Preparation for Movement: Neural Representations of Intended Direction in Three Motor Areas of the Monkey

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SUMMARY AND CONCLUSIONS

1. The purpose of this study was to compare the functional properties of neurons in three interrelated motor areas that have been implicated in the planning and execution of visually guided limb movements. All three structures, the supplementary motor area (SMA), primary motor cortex (MC), and the putamen, are components of the basal ganglia–thalamocortical "motor circuit." The focus of this report is on neuronal activity related to the preparation for movement.

2. Five rhesus monkeys were trained to perform a visuomotor step-tracking task in which elbow movements were made both with and without prior instruction concerning the direction of the forthcoming movement. To dissociate the direction of preparatory set (and limb movement) from the task-related patterns of tonic (and phasic) muscular activation, some trials included the application of a constant torque load that either opposed or assisted the movements required by the behavioral paradigm. Single-cell activity was recorded from the arm regions of the SMA, MC, and putamen contralateral to the working arm.

3. A total of 741 task-related neurons were studied, including 222 within the SMA, 202 within MC, and 317 within the putamen. Each area contained substantial proportions of neurons that manifested *preparatory* activity, i.e., cells that showed task-related changes in discharge rate during the postinstruction (preparatory) interval. The SMA contained a larger proportion of such cells (55%) than did MC (37%) or the putamen (33%). The proportion of cells showing *only* preparatory activity was threefold greater in the SMA (32%) than in MC (11%). In all three areas, cells that showed only preparatory activity tended to be located more rostrally than cells with movement-related activity. Within the arm region of the SMA, the distribution of sites from which movements were evoked by microstimulation showed just the opposite tendency: i.e., microexcitable sites were largely confined to the caudal half of this region.

4. The majority of cells with task-related preparatory activity showed selective activation in anticipation of elbow movements in a particular direction (SMA, 86%; MC, 87%; putamen, 78%), and in most cases the preparatory activity was found to be independent of the loading conditions (80% in SMA, 83% in MC, and 84% in putamen). A minority of cells in each area showed preparatory activity that was weakly modulated by the presence of constant torque loads, but in nearly all such cases the "loading effects" were not confined to the postinstruction interval and therefore did not appear to be "preparatory" in nature; rather, they appeared merely to reflect the current loading conditions.

5. The average onsets and offsets of directional preparatory activity in the SMA and MC were significantly earlier than those in the putamen. This is consistent with the possibility that some of the preparatory activity in the putamen may arise from corticostriatal inputs to this nucleus from the SMA and/or MC. It should be noted, however, that preparatory neurons in all three motor areas were active simultaneously throughout most of the postinstruction interval.

6. The results of this study indicate that directionally selective preparatory activity is distributed across the SMA, MC, and the putamen. The near absence of preparatory loading effects in all three motor areas suggests that directional preparatory activity, at least in these structures, may not play a significant role in coding for either the dynamics or the muscle activation patterns of preplanned movements. Instead, such activity may be coding for the intended direction of movement at a more abstract level of processing (e.g., trajectory and/or kinematics), independent of the forces that the movement will require.

INTRODUCTION

To control visually guided limb movements, the brain must translate the spatial information specified by the target or goal of the movement into an appropriate set of muscle activation patterns that will carry the limb along a specific trajectory to the desired location (Bernstein 1984; Lacquaniti et al. 1986; Morasso 1981; Saltzman and Kelso 1987; Soechting and Lacquaniti 1981). There are several ways in which this might be accomplished (Albus 1975; Keele 1981; Kuperstein 1988; Pellionisz and Llinas 1985; Pew 1989; Raibert 1978; Rosenbaum and Saltzman 1984; Schmidt 1975), but the approach employed by the brain has yet to be determined. One of the clearest formulations of the issues involved in controlling goal-directed limb movements has emerged from attempts to develop explicit, analytic solutions to this type of problem (An et al. 1988; Hollerbach 1982a; Paul 1981; Whitney 1972). From this perspective, the control of goal-directed movements can be divided into a sequence of computations that successively determine *1*) the location of the target in space, *2*) the hand trajectory needed to acquire the target, *3*) the joint kinematics needed to achieve that trajectory (inverse kinematics), *4*) the joint torques needed to satisfy those kinematic constraints (inverse dynamics), and *5*) the patterns of effector ("muscle") activations needed to satisfy the required dynamics. Included within these computations are a series of coordinate transformations needed to permit accurate mapping between different spatial frames, including those of the target, the hand, the joints, and the muscles. This serial, analytic model of motor control is depicted in Fig. 1.

