

# Cerebellar Neuronal Activity Related to Whole-Arm Reaching Movements in the Monkey

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## SUMMARY AND CONCLUSIONS

1. Three monkeys were trained to make whole-arm reaching movements from a common central starting position toward eight radially arranged targets disposed at 45° intervals. A sample of 312 cerebellar neurons with proximal-arm receptive fields or discharge related to shoulder or elbow movements was studied in the task. The sample included 69 Purkinje cells, 115 unidentified cortical cells, 65 interpositus neurons, and 63 dentate units.

2. The reaching task was divided into three movement-related epochs: a reaction time, a movement time, and holding over the target. All neurons demonstrated significant changes in discharge during one or more of these three epochs. Almost all of the cells (95%) showed a significant change in activity during the movement, whereas 68–69% of the cells showed significant changes from premovement activity during the reaction time and holding periods.

3. During the combined reaction time–movement period, 231/312 cells were strongly active in the task. Of these, 151 cells (65.4%) demonstrated unimodal directional responses. Sixty-three had a reciprocal relation to movement direction, whereas 88 showed only graded increases or decreases in activity. A further 37 cells (16.0%) were nondirectional, with statistically uniform changes in discharge in all eight directions. The remaining 43 cells (18.6%) showed significant differences in activity for different directions of movement, but their response patterns were not readily classifiable.

4. The proportion of directional versus nondirectional cells was consistent across the four cell populations. However, graded response patterns were more common and reciprocal responses less common among Purkinje and dentate neurons than among unidentified cortical cells and interpositus neurons.

5. The distribution of preferred directions of the population of cerebellar neurons covered all possible movement directions away from the common central starting position in the horizontal plane. When the preferred direction of each cell in the sample population was aligned, the mean direction-related activity of the cerebellar population formed a bell-shaped tuning curve for the activity recorded during both the reaction time and the movement, as well as during the time the arm maintained a fixed posture over the targets. A vector representation also showed that the overall activity of the cerebellar population during normal reaching arm movements generated a signal that varied with movement direction.

6. These results demonstrate that the cerebellum generates a signal that varies with the direction of movement of the proximal arm during normal aimed reaching movements and is consistent with a role in the control of the activity of muscles or muscle groups generating these movements.

## INTRODUCTION

The ability to make smooth, coordinated movements is lost following cerebellar damage (Babinski 1909; Dichgans 1984; Dow and Moruzzi 1958; Holmes 1939). This would be expected to result from a disruption of the normal pattern of cerebellar neuron discharge observed during coordinated limb movements. During wrist flexion and extension movements, the discharge pattern of some Purkinje, interpositus, and dentate cells was shown to vary with different movements and also, to a lesser extent, with the posture of the wrist at the end of the movements (Thach 1970a,b, 1978). Harvey and co-workers (1977, 1979) have also observed Purkinje cell and cerebellar nuclear activity related to movement direction during self-paced arm movements. Other studies have demonstrated that the activity of cerebellar cortical and nuclear cells is correlated with the patterns of muscle activity generated during prehension and during wrist flexion and extension movements (Frysinger et al. 1984; Wetts et al. 1985). Furthermore, the activity of Purkinje, interpositus, and dentate cells has been shown to be correlated with the speed of movement (Frysinger et al. 1984; Mano and Yamamoto 1980; Stein 1978; Wetts et al. 1985), which suggests that the discharge of cerebellar cortical and nuclear cells is related not only to movement direction but even more directly to EMG activity producing movement.

In contrast, other authors have reported that the activity of cerebellar dentate cells did not vary with the direction of movement (Grimm and Rushmer 1974; Robertson and Grimm 1975). More recently, cerebellar nuclear cell activity recorded during slow wrist-tracking movements was found to be similar during movements in both flexion and extension directions (Schieber and Thach 1985a,b). This pattern of activity was called bidirectional to indicate that it was similar for movements in opposite directions. Single-unit recordings of partially identified muscle spindle afferents in the dorsal root ganglion also demonstrated a bidirectional discharge pattern, even though the EMG activity during these slow wrist-tracking movements was reciprocal. It was therefore proposed that the bidirectional cerebellar activity could adjust the muscle spindle sensitivity during both muscle lengthening and shortening during slow movements, which were presumed to be under continuous proprioceptive feedback control. In contrast, many of these same cells behaved in a reciprocal fashion during

rapid self-paced alternating movements (Schieber and Thach 1985b). Mano and Yamamoto (1980) found bidirectional Purkinje cell responses during both slow and fast wrist-tracking movements in the monkey and suggested that this might reflect the control of groups of muscles by single Purkinje cells. Bidirectional activity has also been observed in stimulus-related dentate cells during fast elbow movements triggered by visual and auditory stimuli that provided no signal as to the direction of movement (Chapman et al. 1986). The authors suggest that these nondirectional dentate units participate in the triggering of movement irrespective of direction. However, the nondirectional units were observed less frequently when the triggering stimulus carried information about the direction of movement (Chapman and Lamarre 1987). Moreover, in spite of the fact that these stimulus-related dentate cells were nondirectional before the movement onset, their activity during the movement was related to the movement direction (Chapman et al. 1986, 1987).

Because previous studies using simple flexion-extension

movements have provided a variety of different results, the present study was designed to investigate whether a relation between cerebellar activity and movement direction could be established by examining a wider range of movements. We used the task developed by Georgopoulos and co-workers (1982), which required the execution of guided whole-arm reaching in eight different directions away from a common central starting position toward visual targets in different spatial locations. This task makes possible the quantitative evaluation of the relationship between neuronal activity and movement direction in the horizontal plane.

## MATERIALS AND METHODS

### Animals

Recordings of cerebellar neuronal discharge were obtained from one *Macaca mulatta* monkey and two *Macaca fascicularis* monkeys that were trained to make whole-arm reaching movements in eight directions. The monkeys were handled according to the principles of the Canadian Council on Animal Care.

