n</td>
<td>%</td>
<td>n</td>
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<tr>
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<td>21.6</td>
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<tr>
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<td>45</td>
<td>29.8</td>
<td>38</td>
<td>25.2</td>
</tr>
</tbody>
</table>

Distribution of Purkinje cells coding for direction, distance, or both parameters, on the basis of the cosine tuning and simple linear regression models (Eq. 1 and 2). No Response: cells that were found to be modulated with the task on the basis of the initial analysis of variance (ANOVA), but that failed to yield a significant partial $R^2$ when the single parameter models were fitted to the simple spike discharge. Total Significant: sum of the cells with a significant fit for direction, distance, or both parameters. Grand Total: sum of all cells analyzed in each time period. PT, premovement time period; MT, movement time period; TT, total time period; n, number of cells.
FIG. 2. Example of Purkinje cell showing modulation of simple spike activity with movement direction. All data aligned on movement onset, marked by vertical dotted line. Histograms of average firing at 8 directions and 6 distances; each histogram was generated from 10 trials and plotted with 20-ms binwidths. Superimposed curve is velocity profile. Plot at bottom of each histogram set is average activity during total time (TT) vs. movement direction with superimposed cosine tuning curve. Significant directional tuning ($F$ test, $P < 0.05$) was seen along 4 distances (3.0, 4.0, 5.0, and 6.0 cm). Average index of depth of directional modulation ($I_{dir}$) = 0.87 ± 0.18 (SD) and average mean slope ($c_i$) = 13.7 ± 2.8 for the 4 distances.
distance, and during MT, 56% had such activity. Figure 5 shows the discharge of a Purkinje cell whose simple spike activity was correlated significantly with distance at one direction (0°). The receptive field for this cell was localized to the shoulder. The slope with distance for this direction was 2.91 spikes s⁻¹ cm⁻¹. Although there was a trend toward increasing simple spike discharge with increasing distance, the simple spike-distance relationships along the other seven directions were not significant (F test, P > 0.05).

If a cell’s simple spike discharge was significantly correlated with distance, the correlation was likely to have occurred along only one direction (Fig. 6A). This finding was consistent across analysis periods. The mean slope (\(a_i\)) for distance was 3.25 ± 1.85 (SD) spikes s⁻¹ cm⁻¹ (\(n = 83\)) in TT. There were no significant differences in the mean slope (\(a_i\)) with distance in any of the eight movement directions for any of the three time epochs (ANOVA, \(P > 0.05\), Fig. 6B). The distribution of cells modulated with distance and direction only and with both parameters during the different time periods is summarized in Table 1. Direction modulation was equally likely to occur in any of the three analysis periods (\(\chi^2\) test, \(P > 0.05\)), as was distance modulation. Interestingly, distance modulation had a slightly higher overall incidence than direction modulation. As reviewed in the DISCUSSION, when considering distance modulation, the covariation of movement amplitude and velocity must be taken into consideration.

Correlations with multiple movement parameters

Use of the simple distance and direction regression models revealed that the discharge of some cells correlated significantly with more than one parameter (Table 1). Therefore we extended the analysis by fitting the data to the multiple linear model (Eq. 3). Figure 7A shows the mean PRE for pairs of model comparisons. The PRE is an index that indicates which of several models best fits the data; a higher PRE indicates that more of the variability in simple spike discharge is accounted for by a particular model. Solid bars represent statistically significant improvements in mean PRE and unshaded bars represent nonsignificant improvements. Sequentially, the graphs illustrate that models 3 (Eq. 3) and 2 (Eq. 4) better predict the simple spike firing rate than model 1 (Eq. 1), and that model 3 better predicts the firing than model 2. For those cells in which the fit improved with the additional parameters, the mean PRE is quite large (i.e., ~30% in the comparison of models 1 and 3). Therefore distance and target position are important parameters that need to be included in the model. A determination of the optimal number of predictors also justifies the use of the larger model with six predictors. Figure 7B shows the relationship between the mean Mallows' C_p statistic and the number of predictors included in different models. The C_p statistic gives the standardized total mean squared error of estimation for the data. For the optimal number of predictors (p), a criterion of C_p 64 p is used. Using six predictors we obtained a C_p of 5.4, which justifies the use of a model with six predictors (Eq. 3). On the basis of this model, we calculated partial \(R^2\) values for direction, distance, and target position (\(R^2_{\text{dir}}, R^2_{\text{dis}}, \text{and } R^2_{\text{tar}}\), respectively), and a total \(R^2\)
FIG. 5. Movement distance-related simple spike activity of a Purkinje cell. Conventions as in Fig. 2, except each histogram set represents the activity for 6 distances at movement direction indicated. Below or next to each histogram, simple spike activity during TT is plotted as a function of movement distance. A least-squares regression line is drawn through points and coefficient of determination is given by $R^2$. Significant distance-related modulation occurs only at a direction of $0^\circ$. 
![Table 2. Discharge-parameter relationships](Image)