Although it is not known whether the brain employs this sequential approach to motor processing, which requires precise solutions to a series of lengthy and complex computations (Abend et al. 1982; Hinton 1984; Hollerbach 1982a,b; Saltzman 1979), there are good reasons to suspect otherwise: e.g., the brain's well-known structural parallelism (Barbas and Pandya 1987; Ghosh et al. 1987; Jones
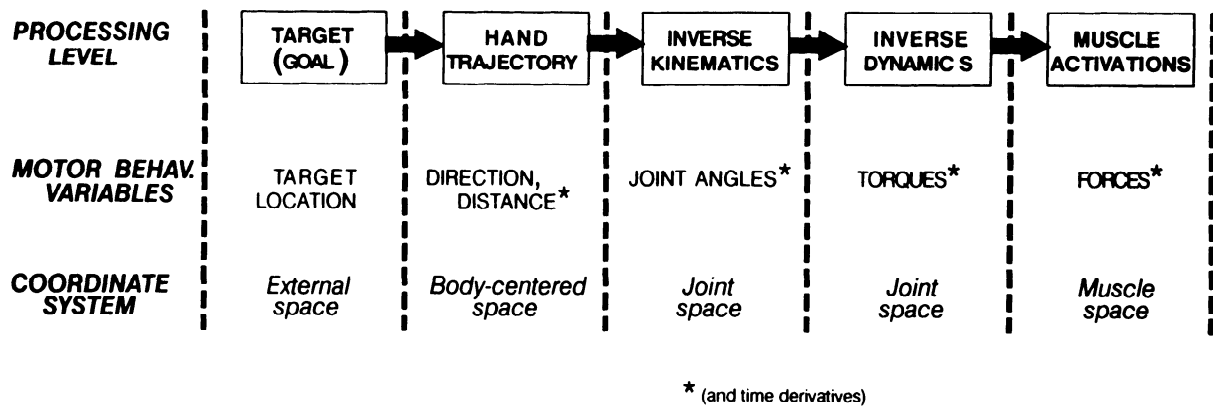
PROCESSING LEVEL	TARGET (GOAL)	HAND TRAJECTORY	INVERSE KINEMATICS	INVERSE DYNAMICS	MUSCLE ACTIVATIONS
MOTOR BEHAV. VARIABLES	TARGET LOCATION	DIRECTION, DISTANCE*	JOINT ANGLES*	TORQUES*	FORCES*
COORDINATE SYSTEM	External space	Body-centered space	Joint space	Joint space	Muscle space

*(and time derivatives)

FIG. 1. Schematic representation of the theoretical levels of motor processing that would be required if the brain used a sequential, analytic approach to motor processing.

and Powell 1970; Leichnetz 1986; Martino and Strick 1987; Muakkassa and Strick 1979; Pandya and Vignolo 1971) and the inherently slow, noisy, and stochastic operations of its constituent neurons (Loeb 1983; Rumelhart and McClelland 1986). Nevertheless, the serial, analytic model has the dual advantage of clarity and comprehensiveness and thus forms a useful conceptual framework for exploring the neural substrates of motor control. In fact, this framework is implicit in many contemporary theories of motor control, which vary principally in the relative importance they assign to the different processing levels.

If any or all of the analytically defined levels of processing are represented within the motor system, there are at least two ways that such representations might be organized. One possibility, consistent with the serial model, is that the different processing levels (and their associated motor variables) might be represented in separate, *serially* connected motor structures, each of which would be functionally specialized to deal with a particular aspect of motor control. The motor system might also be organized *in parallel*, however, with individual motor structures participating simultaneously in several levels of processing and each processing level being distributed over multiple structures.