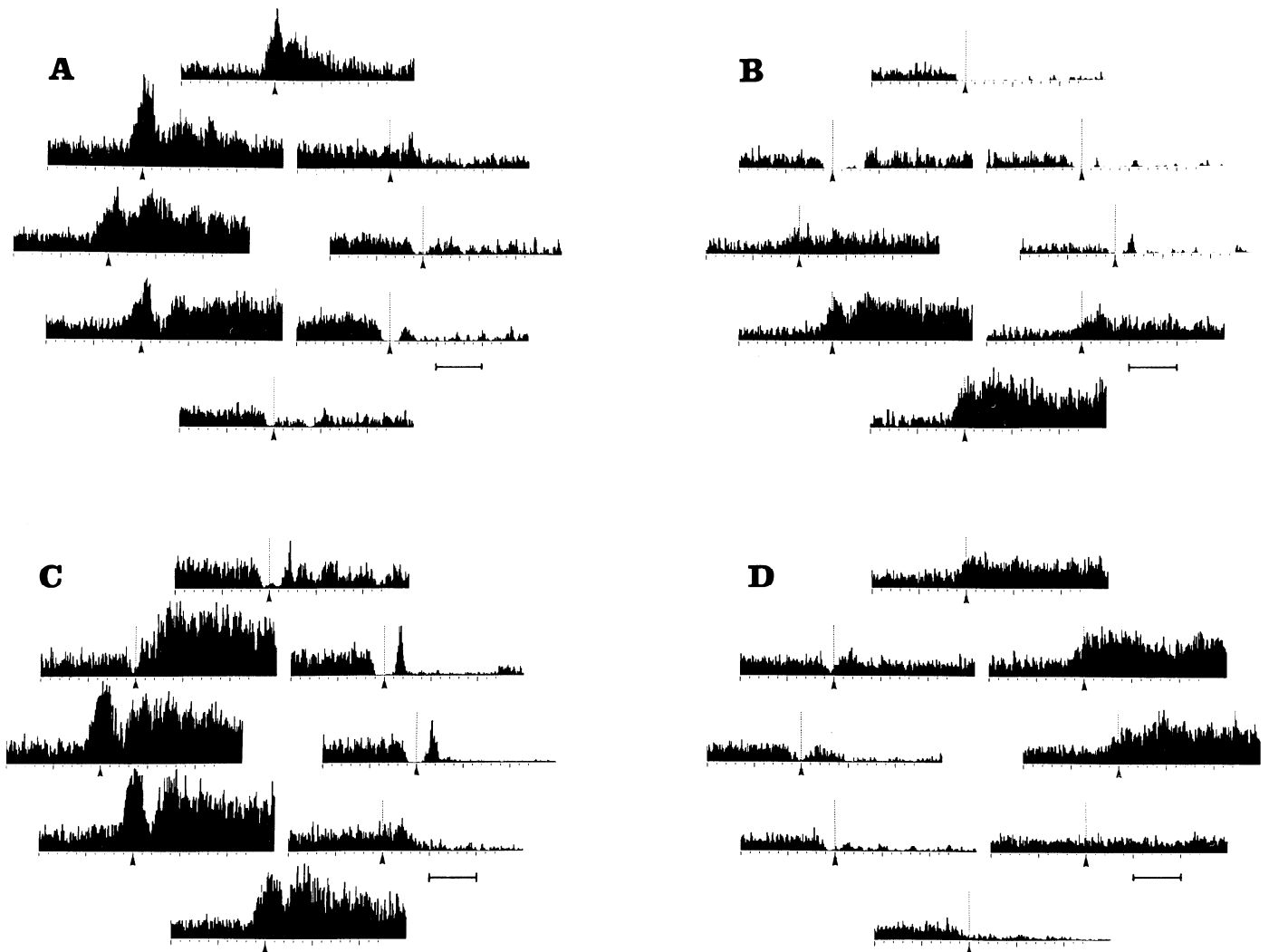


FIG. 1. Examples of the EMG activity of 4 shoulder muscles of the left arm recorded with chronically implanted electrodes. Each histogram is the summed average of the rectified and integrated EMG activity recorded during 5 movements to the target. The position of each histogram corresponds to the direction of movement away from the central starting position. *A*: infraspinatus. *B*: latissimus dorsi. *C*: posterior deltoid. *D*: pectoralis major. Arrowheads indicate the onset of movement, and the horizontal calibration = 500 ms.

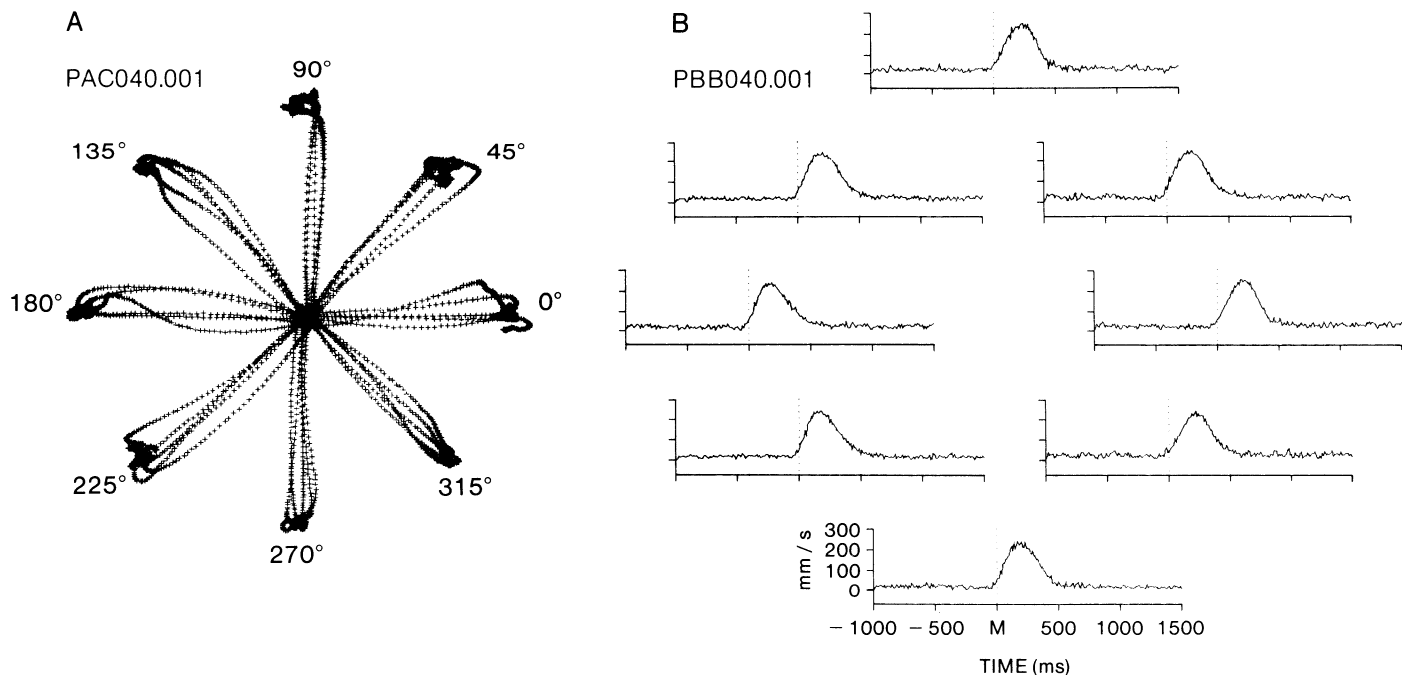


FIG. 2. Kinematics of whole-arm reaching. *A*: path of the pointer during 5 replications of the 8 movement directions. *B*: velocity profiles, aligned on the onset of movement, for all 8 movement directions. Each velocity profile represents the average of 5 trials. M, onset of movement.

### Behavioral task

The experimental apparatus has been described elsewhere (Georgopoulos et al. 1982; Kalaska et al. 1983). The monkey was seated in a chair and was required to displace a handle fixed to the distal end of a 1-m-long pendulum suspended by a universal joint over a target panel. The pendulum was free to move in any direction in the horizontal plane. Attached to the lower end of the handle was a pointer. The position of the pointer over the display panel was sampled every 10 ms by the use of an ultrasonic digitizer (Sciences Accessories; GP-3) with a resolution of 0.1 mm. Through successive shaping of arm movements, the monkeys were trained to align the pointer over the lights on the target panel positioned in front of the monkey. The target panel contained a central light-emitting diode (LED) surrounded by eight target lights arrayed at 45° intervals around a circle with a radius of 8 cm (Georgopoulos et al. 1982; Kalaska et al. 1983). The target to the right of the start position is defined as the 0° direction and targets at successive counter-clockwise positions are given in 45° increments.

### Control of movement direction

Data were collected in blocks of 40 trials comprised of five repetitions of movements to each target light. The eight target lights were presented in a pseudorandom sequence, using a randomized-block design (Snedecor and Cochran 1980). In a typical successful trial, the central light was illuminated, and the monkey initiated the trial by positioning the pointer over the central light. After a random period between 1.2 and 2.8 s, the central light was extinguished, and one of the eight target lights was illuminated. The monkey was then required to initiate movement of the pointer with a reaction time no shorter than 150 ms and no longer than 750 ms and to reach the target light within a movement time of 750 ms. The monkey was then required to hold the pointer over the target light for 2 s to obtain a liquid reward. The window radius of the central light was 10 mm, and each target light had a window radius of 15 mm.

### Task-related muscles

This task was performed by many muscles producing relatively complex movements at several joints. Georgopoulos et al. (1984) have recorded the EMGs of shoulder and elbow muscles during performance of a similar task. All of the shoulder and some of the elbow muscles demonstrated broadly tuned activity over a range of arm directions. Preferred directions that were reliable from trial to trial and from animal to animal could be established for these muscles. The EMG studies conducted in the present experiment essentially confirmed these observations. Figure 1 illustrates the mean activity of four shoulder muscles for movements in each of the eight directions.

In this task, the primary function of the hand was to maintain a grasp on the handle, and the posture of the hand varied from monkey to monkey. The more distal muscles of the wrist and fingers also showed some directional preference, but the variability over consecutive trials and between animals was greater than for the more proximal muscles. For this reason, an attempt was made to restrict the recorded neuron population to cells related to the shoulder and elbow joints.

### Surgical preparation

Once the monkeys were fully trained, standard surgical procedures were used to place a recording chamber with an internal diameter of 18 mm over the stereotaxic coordinates posterior 5 mm and lateral 5 mm. The chamber and a fixation bar used to stabilize the head of the animal were imbedded in dental acrylic and anchored to the skull with vitalium orthopaedic screws.

**SINGLE-UNIT RECORDINGS.** The activity of cerebellar neurons was recorded using glass-coated tungsten microelectrodes with an impedance between 1 and 2 M $\Omega$  at 1 kHz. The microelectrodes were advanced by a Trent Wells manipulator fitted with a micro-positioner, which permitted adjustable coordinates in the *x*- and *y*-plane. To reduce movements of the brain tissue, the recording chamber was filled with low-melting-point paraffin.