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<th>Parameter</th>
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<th>%</th>
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</table>

Distribution of Purkinje cells coding for direction, distance, or target position, on the basis of the multivariate regression model (Eq. 3). Responses are subdivided into whether the discharge was significantly related to 1, 2, or 3 parameters. The “significant” subtotal is the sum of these three categories. Nonsignificant: cells that were found to be modulated with the task, on the basis of the initial ANOVA, but that failed to yield a significant partial $R^2$ when the multivariate model was fitted to the simple spike discharge.

For the majority of cells the simple spike discharge correlated significantly with only a single parameter (Table 2). In contrast to the results based on the direction and distance models (Table 1), the multiple linear regression analysis revealed that direction coding occurred for a greater number of cells than either distance or target position coding. This finding reflects the fact that distance correlations must occur in several directions to reach statistical significance in the multiple linear model; the simple linear regression analysis showed that distance coding mostly occurred at only one direction. The occurrence of significant correlation with two or more parameters for the simple spike discharge in a single cell was found in all three time periods, in the combinations of direction and distance (dir×dis), direction and target position (dir×tar), distance and target position (dis×tar), or all three (dir×dis×tar, Table 2). The prevalence of correlations with two parameters ranged from 20 to 29% for the different analysis periods. The simple spike discharge of only a few cells was correlated significantly with all three parameters (Table 2).

In Fig. 8 the actual and predicted simple spike activity for three Purkinje cells’ discharge during TT is illustrated in polar plots from both the actual response and the predicted response. The simple spike discharge for the cell in Fig. 8A was correlated only with direction. The predicted simple
spike discharge was based on the results of the multiple regression model (Eq. 3). Approximately 22% of the Purkinje cells had significant simple spike modulation limited to direction in MT or TT (Table 2). The pseudocoloring depicts the cell’s modulation relative to background firing. The plots of predicted activity were generated from the model as follows: on the basis of the firing rate at each position in the workspace, the coefficients in the model were calculated, and with the use of these coefficients the predicted firing rate for the workspace was computed. In idealized contour plots, direction-related intensity gradients appear wedge-shaped, distance-related gradients appear in the form of concentric circles, and target position-related gradients are represented by parallel bands (see Fu et al. 1995). The cell shown in Fig. 8A had particularly strong direction-related discharge during each of the three analysis periods, with a preferred direction of 234° for TT. Note that the direction-related discharge was reciprocal, with increases in firing rate above baseline for movements in the left hemifield of the workspace and decreases below baseline in the right hemifield. There were no significant relationships with distance or target position for any of the three time epochs. Although the general features of the simple spike responses were captured by the model, it is clear from the predicted polar contour plots that some properties of the spatial response profile were not. This discrepancy is consistent with the total $R^2$ of $\sim$0.6 obtained for this Purkinje cell; that is, 40% of the variability in the firing was not accounted for by the model.

Eight to 14% of cells were modulated by distance alone depending on the time period (Table 2). Contour plots for a cell whose simple spike activity had significant partial $R^2$s for distance are shown in Fig. 8B. In this cell, simple spike activity was significantly modulated by distance in all three periods ($R^2_{\text{dis}} = 0.31$ in PT, 0.48 in MT, and 0.40 in TT). These correlations with distance are reflected in the circular
pattern. There were also significant, but weaker correlations with direction in PT ($R_{\text{dir}}^2 = 0.13$) and in TT ($R_{\text{dir}}^2 = 0.12$). This directional component can be appreciated in the polar contour plots. There was no significant fit to target position in any of the three periods tested.

Simple spike activity significantly correlated with target position information alone in 22 cells during TT, 19 cells during MT, and 21 cells during PT (Table 2). This type of target-position-related firing is shown in Fig. 8C, in which the pattern is represented by parallel bands. For the unit shown, target-position-related activity was not only significant for TT, but also PT and MT. The preferred direction for this cell’s simple spike discharge was $32^\circ$ during PT, the only epoch in which the partial $R_{\text{dir}}^2$ was statistically significant (data not shown). This cell’s discharge was not significantly correlated with distance for any period.