The studies reported in this and the following two papers attempt to address these different possibilities by comparing the neural representations of motor processing in three interconnected motor areas. We also sought to determine which, if any, of the analytically defined levels of motor processing were represented during the *preparation* for movement and which during movement *execution*. We compared neuronal activity associated with the planning and execution of visually guided limb movements in three motor areas of the monkey: the supplementary motor area (SMA), primary motor cortex (MC), and the putamen. All are components of the recently proposed basal ganglia-thalamocortical "motor circuit" (Alexander et al. 1986), with the SMA and MC sharing reciprocal connections and projecting in turn to the putamen (Jones and Powell 1970; Kunzle 1975, 1978; Liles 1975; Muakkassa and Strick 1979; Pandya and Kuypers 1969; Pandya and Vignolo 1971), which returns its own influences to the SMA and rostral MC (Kievit and Kuypers 1977; Matelli et al. 1989; Schell and Strick 1984; Wiesendanger and Wiesendanger

1985) via intermediate connections in the globus pallidus (DeVito et al. 1980; Nauta and Mehler 1966; Parent et al. 1984) and ventrolateral thalamus (DeVito and Anderson 1982; Kim et al. 1976; Kuo and Carpenter 1973). We used a set of motor tasks that allowed us to dissociate several of the analytically defined levels of motor processing and also to differentiate between processes related to the preparation versus the execution of goal-directed limb movements.

In this first paper we compare neuronal activity in the SMA, MC, and putamen that is specifically associated with the preparation for visually guided arm movements. The focus is on whether neural correlates of motor preparation reflect the direction of intended movement or the pattern of muscle activity that will be required. The second paper compares neuronal activity related to movement execution in these same structures. The emphasis here is also on whether there are neural representations that code for the kinematic variable of movement direction independent of the required force or muscle activation patterns. In the third paper we address the question of whether the motor circuit contains high-level representations of the *target or goal* of a movement independent of the kinematic features of the movement itself. Some of these results have been reported previously in preliminary accounts (Alexander 1987; Alexander and Crutcher 1987; Crutcher and Alexander 1987, 1988).

METHODS

Behavioral paradigm

Five male rhesus monkeys (*Macaca mulatta*), weighing 3–5 kg each, were trained to perform a visuomotor step-tracking task in which elbow movements were made both with and without prior knowledge of the direction of the forthcoming movement. The behavioral paradigm has been described in detail previously (Alexander 1987). Its essential features were as follows. The monkey was seated comfortably in a primate chair, facing the screen of a CRT display (Hewlett-Packard 1322.) On every trial, the subject was required to execute two laterally directed limb movements to capture an eccentric target, with each such movement preceded by a hold interval (Fig. 2). The angular displacement of the working forearm, which rested on a torqueable handle ("manipulandum"), was reflected by the position of a cursor (1-mm spot of light) that moved horizontally across the center of the display in correspondence with flexion and extension movements of the elbow. The cursor would move 1° of visual angle (5.3 mm) for

PRE-INSTRUCTION
(IMPENDING TARGET UNKNOWN)

FIRST MOVEMENT
(MONKEY MOVES CURSOR TO RIGHT TARGET)

POST-INSTRUCTION
(PREPARED TO RECAPTURE RIGHT TARGET)

SECOND MOVEMENT
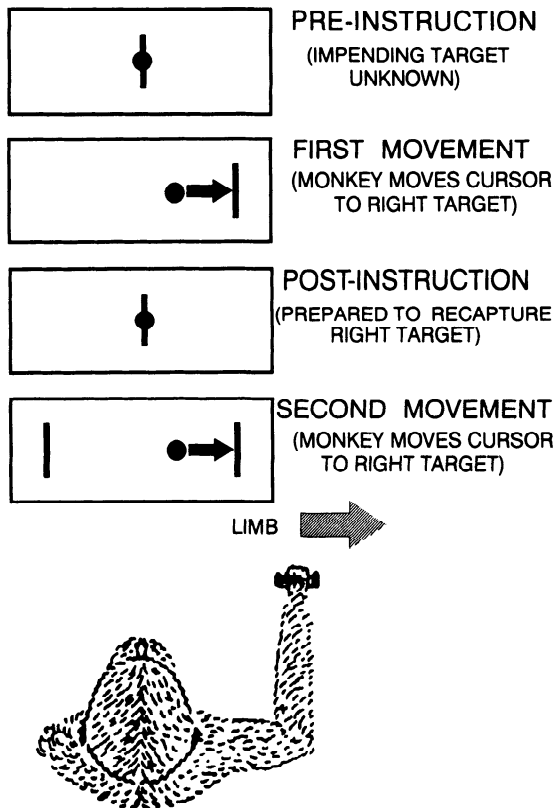(MONKEY MOVES CURSOR TO RIGHT TARGET)