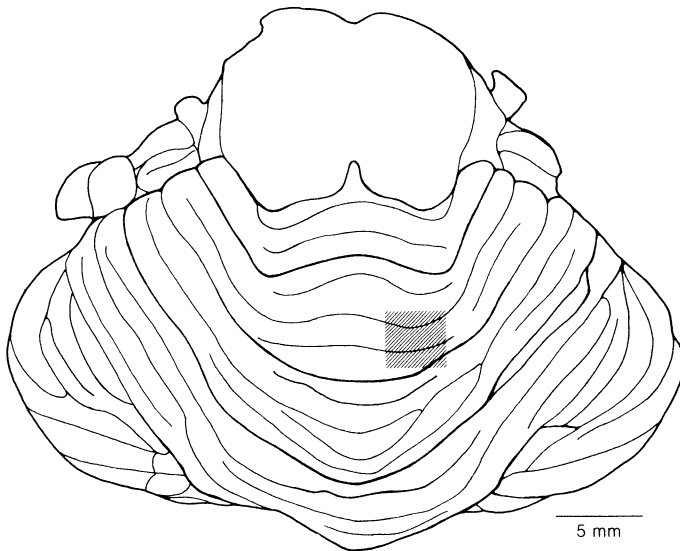


FIG. 3. Approximate location of the shoulder representation area explored in the cerebellar anterior lobe of 1 monkey.

Single units were recorded ipsilateral to the working arm in the intermediate zone of the cerebellar cortex  $\sim 2$ – $5$  mm lateral to the midline (in the 4th, 5th, and 6th lobules), as well as in the interpositus and dentate nuclei. The cerebellar units were recorded during rewarded whole-arm reaching movements over the display panel. The coordinates of each cell were noted, and, in some cases, a small lesion was produced by passing a  $50\text{-}\mu\text{A}$  current for 10 s through the recording electrode to permit identification of the recording site in serial brain sections.

**SENSORIMOTOR RESPONSES.** The discharge properties of every cell were examined to determine its sensorimotor responses. The monkey's arm was generally palpated to check for responses to hair displacement, light touch, deep pressure, tapping of muscles, and imposed movements of the arm and shoulder. Finally, the single-unit discharge was monitored as the monkey reached in various directions for raisins held at different distances from the body. Only cells that appeared to be related to movements of the proximal arm on the basis of these criteria, and that were active in the task, were selected for further quantitative study. Cells that were related primarily to movements of more axial structures or the distal arm were not studied further, even if they were active in the task. These steps were taken because of the previously demonstrated importance of shoulder muscles in controlling the spatial path of the movements and to facilitate a comparison of cerebellar and motor cortex cell properties in the task (Fortier et al. unpublished observations).

### Data analysis

**TIME PERIODS OF A TRIAL.** Each trial was divided into four epochs based on the appearance of the target lights and on the pendulum velocity obtained by differentiating the position record. The first epoch was the center-hold period (CHT), defined as the time during which the monkey held the pointer over the central light before the illumination of the target light. Second was a reaction-time period (RT), calculated as the interval from the appearance of the target light to the onset of movement as shown by the inflection in the movement velocity record. Third was a movement-time period (MT), from the time when the velocity rose significantly above zero (determined by an automatic detection algorithm) to the instant that velocity first returned to zero. Fourth, a target-hold time (HT) was defined as the period during

which the monkey held the pointer over the outer target light. The basic unit for analysis was the mean cell discharge during each epoch. Because cell discharge frequently began late in the RT period and continued during the MT period, the combined activity during RT+MT was also examined.

**QUANTITATIVE ANALYSES.** To be included in the final data set, cells had to show a statistically significant movement-related change in activity during at least one of the epochs RT, MT, or HT, compared with the premovement tonic discharge rate during CHT (multiple comparisons *t* test,  $P < 0.05$ ).

Cells with significant task-related activity were then tested for movement direction-related variation in activity. This analysis has been described in detail elsewhere (Georgopoulos et al. 1982; Kalaska et al. 1983). Briefly, a two-way analysis of variance (Snedecor and Cochran 1980) was used to test for differences in activity among the eight movement directions. The Rayleigh test (Mardia 1972) identified cells that showed a significant unimodal variation of activity with movement direction. A first-order sinusoidal regression (see Georgopoulos et al. 1982) of the activity was then calculated to determine if the changes in neural discharge with movement direction were sufficiently continuous, symmetric, and broad as to show a good fit to a sinusoidal curve (coefficient of determination,  $R^2 > 0.7$ ).

**PREFERRED DIRECTION.** The preferred direction represents the weighted center of the activity recorded for the circular distribution of movement directions and is analogous to the mean of linearly arrayed scalar data (see Georgopoulos et al. 1982; Kalaska et al. 1983). Because the preferred direction is the weighted center of the distribution of spike activity of the cell, it does not necessarily correspond to any of the eight movement directions actually tested in the task.

**VECTORIAL REPRESENTATION.** Eight vectors were drawn to represent the activity of a cell during the eight directions of whole-arm reaching (see Georgopoulos et al. 1982). The vector lengths were proportional to the change in the mean neuronal activity during reaching in the corresponding direction, compared with the mean center-hold activity. This calculation is slightly different from that in Georgopoulos et al. (1982), in which vector length was scaled according to the difference in activity for each direction of movement from the grand mean of discharge for all directions of movement. The orientation of the vectors was always along the preferred axis of the cell: for excitatory changes they were in the preferred direction, and for decreases in activity they were opposite to the preferred direction. The vectorial representations of all cells for each direction of movement were summed to estimate the mean activity of the cerebellar population during whole-arm reaching in each direction.

### Histological data analysis

At the conclusion of the recordings, the monkeys were anesthetized and perfused with saline and then Formalin solution. The cerebellum was fixed with Bouin's solution, frozen, cut into  $20\text{-}\mu\text{m}$  frontal sections, and stained with cresyl violet. The histological sections were viewed on a projection screen at a magnification  $\times 17.5$ . The sites of the neurons recorded were determined by reconstruction of the electrode penetrations, by the use of the stereotaxic coordinates of the lesion sites as reference points.

## RESULTS

### Kinematics of movement

Figure 2A shows an example of the movement paths during five replications of the eight movement directions. The movement paths were generated by plotting the *x*- and *y*-coordinates of the pendulum pointer at 10-ms intervals.

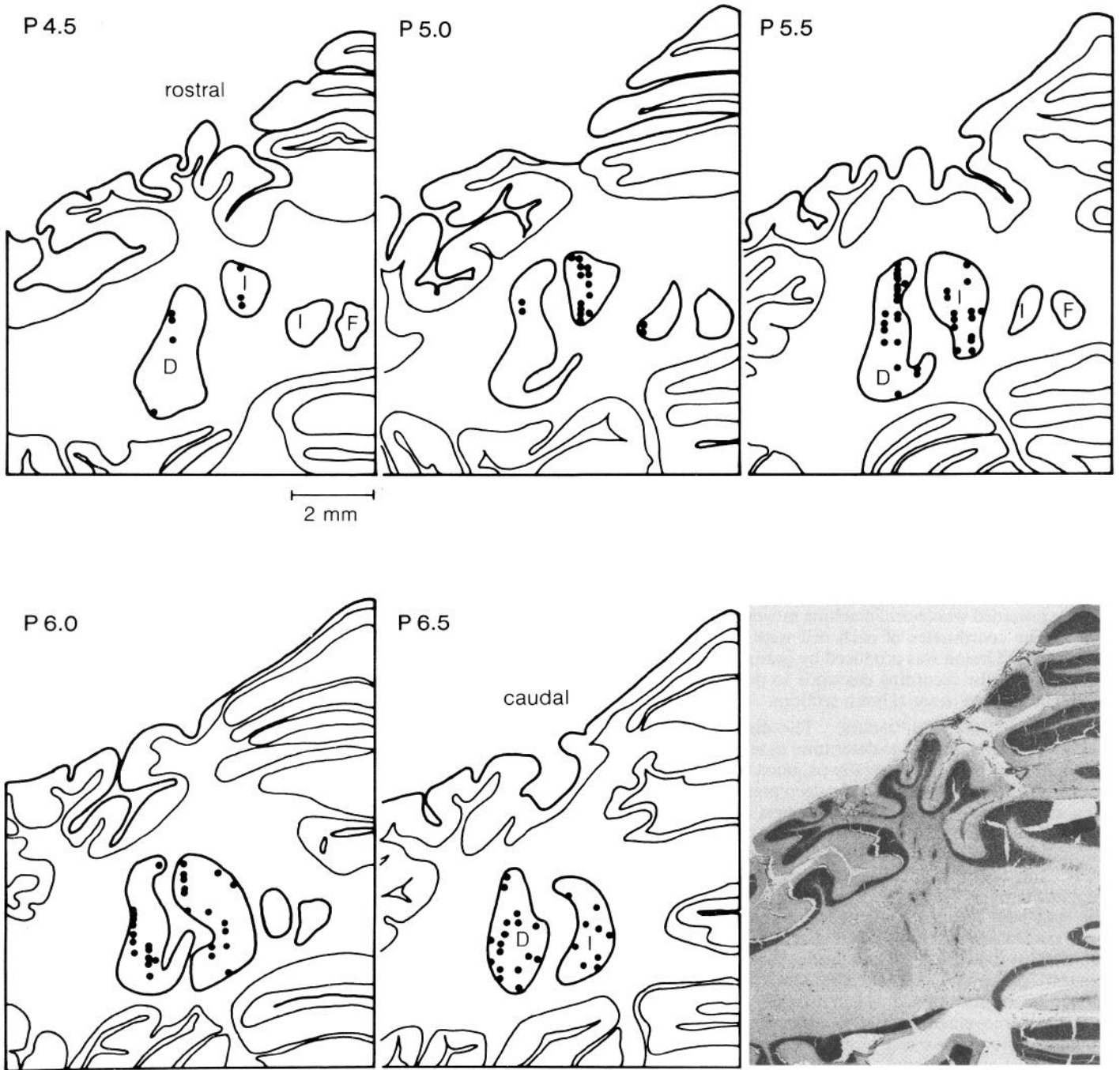


FIG. 4. Histological sites of cerebellar nuclei recordings. The approximate locations of the recorded interpositus and dentate neurons are illustrated on 5 frontal sections from the stereotaxic coordinates posterior 4.5 mm to posterior 6.5 mm. The frontal section in the lower right shows the location of a lesion in the interpositus nucleus. Abbreviations: D, dentate nucleus; I, interpositus nucleus; and F, fastigial nucleus.