**Relations of parameter correlations to receptive fields**

The majority of Purkinje cells analyzed in this study was found to have receptive fields involving the wrist/hand, elbow, and shoulder; a smaller number of cells were audibly modulated during movement, but with an indeterminate receptive field. Therefore we analyzed whether the correlations were defined by the different parameters in either the simple models (direction and distance) or the multiple models were related to the receptive field location with the use of one-way ANOVAs. There were 69 Purkinje cells with direction tuning based on the cosine tuning model, and of these, 30 had receptive fields involving the shoulder, 8 had elbow receptive fields, 18 had hand receptive fields, and 13 had no clear receptive fields. Neither the presence of significant directional tuning ($P > 0.05$, $F$-test) nor the depth of modulation, $I_{\text{dir}} (P > 0.05$, $F$-test), differed on the basis of the receptive field type. There were 83 cells with distance modulation based on the simple linear model, and of these, 30 had shoulder receptive fields, 17 had elbow receptive fields, 24 had hand receptive fields, and 12 cells had no clear receptive fields. Neither the frequency of significant distance modulation ($P > 0.05$, $F$-test) nor the slope ($P > 0.05$, $F$-test) was dependent on the receptive field type.

Lastly, from the results of the multiple linear regression neither the average total $R^2 (P > 0.05$, $F$-test) nor the partial $R^2$'s ($P > 0.05$, $F$-test) for the three parameters differed among the receptive field locations. These analyses were based on 99 Purkinje cells, and of these, 42 had shoulder receptive fields, 17 had elbow receptive fields, 27 had hand receptive fields, and 13 cells had no clear receptive fields. These results suggest that the simple spike discharge of Purkinje cells is not strongly coupled to any single joint and is not related to the site of peripheral input. Instead, these findings suggest that the simple spike discharge is modulated by processes and/or information that involve coordination across multiple joints (see Thach et al. 1992).

**Temporal encoding of movement parameters**

We evaluated whether the simple spike correlation with the different parameters exhibited any temporal parcellation (see Fu et al. 1993, 1995). For units whose discharge was related to only one parameter based on the multiple regression model, we counted the number of cells with a significant partial $R^2$ during each analysis period (Fig. 9A). The number of cells with a significant partial $R^2$ for direction, distance, and target position tended to occur with near-equal frequency during each period. For the population of cells related to two or more parameters, the $R_{\text{dir}}^2$ was greatest during MT and distance correlations were slightly more prevalent during PT (Fig. 9B). These observations differ from the findings in the motor cortices in which direction correlations dominated PT and distance correlations were most prevalent in MT (Fu et al. 1993).

The extended multiple regression analysis (Eq. 5) was used to determine more precisely the timing of each significant partial $R^2$ for each parameter. Figure 10, A and B, illustrates, for two individual Purkinje cells, the partial and total $R^2$ values as a function of time over a 2,000-ms interval. The pattern is represented by parallel bands. For the unit shown, target-position-related activity was not only significant for TT, but also PT and MT. The preferred direction for this cell’s simple spike discharge was $32^\circ$ during PT, the only epoch in which the partial $R_{\text{dir}}^2$ was statistically significant (data not shown). This cell’s discharge was not significantly correlated with distance for any period.
FIG. 10. Partial $R^2$'s for direction, distance, and target position and total $R^2$ over the 2,000-ms analysis period for 2 individual cells. A: example of cell modulated with direction and target position. B: example of cell modulated with direction, distance, and target position. Movement onset at time 0 (vertical dotted lines).

FIG. 11. Population analysis of partial $R^2$ s and latency for each parameter. A: averaged (mean ± SD) temporal profiles of partial $R^2$ values for all units that showed significant modulation of discharge related to given parameter. Movement onset at time 0 (vertical dotted lines). B: frequency distribution of partial $R^2$ onset latencies for all units with discharge significantly correlated to given parameter.

The onset latencies of partial $R^2$ values also demonstrate the extensive overlap in the timing of significant correlations with the given parameters. The distributions of the latencies for the population are shown in Fig. 11B. For direction, the majority of the cells' latencies were between -200 and 300 ms. The latency for target position occurred primarily between 200 and 400 ms, whereas the latency distribution for distance was extremely wide, with most cells falling in the range of -100-500 ms. The mean onset latencies were as follows: 190.6 ± 337 ms (direction); 147.7 ± 272 ms (target position), and 323.3 ± 421 ms (distance). There were no significant differences in the three distribution functions (Kruskal-Wallis test, $P > 0.05$). Therefore the overlap in the onset of simple spike correlations with the three parameters was pronounced. It should be pointed out that the wide variability in latency and timing of the correlations with the individual parameters can have the effect of reducing the amplitude of the mean partial $R^2$ temporal profiles. This probably contributed to the low mean partial $R^2$'s shown in Fig. 11A.
**DISCUSSION**