LIMB

FIG. 2. Schematic of the display viewed by the monkey during performance of the visuomotor step-tracking task. The 4 rectangles show the CRT display in front of the monkey at 4 different times within a single trial. Targets are represented by vertical bars, and the cursor by a closed circle. See text for details.

every 1° of elbow displacement. The monkey was required to make such movements to align the cursor with a set of computer-controlled targets (0.5 × 7.5 mm vertical lines) presented sequentially on the display screen. Three targets were used in this paradigm, each defined by its location on the display screen: a "center" target was presented in the center of the screen; a "right" lateral target was presented 4 cm (7.5° of visual angle) to the right of the center position; and a "left" lateral target 4 cm to the left of center.

At the start of the trial, the center target appeared and the monkey "captured" it by making the appropriate arm movement to align the cursor with the target (Fig. 3). Throughout the ensuing "preinstruction" interval, the monkey held the cursor stationary over the center target for 1.5–3.0 s. During this time, the monkey could not predict the location of the upcoming target or the required direction of the next limb movement. When the center target shifted to one of the two (randomly selected) side locations, the monkey was required to capture this new target by moving his forearm in the appropriate lateral direction. After the first side target had been captured (and the cursor held in alignment with it for 500 ms), it shifted back to the center position, and the monkey was required to track the apparent target movement by returning the cursor to the center position. During the ensuing 1.5–3.0 s "postinstruction" interval, the monkey knew the direction of the upcoming (second) lateral movement of the trial because he was required to recapture the same target as for the first lateral movement. The simultaneous appearance of both side targets was the cue for the monkey to make the second lateral movement. After holding the cursor in alignment with the correct lateral target for 500 ms, the monkey was then required to recapture the center target (which reappeared as both lateral targets were extinguished), after which he received a liquid reward. For each trial, the durations of the pre- and postinstruction intervals were independently and completely randomized over the interval 1.5–3.0 s, with the use of the computer's random number generator.
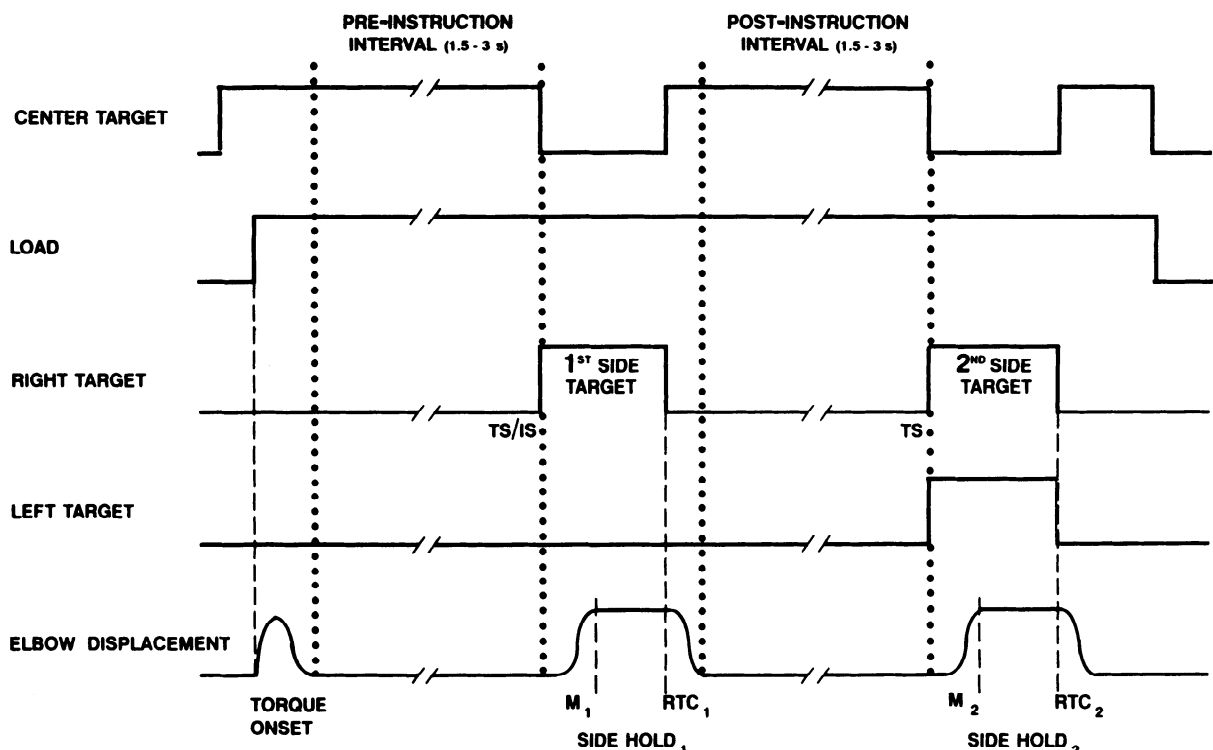
PRE-INSTRUCTION
INTERVAL (1.5 - 3 s)