The movements were directed from the central starting position toward the target lights with little deviation from the straight-line path. Movements with very curved paths were excluded from the analyses. Velocity profiles of the hand paths, obtained by differentiating the  $x$ - and  $y$ -coordinates of the pendulum, are illustrated in Figure 2B. The velocity profiles represent the mean of five replications of each movement direction aligned on the onset of movement. The movement velocity profiles were approximately

bell-shaped, although the terminal phase of the movement often showed a more gradual deceleration when the pointer was in the proximity of the target. Behavioral reaction times during these arm movements were  $281 \pm 94$  (SD) ms ( $n = 12,312$  trials).

#### Neurons recorded

A total of 312 cerebellar neurons with significant changes in activity during whole-arm reaching movements

TABLE 1. *Quantitative analysis of neuronal activity during reaching*

	RT	MT	HT	RT+MT
<i>A. Tests on individual neuron groups</i>				
Unidentified, %				
<i>F</i> test ( $P < 0.05$ )	54	80	67	82
Rayleigh ( $P < 0.05$ )	50	67	43	59
Sinusoid ( $R^2 > 0.70$ )	36	51	47	55
Purkinje, %				
<i>F</i> test	43	91	68	83
Rayleigh	42	74	45	57
Sinusoid	28	46	43	42
Interpositus, %				
<i>F</i> test	60	85	69	82
Rayleigh	54	62	40	51
Sinusoid	43	46	49	57
Dentate, %				
<i>F</i> test	51	84	57	83
Rayleigh	48	62	33	51
Sinusoid	38	43	27	44
<i>B. Total sample of cerebellar neurons</i>				
<i>F</i> test				
sig	163	263	205	256
non-sig	149	49	107	56
%	52	84	66	82
Rayleigh				
sig	152	207	128	172
non-sig	160	105	184	140
%	49	66	41	55
Sinusoid				
sig	113	148	133	157
non-sig	199	164	179	155
%	36	47	43	50

RT, reaction time; MT, movement time; HT, target-hold time.

was recorded from three monkeys. Sixty-nine Purkinje cells (identified by the presence of characteristic climbing fiber discharges) and 115 unidentified cortical cells were collected mainly from lobule V of the intermediate zone ~1.8–5.4 mm lateral to the midline, although some cells were recorded in lobules IV and VI as well. Figure 3 illustrates the approximate area of shoulder representation explored in the anterior lobe of the cerebellar cortex in one monkey. In general, the shoulder area is smaller and more medial than the hand area. We are unsure whether the Purkinje cells efferents from within this area project to both the interposed and dentate nuclei or whether only interpositus receives inhibition from the portion of lobule V overlying the interposed nuclei (Brodal 1981). Sixty-five interpositus neurons and 63 dentate units were identified on the basis of their distance from the midline and the vertical distance below the estimated point of entry into the dorsal contour of the nucleus, and their very approximate location is shown in Fig. 4.

For every cell that was recorded, an attempt was made to identify the body part that was most closely associated with the neuronal activity. With the use of techniques described in the METHODS, it was possible to identify many cells that were active in the task but had sensorimotor responses related to the distal arm and other parts of the body. These were eliminated from detailed study. Sensorimotor responses were obtained for 247 of 312 cells selected for

further study. Of these, most cells were responsive to cutaneous or proprioceptive stimulation centered on the shoulder (46%) or the shoulder girdle (32%) or to active movements of these regions. Another 12% of the cells had sensorimotor responses primarily to stimulation or movement around the elbow. However, it was also common that cells were activated somewhat less intensely or reliably by movements of adjacent parts of the body. At the extreme was a small group of cells (10%) that showed sensory and motor responses related to movements of the entire arm, including the shoulder, although we could not identify a relationship to movement of any particular segment of the arm. The remaining 65/312 cerebellar neurons included in this study showed consistent activity changes during whole-arm reaching in the task, but responses to elicited and imposed movements were obtained with difficulty, and a relation to movements of the arm could not be adequately identified. These 65 cells were adjacent to cerebellar neurons with sensorimotor responses related to the shoulder and shoulder girdle, and their task responses were not significantly different from the other 247 cerebellar neurons with identified sensorimotor responses.

### Quantitative analyses

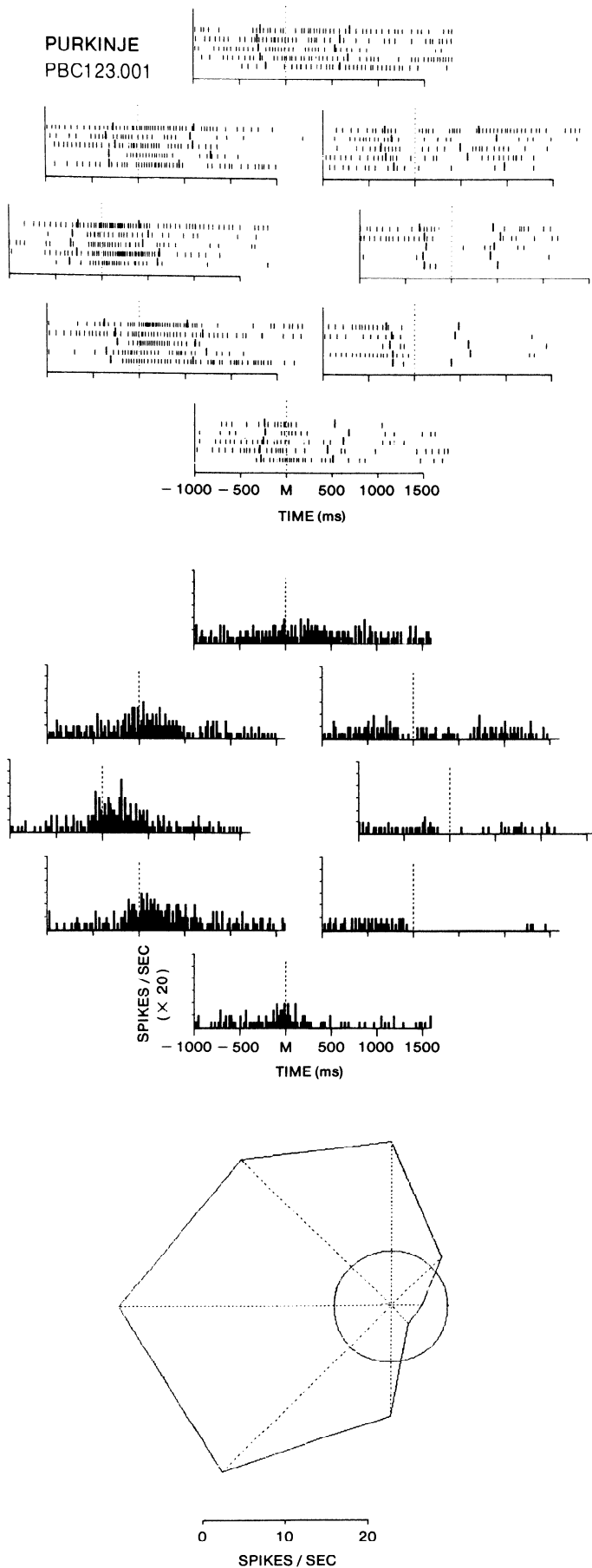
The *t* test was used to identify cells which showed significant changes in activity during different movement epochs, compared with the CHT pre-movement tonic rate. All cells showed significant movement-related changes in activity for at least one direction of movement in one epoch. More typically, however, cells showed significant changes in activity for many movement directions in most or all epochs. The highest incidence (95%) of significant activity change was found while the limb was moving to the target (MT). Activity changes were less common during RT and HT (68–69%).