**Direction-related modulation in Purkinje cell simple spike discharge**

For approximately half of the Purkinje cells studied, the simple spike discharge significantly fitted a cosine tuning function to movement direction. This same relationship has been used to describe the directional dependency of premotor, primary motor, and parietal cortical neurons (Caminiti et al. 1991; Fu et al. 1993; Georgopoulos et al. 1982, 1984, 1988; Kalaska et al. 1983; Schwartz et al. 1988), as well as cerebellar neurons (Fortier et al. 1989, 1993). Earlier cerebellar studies that found limited or no directional coding emphasized primarily reciprocal changes in modulation and concentrated on single-joint movements (Chapman et al. 1986; Harvey et al. 1979; Schieber and Thach 1985). As discussed by Fortier et al. (1989), the directional tuning of cerebellar neurons is not limited to reciprocal changes in the simple spike discharge, but has more graded changes in the degree of modulation. The present study confirms earlier observations on the discharge of cerebellar cortical neurons, establishing that the simple spike discharge of a large population of Purkinje cells exhibits significant directional tuning. It should be noted that the present study differs from previous work (Fortier et al. 1989) in that only identified Purkinje cells were recorded and movements were performed at six distances in addition to the eight directions.

Comparing the present results with those of previous studies of the discharge of motor cortical neurons in which an identical paradigm and analyses were used (Fu et al. 1993, 1995), there were several differences in the directional tuning. First, the fit of the simple spike discharge to the cosine tuning function was not maintained over several distances. Typically, this type of directional modulation was limited to only one distance. This result differed conspicuously from that in the primary motor and premotor cortices, in which the directional tuning and preferred directions were relatively constant over a range of distances (Fu et al. 1993).

A second major difference in the directional tuning involves the distribution of preferred directions. For Purkinje cells with direction-related discharge, the preferred directions covered all orientations within the 360° workspace, as also reported by Fortier et al. (1989) for cerebellar units. However, in both the present and previous cerebellar studies the distribution of preferred directions was not uniform. Both studies had a predominance of preferred orientations for movements of the arm crossing the midline and away from the animal’s body to the left (≈135°). Additionally, in this study there were a large number of Purkinje cells with preferred orientations in the opposite direction, ipsilaterally and toward the animal’s right side (≈315°). This nonuniformity is in distinct contrast to the motor (Georgopoulos et al. 1982, 1984, 1988) and premotor cortices (Caminiti et al. 1991; Fu et al. 1993, 1995), in which the preferred directions are uniformly distributed in two- and three-dimensional space. The modulation of the simple spike discharge of Purkinje cells with direction is markedly different from that in the motor cortical areas.

There are several factors that could give rise to a nonuniform distribution of preferred directions. One possibility is that one of the movement variables is not uniformly distributed across the workspace. However, this nonuniform directional tuning was not due to differences in the peak velocities, which were found not to vary with direction. However, the joint torques and endpoint forces would not be expected to be uniform for these reaching movements. For example, stiffness would be largest at 135° and 315° (Gordon et al. 1994). The second possibility is that the preferred directions represent a type of coordinate axes for Purkinje cell simple spike discharge. Nonuniform preferred directions have been described for Purkinje cell simple spike discharge in the flocculus (Graf et al. 1988). A third possibility is that other, unsampled populations of Purkinje cells would have a different set of preferred directions. However, this also could be consistent with a coordinate axes representation in which preferred directional tuning is parcelled into anatomically distinct groups of Purkinje cells.

**Distance and target position modulation in Purkinje cell simple spike discharge**

The encoding of movement distance in the simple spike discharge of Purkinje cells has been largely ignored in previous cerebellar single-unit studies (Fortier et al. 1989, 1993; Marple-Horvat and Stein 1987). In the present study, ~70% of the Purkinje cells had a significant partial R² for distance based on the univariate regression analyses (Table 1). This percentage was actually slightly higher than the percentage of Purkinje cells (~60%) correlated with distance based on the cosine tuning regression model. The multiple regression model also yielded significant fits with distance, including a large number of Purkinje cells related to distance only as well as cells related to multiple parameters (Table 2). The model comparison results show that distance explains a significant amount of the variability in the simple spike firing for a fraction of the Purkinje cells. Furthermore, both the single and multiple linear regression models revealed considerable distance-related simple spike firing during PT and MT.