POST-INSTRUCTION
INTERVAL (1.5 - 3 s)

CENTER TARGET

LOAD

RIGHT TARGET

1ˢᵀ SIDE TARGET

2ᴺᴰ SIDE TARGET

TS/IS

TS

LEFT TARGET

ELBOW DISPLACEMENT

TORQUE ONSET

M₁   RTC₁

SIDE HOLD₁

M₂   RTC₂

SIDE HOLD₂

FIG. 3. Schematic representing the sequence of events associated with a single behavioral trial. M₁, first lateral movement; M₂, second lateral movement; RTC₁, first return-to-center movement; RTC₂, second return-to-center movement; TS, trigger stimulus; IS, instruction stimulus.

The basic behavioral paradigm required the monkey to remember the location of the first side target, which was extinguished throughout the postinstruction interval, to be able to make the second lateral movement to the correct target when both side targets appeared. This feature of the task was designed to ensure that the sensory and motor conditions during the pre- and postinstruction intervals were identical and to guarantee the development of a directional "motor set" during the postinstruction interval. While movement accuracy was enforced with small ($\leq 1°$) capture windows, minimal constraints were placed on response time: the monkey was allowed 900 ms in which to capture each target after its presentation. To dissociate the directions of motor set (and limb movement) from the patterns of tonic (and phasic) muscle activation associated with task performance, some trials (in random order) included the application of continuous torque loads that either opposed or assisted the movements required by the paradigm. On these "loaded" trials, a constant torque (0.1 Nm) that loaded either the flexors or extensors of the elbow was applied at the beginning of the trial and was maintained throughout the trial, via the torqueable manipulandum (Fig. 3).

Surgical procedures

When behavioral training had been completed, each monkey was surgically prepared, by the use of aseptic technique and intravenous pentobarbital sodium anesthesia, for chronic, transdural recordings of single-cell activity from the arm regions of the putamen, the SMA, and/or the MC. In all aspects of their care, the monkeys were treated in accordance with the *Guiding Principles in the Care and Use of Animals* of the American Physiological Society.

With stereotaxic guidance, stainless steel recording chambers (18 mm ID) were positioned over burr holes that permitted access to the targeted regions. For the putamen and MC, the recording chamber was oriented parallel to the coronal plane and at an angle of 40–45° relative to the sagittal plane (i.e., approximately normal to the cortical surface), whereas for SMA recordings the chamber was oriented strictly vertically, parallel to both the sagittal and coronal planes. The chambers were affixed to the skull with dental acrylic. Bolts were embedded in the acrylic assembly to permit subsequent head fixation during the recording experiments. A scleral search coil, constructed from three loops of Teflon-coated stainless steel wire, was implanted to measure eye position (Judge et al. 1980).

Recording procedures

Action potentials were recorded extracellularly with glass-coated platinum-iridium microelectrodes (with impedances of 0.5–2 MΩ measured at 1,000 Hz) and displayed on a storage oscilloscope after passing through an analog delay network. This permitted visualization of the entire waveform, thereby facilitating the differentiation of the action potentials of cell bodies from those of fibers. The action potentials of each "isolated" neuron were discriminated from background activity with a time-amplitude window discriminator (Bak Electronics).

Output from a potentiometer coupled to the manipulandum provided a record of forearm position. Velocity signals were obtained by analog differentiation. Horizontal and vertical components of eye position were monitored with the scleral coil–magnetic-field technique, with the use of two magnetic fields oscillating at separate frequencies of 45 and 67 kHz (C-N-C Engineering).