For the large majority of cerebellar cells, the activity changes varied significantly with the direction of movement (Table 1B, *F* test). In many cases, cell discharge had a significant directional preference, that is, it showed a uni-

TABLE 2. *Percentage of directional activities and nondirectional discharges in the four cerebellar neuron populations*

	Cortical		Nuclear		Total
	Unidentified	Purkinje	Interpositus	Dentate	
Population, <i>n</i>	91	53	41	46	231
Reciprocal					
<i>n</i>	34	5	15	9	63
%	37	9	37	20	27
Graded					
<i>n</i>	26	29	14	19	88
%	29	55	34	41	38
Nondirectional					
<i>n</i>	14	9	6	8	37
%	15	17	15	17	16
Unclassed					
<i>n</i>	17	10	6	10	43
%	19	19	15	22	19

*n* = no. of neurons.



modal variation with movement direction (Table 1B, Rayleigh test). Finally, the movement-direction-related activity changes frequently showed a good fit to a sinusoidal curve (Table 1B). The directional activity was most commonly observed during the MT epoch. Cells demonstrating a statistically defined nondirectional relation to whole-arm reaching in this task, that is, cells with significantly different activity from premovement (*t* test results) but that was not significant with respect to direction, were a small minority. Also of note in Table 1 is the finding that arm posture-related discharge variation during HT is less common in the dentate nucleus than in other structures. Moreover, directional activity was present before movement onset in all four cell populations, including the interpositus neurons. A  $\chi^2$  test failed to identify any significant difference in the results of these various tests for directionality among the Purkinje, unidentified cortical, interpositus, and dentate subgroups (Table 1A).

#### *Reciprocal, graded, and non-directional cells*

The statistical tests were used to divide the cerebellar units into reciprocal, graded, and nondirectional groups of activity patterns, according to their discharge during the combined RT+MT epoch. To make this classification more reliable, we considered only the cells which were strongly activated during RT+MT. We eliminated the weakly related cells whose strongest observed response among the eight movement directions represented  $<50\%$  change in discharge from the tonic rate during CHT. This was done to minimize the uncertainties involved in attempting to classify the response pattern of cells whose activity was only weakly modulated and that may have been only marginally implicated in the task. By this criterion, 231/312 cells were strongly activated during RT+MT.

Reciprocal cells were defined as having a significant unimodal directionality (*F* test and Rayleigh test), as well as an increase in activity during movement in one direction and a decrease in activity during movement in the opposite direction. About 27% of the neurons (63/231) showed a reciprocal pattern of activity during whole-arm reaching (Table 2). Figure 5 illustrates an example of a Purkinje cell with a reciprocal pattern of activity, represented in raster, histogram, and polar plot form. The preferred direction for the activity during RT+MT was at  $171^\circ$ . It can be seen that reaching to the left caused an increase in cell activity, whereas reaching toward the right produced a decrease. The activity of this neuron demonstrated a unimodal distribution (Rayleigh test,  $P < 0.01$ ) and had an excellent fit to a sinusoidal curve ( $R^2 = 0.97$ ).

The distribution of responses in graded cells was also directional with a single mode (*F* test and Rayleigh test); but the activity changes were always the same, showing

FIG. 5. Reciprocal pattern of cerebellar neuron activity. The activity of this Purkinje cell is displayed in raster (*top*) and histogram (*middle*) formats aligned on the onset of movement and also as a polar plot (*bottom*). The circle in the middle of the polar plot represents the mean activity of the cell during the center-hold time. The length of each axis represents the mean neuronal activity during RT+MT for the corresponding movement direction. Binwidth = 20 ms.

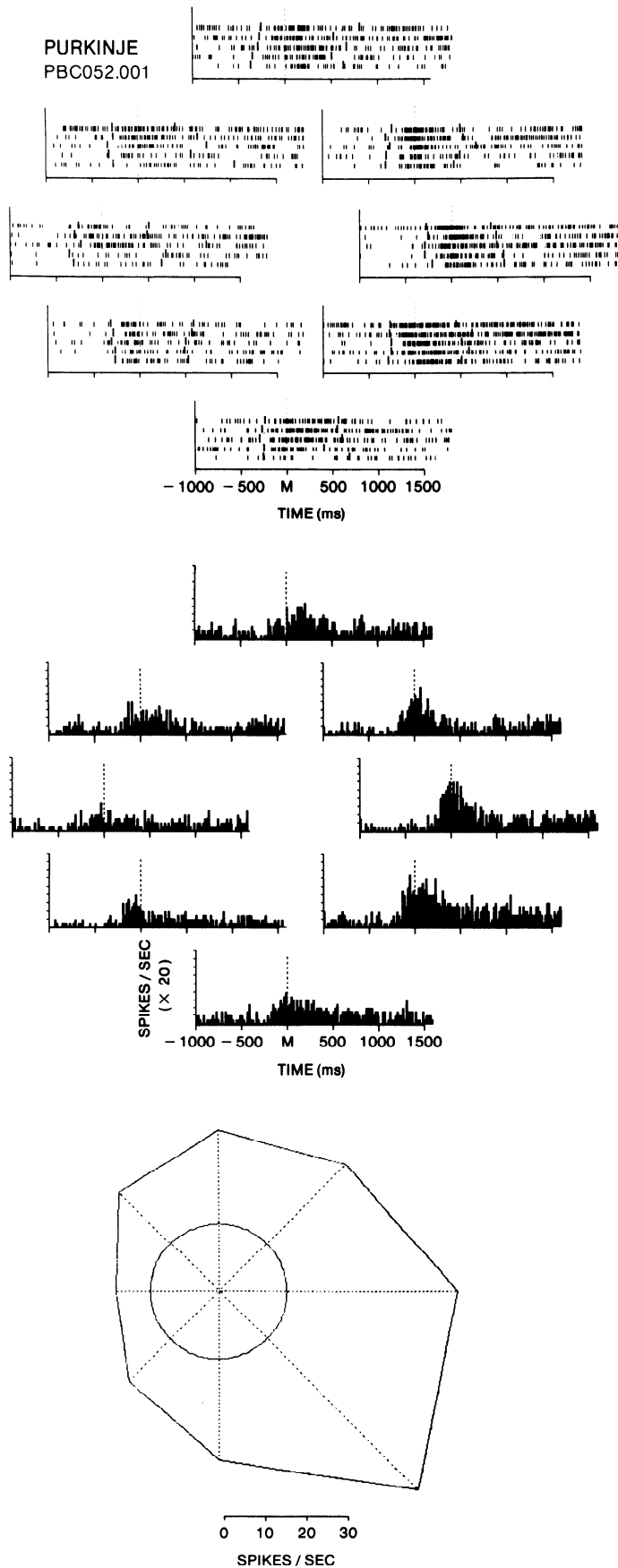


FIG. 6. Graded pattern of cerebellar neuron activity. The activity of this Purkinje cell is displayed in the same format as described in Fig. 5.

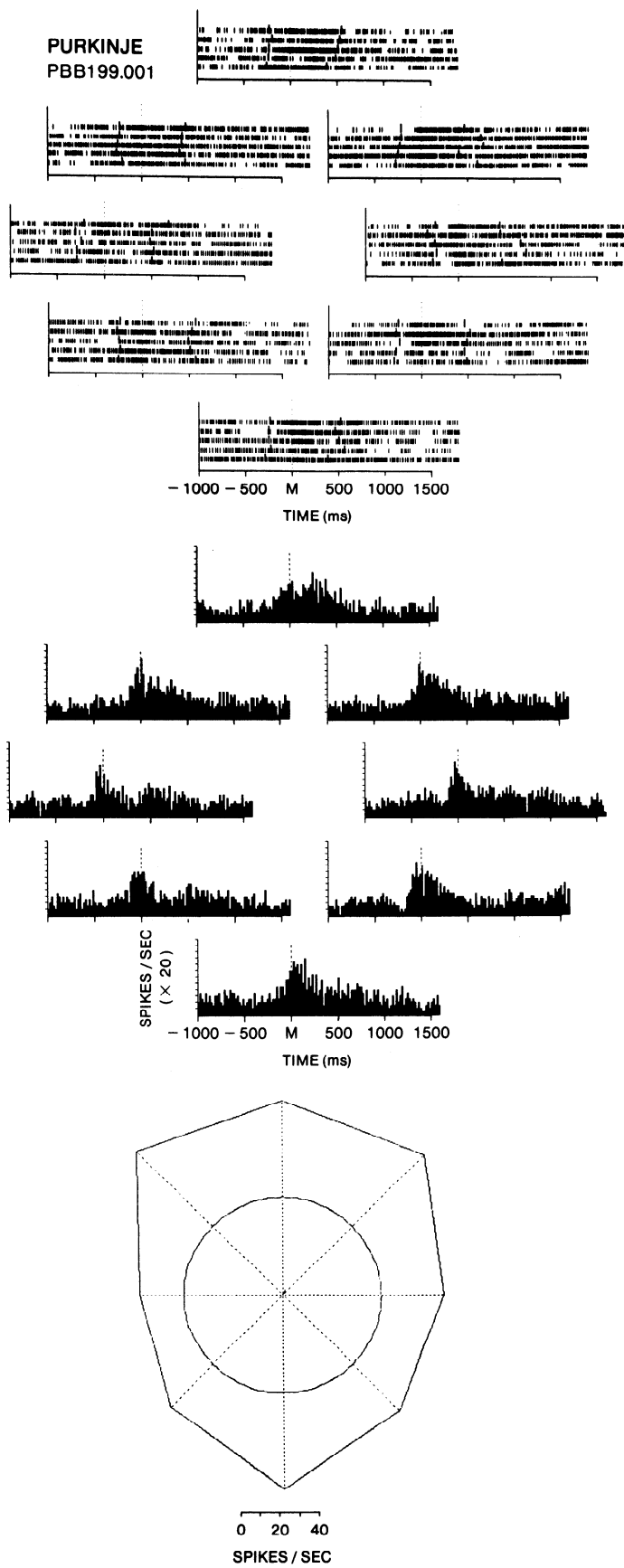


FIG. 7. Nondirectional pattern of cerebellar neuron activity. The activity of this Purkinje cell is displayed in the same format as described in Fig. 5.