Several studies have documented the encoding of movement distance in the motor and premotor cortices (Fu et al. 1993, 1995; Kurata 1993; Riehle and Requin 1989). The present study demonstrates that the simple spike discharge of Purkinje cells is correlated with movement distance. Although the slope of the regression (a1) was similar to that found in our previous study (Fu et al. 1993), there is an important difference. The simple spike discharge of many more Purkinje cells was significantly related only to distance. A similar difference was seen for target position, with 17% of cells having simple spike discharge correlated with this parameter only.

Any interpretation and discussion of the relationship between cell firing and distance must acknowledge the proportional relation between velocity and distance in reaching movements (Fitts 1954); therefore the correlations with distance could reflect velocity sensitivity (see Fu et al. 1993). This is of particular importance in the cerebellar cortex, where several studies have documented that the discharge of cerebellar neurons, including Purkinje cell simple spike firing, has velocity sensitivity during limb movements (Mano and Yamamoto 1980; Marple-Horvat and Stein 1987;
and premotor cortices (van Kan et al. 1993b). Therefore, when referring to distance, this important caveat must be considered.

The finding that for most Purkinje cells direction-related modulation occurred along one or two distances (Fig. 3) or that distance modulation occurred at only one direction demonstrates that the simple spike firing is tuned spatially. This spatial tuning is evident from the polar plots (Fig. 8), which demonstrate that the tuning could occur with direction, target position, or amplitude. This spatial tuning of simple spike discharge was primarily in relation to a single parameter (Table 2), with only a minority of the Purkinje cells having multiple parameters as significant predictors.

Temporal characteristics of multiple parameter correlations

In our previous studies of the primary and premotor cortices, there was a temporal parcellation of the cell discharge correlations with direction, distance, and target position (Fu et al. 1993, 1995). Specifically, significant correlations with direction occurred first and preceded movement onset. These were followed closely by encoding of target position, with distance coding beginning sometime after movement initiation. For the Purkinje cell simple spike discharge, no temporal order was found. As shown in Fig. 9A, for cells related to a single parameter, only slight differences were found in the number of cells correlating significantly with direction, distance, or target position in PT and MT. For cells encoding multiple parameters, no clear order of the encoding emerged (Fig. 9B), although correlations with distance and target position occurred commonly in the premovement period. This question of temporal encoding was refined with the use of the temporal regression analysis applied previously to the motor cortices (Fu et al. 1995). Across the population of Purkinje cells recorded, the distributions of onset latencies for the three parameters overlapped extensively and no significant difference was obtained among the three distributions (Fig. 11). It would appear from the present results that in contrast with the serial elaboration of kinematic information found for the motor cortices (Fu et al. 1995), the simple spike discharge of Purkinje cells processes the same information in parallel. This tendency for parallel processing of the kinematic variables suggests that the cerebellar cortex is concerned with the entire spectrum of movement information at all times (i.e., premovement and postmovement).

Kinematic coding differences between simple spike discharge and motor cortical discharge

Previous studies comparing cerebellar and motor cortical neuronal activity during these types of reaching movements emphasized some of the similarities (Fortier et al. 1993). In this discussion we have concentrated on some of the differences in the correlations of movement kinematics between the discharge of cerebellar Purkinje cells and that of cells in the motor cortices. Two additional differences should be stressed. First, the degree to which the variability in simple spike firing is explained by movement direction, distance, and target position is ~57% of that observed in the primary and premotor cortices (mean total $R^2 = 0.35$ in cerebellum vs. 0.61 in motor cortices). This is one of the more striking differences among the two populations of cells. Because a large component of the variability in simple spike discharge is unexplained, other parameters of movement may account for some of this variability. As described above, movement velocity is a likely candidate (Mano and Yamamoto 1980; Marple-Horvat and Stein 1987). Another possibility is that Purkinje cell simple spike discharge is modulated by the kinematics as it evolves in time, as opposed to simply the movement endpoints of direction, target position, and distance. We are presently evaluating this possibility.

Second, the simple spike firing of the majority of Purkinje cells was significantly related to a single parameter, with only 30% significantly related to multiple parameters. In contrast, >90% of cells in the motor and premotor cortices (Fu et al. 1993, 1995) were significantly correlated with more than one parameter. Instead of representing multiple parameters within the discharge of a single cell, the parameters are represented in different Purkinje cells. Considering the lack of any definite temporal ordering in the correlations, these differences suggest that the cerebellum parcels kinematic information among different cells as opposed to temporally within a single cell.

In summary, these differences suggest that the encoding of kinematic information in the simple spike discharge of Purkinje cells is fundamentally different from that in the primary and premotor cortices. These differences undoubtedly reflect the unique role played by the cerebellum in motor control.

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