Electromyographic (EMG) activity was recorded differentially from Teflon-insulated stainless steel wires inserted percutaneously in separate recording sessions. The EMG activity was amplified, filtered (100–2,000 Hz), and rectified and then processed by a sample-and-hold integrator (Bak Electronics).

Microstimulation through the recording electrode was used to help identify the "arm" regions of the different motor areas. Currents were limited to <45 µA, delivered in 100–200 ms trains of balanced bipolar pulse pairs (200-µs cathodal pulse/100-µs gap/200-µs anodal pulse) at a frequency of 400 Hz. For all three motor areas, microelectrode penetrations were made according to either a 0.5 or a 1.0 mm X/Y grid. Microstimulation was carried out systematically at 0.5-mm intervals along most penetrations through both the SMA and MC. In the putamen, however, where much of the arm region is not microexcitable (Alexander and DeLong 1985b), we placed less emphasis on this approach, relying instead on a manual sensorimotor examination to help characterize the somatotopic features of the neurons encountered along each track (see below).

Data acquisition

Several days after the monkey had fully recovered from surgery, experimental recordings were begun. Administration of the behavioral paradigms and collection of neural and analog data were controlled by a laboratory computer (LSI-11/73). The times of occurrence of discriminated action potentials were recorded with a temporal precision of 1 ms. Analog data, which included forearm velocity signals, horizontal and vertical eye position signals, and EMG activity, were all sampled at 100 Hz. All experimental data, including behavioral event codes, neuronal activity, and analog data, were collected on 20-megabyte disks and then transferred to magnetic tape for archival storage and subsequent off-line analysis on a second computer (VAXstation 3200).

During recording sessions, the monkey's head-fixation bolts were attached to a restraining device. Under the control of a hydraulic microdrive (Narishige MO-95), a microelectrode was advanced through the dura and into the brain until the target structure was identified. The external border of the putamen was identified by the spontaneous neuronal activity patterns that are both characteristic of this nucleus and easily differentiated from those of adjacent structures. MC was identified by its characteristically low threshold of microexcitability (generally <20 µA). In the vertical penetrations employed in studies of the SMA, the arm region of the SMA was generally first encountered 1–3 mm below the cortical entry point. With the monkey performing the basic behavioral paradigm, the microelectrode was slowly driven deeper into each targeted structure, while the acoustically transduced neuronal activity was monitored continuously for signs of task relatedness. If an isolated neuron was judged to be task related, based on on-line inspection of rastered neuronal activity, a complete data file was collected. As there were two possible target locations and three loading conditions (no load, flexors loaded, extensors loaded), there were six trial types. Trials of all six classes were presented in a balanced but unpredictable sequence until data had been collected from at least eight (usually 10–15) repetitions of each trial type.

After the task-related data had been collected from each neuron, its sensorimotor response properties were usually assessed outside the behavioral paradigm by manual administration of a detailed sensorimotor examination of the leg, arm, face, and trunk, as described previously (Alexander and DeLong 1985b). Briefly, this consisted of observing the cell's response to passive displacement of the manipulandum, followed by release of the working arm from its restraints and assessment of the relation of cell discharge to passive joint rotation, muscle palpation, tendon taps, and cutaneous stimulation, as well as to active reaching and grasping movements of the upper and lower extremities.

After the sensorimotor examination, microstimulation was carried out at most recording sites in both the SMA and MC and

at some sites in the putamen. In addition, in both cortical areas microstimulation was also carried out systematically at 0.5-mm intervals along most penetrations, irrespective of the locations of task-related activity. This was done as the microelectrode was being withdrawn from each track, after single-cell recording had been completed for that penetration.

Small electrolytic marking lesions were made at one or more points along selected microelectrode tracks by passing 4–10 μA of direct cathodal current through the microelectrode tip for 10–20 s.

In separate sessions that preceded and followed the period of single-cell recording from each chamber, EMG activity was recorded during task performance from the following muscles: (upper extremity) brachialis, long head of biceps, lateral head of triceps, long head of triceps, brachioradialis, acromiodeltoid, spinodeltoid, pronator teres, pectoralis major and minor, supraspinatus, infraspinatus, atlantoscapularis anterior, latissimus dorsi, teres major, extensor carpi radialis, extensor carpi ulnaris, flexor carpi radialis, flexor carpi ulnaris, extensor digitorum communis, flexor digitorum profundus, and superficialis, palmaris longus; (lower extremity) quadriceps femoris, semitendinosus, biceps femoris, gastrocnemius, tibialis anterior; (head and neck) splenius capitus, cervical rhomboids, cervical paraspinous, trapezius, sternocleidomastoid, cleidooccipitalis, temporalis; (trunk) serratus anterior, panniculus carnosus, thoracic paraspinous, and lumbar paraspinous.