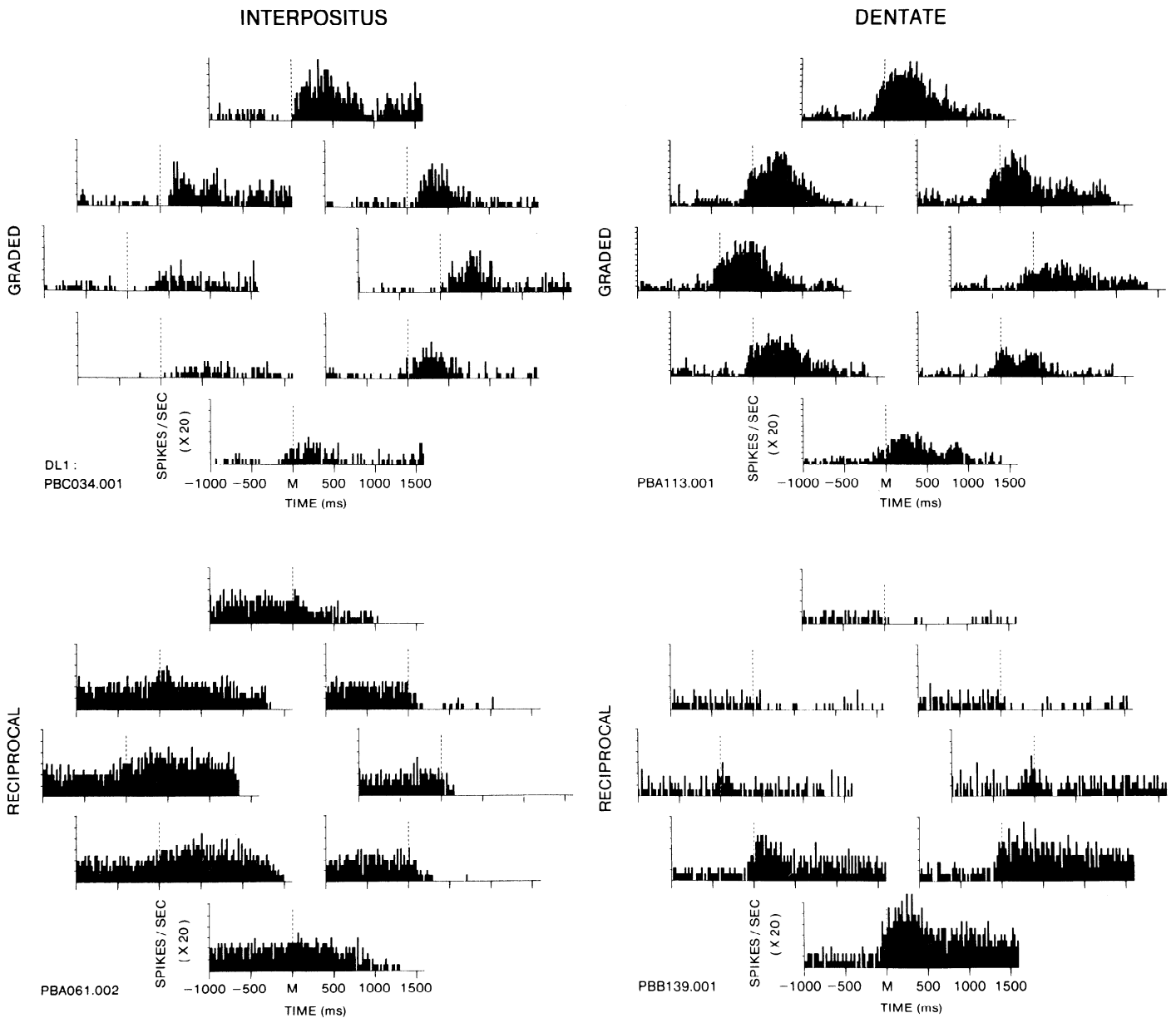


FIG. 8. Examples of reciprocal and graded activity patterns from the interpositus and dentate cell populations.

either only increases or only decreases in activity. This was the most common response seen (Table 2, 88/231 cells, 38%). Figure 6 illustrates a Purkinje cell demonstrating a graded activity pattern with a preferred direction at  $346^\circ$ . For movements around the preferred direction, there were submaximal increases in cell activity, but, unlike the reciprocal cells, the movement opposite to the preferred direction was not associated with a significant decrease of cell activity below the tonic rate recorded during the CHT. The Rayleigh test identified a significant ( $P < 0.01$ ) unimodal variation in the activity of this cell, which closely approximated a sinusoidal curve ( $R^2 = 0.82$ ). The symmetrical changes in activity for successive movements away from the preferred direction resulted in an almost identical pattern of discharge for both movements along the axis perpendicular to the preferred direction. For cells of this sort, if only one pair of opposing movements had been studied,

as in a bidirectional task, the gradation of discharge with movement direction would not have been evident.

Nondirectional cells had significant activity changes only with respect to the CHT levels ( $t$  test) but no significant variation in activity with movement direction ( $F$  test). Moreover, the activity of these cells consistently failed the Rayleigh test and could not be fitted to a sinusoidal function. Only  $\sim 16\%$  of the cells (37/231) showed a nondirectional pattern of activity. Figure 7 shows a Purkinje cell with a nondirectional pattern of activity for which there was a statistically uniform increase in activity in all eight directions of movement during RT+MT.

The other 43 cells (18.6%) were not readily classifiable. These neurons all showed statistically significant changes in their discharge in different movement directions ( $F$  test) and so could not be considered as nondirectional. However, they all failed to meet the criterion of unimodal direc-

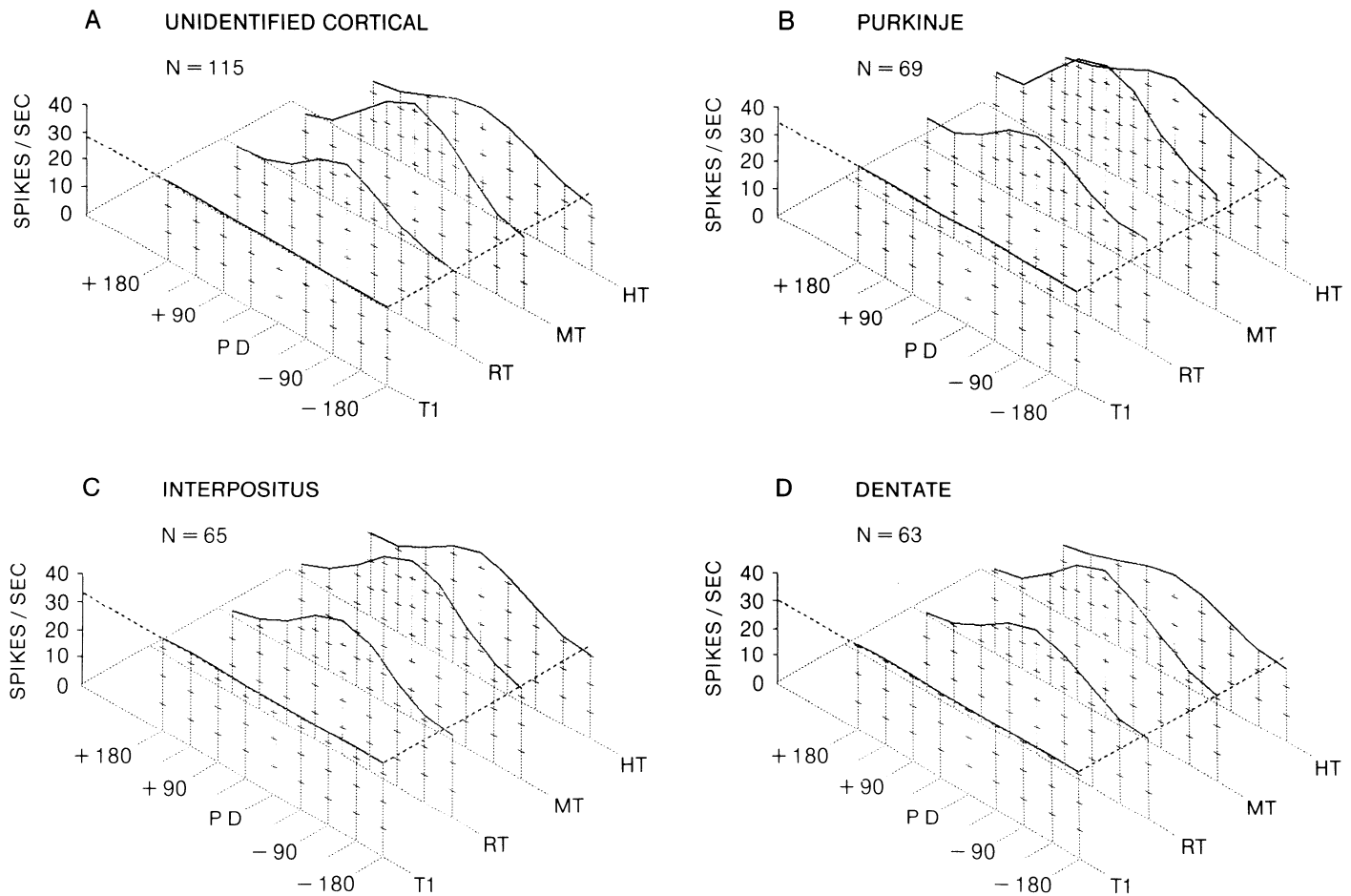


FIG. 9. Population curves of activity changes with direction and time of reaching. Each curve represents the mean activity of a population of cells during reaching in all directions relative to the preferred direction. *A*: unidentified cortical cell population. *B*: Purkinje cell population. *C*: interpositus cell population. *D*: dentate cell population. Abbreviations: T1, center-hold time; RT, reaction time; MT, movement time; and HT, target-hold time.

tionality (Rayleigh test). For most of these cells, the pattern of activity changes was too erratic to fit into either of the two directional classes.

Graded and non-directional cells most commonly showed excitatory changes in activity. Only  $\sim 7\%$  of the graded and nondirectional cells had discharge patterns composed exclusively of decreased firing during the task.

The reciprocal, graded, and nondirectional patterns of activity were seen in all four populations of cells (Table 2). Examples of reciprocal and graded interpositus and dentate neurons are given in Fig. 8. The proportion of directional (reciprocal and graded) versus nondirectional cells was the same in all four cell populations. However, the two directional response patterns were present in different frequencies among the four neuronal populations. Reciprocal cells were more common and graded cells proportionately less common among unidentified cortical and interpositus cells than among Purkinje and dentate cells (Table 2). These differences were statistically significant ( $\chi^2$  test,  $P < 0.01$ ). Nondirectional and unclassified cells were distributed uniformly among the four populations.

#### Modulation of activity with direction in different epochs

The discharge frequency of each cerebellar cell during each epoch could be centered about its direction of maxi-

um response and the lesser responses to successively more distant targets up to  $180^\circ$  displayed on each side. The discharge rates vary substantially from one cell to another, but for all cells, the activity decreases progressively as one moves away from the preferred direction. By aligning the tuning curve of each cell at its preferred direction, one can calculate the mean activity curves for separate populations of neurons during the RT, MT, and HT periods. Curves for Purkinje cells, unidentified cortical cells, interpositus neurons, and dentate units were plotted separately and are shown in Fig. 9. Striking similarities exist among the four groups of cells. The mean activity during the initial holding posture (T1) was practically identical (i.e., between 28 and 34 spikes/s) in the four cerebellar neuron populations. The distributions of activity for the RT, MT, and HT periods in the cerebellar cortical and nuclear cells all formed bell-shaped unimodal tuning curves. The shape of these tuning curves is very similar over the different epochs of the task and among the different cerebellar cell populations.

#### Preferred directions

The preferred direction of movement varied from one cell to another. The preferred direction of each cell was calculated using the mean discharge during the entire trial

N = 312

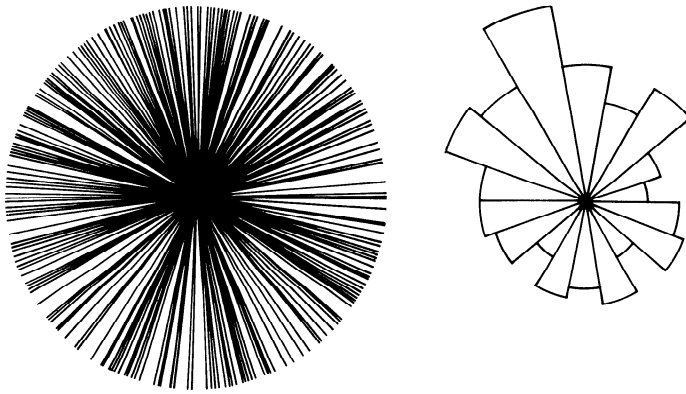


FIG. 10. Preferred directions of cerebellar neuron population. *Left*: orientations of the preferred directions of each cell ( $n = 312$ ). *Right*: frequency distribution of preferred directions (binwidth =  $20^\circ$ ).

from the start of RT to the end of HIT (Fig. 9). It can be seen in Fig. 10 that all possible directions of movement away from the central starting position were represented in our sample of cerebellar neurons. However, this distribution is not uniform. It demonstrates a significant skew toward movements of the right arm across the midline and away from the body to the upper left target. This figure includes the populations of Purkinje cells, unidentified cortical cells, interpositus neurons, and dentate units. There was no significant difference in the preferred direction distributions of these four subgroups.

#### Vectorial description of the population

The "vector hypothesis" is a method that was used by Georgopoulos and coworkers (1983, 1986) to represent the activity of a population of motor cortex cells during movements in different directions. A slightly modified method was used here to represent cerebellar responses (see METHODS).

The results of this vectorial representation for the entire cerebellar neuronal population are seen in Fig. 11. The heavy arrows in the figure represent the sum of the vectors drawn for each direction of movement. This figure illustrates several features of cerebellar activity during normal whole-limb reaching movements. First, the pattern of activity of the population varies with the direction of movement. Second, the greatest level of activity occurs during the MT (see also Fig. 9). Third, the vector sums (heavy arrows) correspond very well to the direction of intended movement (RT) and with posture (HT), but show some deviation from the actual movement direction during the movement (MT). Similar observations were made when

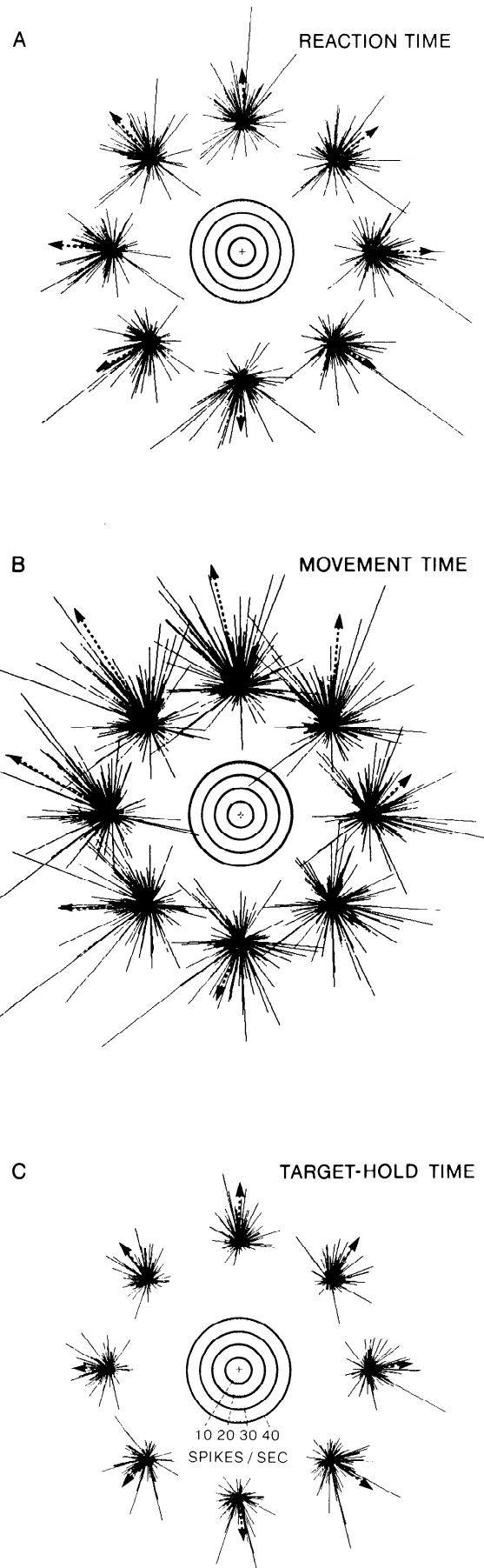


FIG. 11. Vector representation of cerebellar population. Illustrated in this figure are the cerebellar activities during the reaction (A), movement (B), and target-hold (C) times. The 8 groups of vectors arrayed in a circle represent the cerebellar neuron activities during the 8 directions of reaching. The position of a group of vectors, relative to the center of the array, represents the direction of movement, and each vector within a group represents the mean activity and preferred direction of a single neuron during this movement. The heavy arrows represent the vector sum for each group of vectors.

vectorial representations were drawn for the populations of Purkinje, unidentified cortical, interpositus, and dentate cells separately (not illustrated).