After the final experimental session, each monkey was deeply anesthetized with pentobarbital and perfused transcardially with normal saline followed by 10% neutral formalin. Each brain was blocked, frozen, and sectioned in the coronal plane. The 40-μm sections were stained with cresyl violet. Recording sites were reconstructed by localizing 1) the electrolytic microlesions, 2) the linear gliosis associated with each microelectrode track, and 3) the tracks left by pins inserted preterminally to mark the cardinal axes of each recording chamber.

Data analysis

All data files containing task-related neuronal activity were subjected to computerized analysis. Movement- and stimulus-aligned rasters and histograms of each cell's task-related activity were inspected and evaluated, but final classification of the cell's functional properties was based on the following statistical analysis. For each neuron, the mean discharge rate was computed separately for each of the following epochs (see Fig. 3) of every recorded trial: 1) preinstruction interval; 2) first movement interval; 3) postinstruction interval; 4) second movement interval. The rates associated with these epochs were used to analyze each cell's task-related properties by employing the discharge rate as the dependent variable in a 3-way analysis of variance (ANOVA): 4 epochs [2 motor conditions (move 1 vs. move 2) and 2 instruction conditions (pre- vs. postinstruction)] × 2 directions (right vs. left target) × 3 loading conditions (no load vs. flexor load vs. extensor load), with repeated measures because of the repeated (minimum 8) presentations of each trial type. The predefined significance level used for determining each cell's functional classification was $P < 0.001$. This level of significance was chosen after preliminary tests revealed that using lower levels of significance with this type of analysis resulted in the identification of some task-related neuronal "responses" that were too weak to be evident in the visual displays (rasters and histograms) of neuronal activity. [Further details on the data analysis procedures are provided in the following paper (Crutcher and Alexander 1990).]

The times of occurrence of epoch-specific changes in neuronal activity were computed on a trial-by-trial basis, using algorithms described in the following paper. Latencies of changes in neuronal activity were compared across nuclei by means of t tests.

Data from individual neurons were included in the final data base if, and only if, all of the following criteria were fulfilled: 1) the neuron showed sustained discharge during the postinstruction interval and/or the movement interval that was significantly different from that in the preinstruction interval; 2) if the neuron showed only movement-related activity, such activity was directionally selective; 3) physiological data from the recording site and/or surrounding sites confirmed that the cell had been located within a region of arm representation; 4) histological reconstruction demonstrated that the recording site had been located within the putamen, the MC, or the SMA. Identification of the two cortical motor areas was based on sulcal landmarks and standard cytoarchitectonic criteria, although we did not perform quantitative cytometric analyses. In addition, to ensure that none of the cells identified as being in MC were actually located within caudal premotor cortex, we included in the MC category only those precentral neurons whose activity was recorded at or caudal to sites where microstimulation evoked arm movements at low threshold, i.e., ≤ 30 μA (see Weinrich and Wise 1982).

Categorical comparisons of the proportions of different functional classes of neuronal activity were made *between* the three motor areas by means of χ^2 tests. Where appropriate, detailed comparisons were made within contingency tables by the use of log odds ratios. T tests were used to determine whether there were differences, *within* each motor area, in the spatial distributions of neurons belonging to the various functional classes.

RESULTS

Task performance

Throughout the period of data collection, all subjects showed $\geq 98\%$ accuracy in capturing the correct target at the end of the postinstruction interval (i.e., there were $\leq 2\%$ directional errors). Performance accuracy was no different for loaded or unloaded trials.

The patterns of muscular activity, as indicated by EMGs recorded during task performance, were similar for the first and second movements, as were the EMG patterns associated with the pre- and postinstruction intervals. Both of these features are illustrated by the task-related activity of a prime extensor of the elbow (m. triceps lateralis) shown in Fig. 4. Periodic assessments of task-related EMG activity, which were carried out in all subjects both before and after recording from each separate motor area, confirmed that the patterns of task-related activity in the prime movers (elbow flexors and extensors) were consistently dissociated from the direction of limb movement throughout the periods of data collection.