## DISCUSSION

### *Cerebellar discharge and movement direction*

The present study showed that the activity of many Purkinje, unidentified cortical, interpositus, and dentate cells was modulated according to the direction of whole-arm reaching movements. The directional character of cerebellar activity was demonstrated in three ways—statistical analysis of the activity of single cells, the mean directional tuning curves of cell populations, and a vectorial representation of the activity of the cerebellar sample populations during different directions of movement. The presence of direction-related cerebellar activity is consistent with other reports (Frysinger et al. 1984; Harvey et al. 1977, 1979; Thach 1970a,b; Wetts et al. 1985). In the present study, only 16% of the cerebellar units showed statistically uniform changes in activity for all eight movement directions. Consequently, the results of the present study clearly demonstrate that the contribution of the cerebellum to the control of normal whole-arm reaching movements is primarily exerted through cerebellar neurons whose activity is modulated according to the direction of movement. Whether the correlation between cerebellar unit activity and movement direction is strong enough to imply a causal connection may be debated. However, cerebellar ataxia after lesions encompasses a fundamental deficit in the voluntary control of movement direction (Holmes 1939).

This experiment provides no direct evidence as to the origin or function of these directional discharges in each cerebellar structure. In particular, we do not suggest from these results that the cerebellum generates an abstract signal of movement direction that can be distinguished from other movement parameters such as muscle activity, forces or torques, and joint-angle changes that covary with movement direction. It is clear, however, that, whatever movement parameters are encoded by cerebellar neurons, those signals are frequently modulated according to the direction of movement during normal whole-arm reaching movements.

Although the present study disagrees with the suggestion that the activity of the majority of cerebellar neurons is unrelated to movement direction, there is support for the finding that similar changes in cerebellar activity often can be observed for movements in opposite directions (Chapman et al. 1986; Mano and Yamamoto 1980; Schieber and Thach 1985b). For instance, many of the cells recorded in the present study, although directional, showed graded increases in activity for all eight directions of movement. As a result, opposite directions of movement not corresponding to the preferred direction often showed similar changes in activity, as observed in other experiments (Chapman et al. 1986; Mano and Yamamoto 1980; Schieber and Thach 1985b). Even opposite directions of movement along the preferred direction axis frequently resulted in excitation for both movements, although at different intensities (cf. Fig. 8). This would seem to offer some explanation for why some studies have reported a sizable population of bidirec-

tional cerebellar neurons during flexion and extension movements (Chapman et al. 1986; Mano and Yamamoto 1980; Schieber and Thach 1985b). The pattern of unimodal directional variation of cerebellar activity only became evident in this experiment through the use of a range of different intermediate movement directions.

Other factors may contribute to the large number of directionally-tuned cells in this task. An effort was made in this experiment to study cells related to movements of the proximal arm and shoulder girdle, because muscles acting at these structures have a major role in controlling movement direction in this task (Georgopoulos et al. 1982). Inclusion of cells which were active in the task but clearly related to movements of other parts of the body, such as the leg or face, would have distorted the apparent directional properties of the cerebellar sample. The directional character of cell discharge might also depend on the information provided by sensory signals in the task (Chapman and Lamarre 1987). When monkeys were trained to make elbow flexion and extension movements in response to somesthetic, visual, and auditory signals that indicated when to make a movement but provided no information about movement direction, dentate activity preceding the movement was unrelated to the movement direction (Chapman et al. 1986). In contrast, they found that activity after the onset of movement was directional. However, more directional and less nondirectional activity was observed in dentate cells during the reaction time when the stimulus triggering the movement also indicated the direction in which the movement should be produced (Chapman and Lamarre 1987). In the present study, the position of the target light indicated the direction in which the monkey was required to make a whole-arm reaching movement and would have maximized the directional discharge of dentate neurons.

Many cerebellar cells were directionally tuned in this experiment. Nevertheless, it is also clear that reciprocity of discharge was relatively uncommon, particularly among Purkinje and dentate cells, in a task in which prime-mover muscles and many motor cortex cells (Frysinger et al. 1984; Georgopoulos et al. 1982) showed a reciprocal relation to opposite directions of movement along their preferred direction axis.

### *Similarities among cerebellar neurons*

One of the striking observations of the present study was the similarity in the mean activity of the Purkinje, unidentified cortical, interpositus, and dentate neurons during whole-arm reaching. All four cerebellar neuron populations were similar with respect to the tonic activity before movement and also with respect to the modulation of activity with the direction of whole-arm reaching. Averaging the profiles of activity grouped around the preferred direction of movement for each of the different subpopulations of cerebellar neurons, as shown in Fig. 9, may have created an exaggerated impression of similarity. The meaning as well as the exact extent of the similarities among cerebellar neurons are not entirely clear. Obviously, the cerebellar cortex and nuclei make different contributions to motor control. Efferents from the interpositus and dentate nu-

cleus influence several brain regions including the inferior olive, red nucleus, and a variety of thalamic nuclei that, according to Schell and Strick (1984), influence the motor cortex and anterior premotor cortex independently. In this regard, the differences in the proportions of reciprocal and graded cells among the cell populations may imply different functional roles. However, the monosynaptic convergence of dentate and interpositus neurons on the thalamic neurons projecting to motor cortex has now been well established (Rispoli-Padel et al. 1987; Shinoda et al. 1985). This observation would seem to suggest that some interpositus and dentate efferents converge upon a common path to the motor cortex. The similarity in the continuously graded directional tuning of cerebellar discharge to that in motor cortex (Frysinger et al. 1984; Georgopoulos et al. 1982) and parietal cortex (Kalaska et al. 1983) might represent a common code used for communicating information about the covariation of movement parameters with movement direction among the different motor regions of the brain. That this may be a very general coding mechanism in the CNS is suggested by the finding of similar bell-shaped tuning curves for the discharge of pontine reticular formation cells related to saccadic eye movements (Henn and Cohen 1976) and, in area 7 neurons responsive to visual stimulus movement (Steinmetz et al. 1987).

#### *Cerebellar activity and the vector hypothesis*

The activity of a single cell provides ambiguous information about most directions of movement because the bell-shaped tuning curves result in similar activities for movements made on either side of the preferred direction. In such a situation, information about the direction of movement may reside in the activity of a population of neurons. The vector hypothesis is a method that has been proposed by Georgopoulos and co-workers (1983, 1984, 1986) to describe the encoding of movement direction based on the bell-shaped distribution of response intensities over a variety of movement directions. It assumes that the primary function of each cell is to encode parameters of movement in a specific direction that corresponds to the axis of its preferred direction. The bell-shaped tuning curves indicate that the intensity of discharge of a neuron for any given intended direction is scaled in an approximately sinusoidal fashion with the difference between the intended movement direction and the cell's preferred direction. Therefore the activity of the cell for any movement can be represented by a vector oriented along the axis of its preferred direction, the length of which varies according to the cell's tuning function. The pattern of activity of a cell population is represented by a family of vectors of different orientations and lengths. In the motor cortex and area 5, summation of the vector equivalents of the neuronal activity produces a resultant vector that points in the actual direction of the movement (Georgopoulos et al. 1983; Kalaska et al. 1983). The present study has extended these results to the cerebellum and demonstrated that the pattern of activity of different cerebellar populations varies with the direction of the upcoming movement during the RT epoch and the posture of the limb relative to the central starting point during the HT epoch. Some deviation of this

signal away from the actual movement direction was seen during the MT epoch. This deviation may simply be due to the predominance of preferred directions toward the upper left in our sample. However, because it was not evident in other epochs, it may reflect the nature of the information being processed by these cells from and concerning the moving limb. It may also provide a clue as to the role of these neuronal populations during normal whole-arm movement, although our understanding of these processes is still too rudimentary for a proper interpretation of this observation.

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