Of the 39 different muscle groups sampled in this study, only 3 (cervical rhomboid, latissimus dorsi, teres major) showed significant differences between the pre- and postinstruction intervals, and in two (latissimus dorsi, teres major) the changes were bidirectional. All three of the muscles that showed differential activation in the pre- versus postinstruction intervals showed *maximal* activation during the movement interval. No muscles showed directional activation exclusively during the postinstruction interval, in contrast to the neurons that showed purely "preparatory" activity (see below).

For this study, the emphasis was placed on each monkey's performance accuracy: there were no constraints on the subject's eye movements, and only minimal constraints on reaction time (RT) and movement time (combined
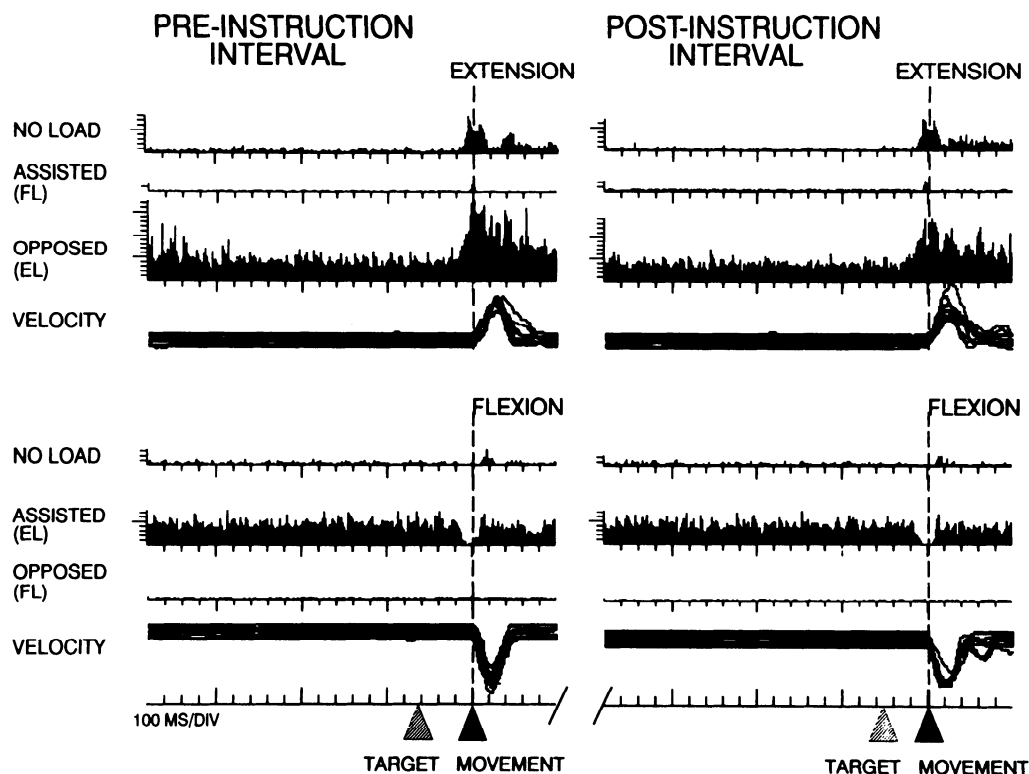
TASK - RELATED EMG ACTIVITY

FIG. 4. Electrical activity of the lateral triceps muscle (a prime extensor of the elbow), monitored during performance of the behavioral paradigm. On loaded trials, a continuous torque that either opposed or assisted the required lateral movements was applied to the working forearm via the torqueable handle. One-third of the trials were unloaded. Trials of all 6 classes (3 loading conditions × 2 directions of movement) were presented to the monkey in a balanced but unpredictable sequence, although they are grouped here and in subsequent raster displays according to class. The histograms represent the average triceps EMG activity (in relative voltage units) for 10 repetitions of each of the 6 classes of trials. Below the EMG records for each direction are the corresponding single trial records of forearm velocity, aligned on movement onset (extension upward, flexion downward). EL, extensors loaded; FL, flexors loaded.

RT + MT ≤ 900 ms). Scleral search coil recordings from each monkey showed frequent, randomly timed saccades (2–5 per trial) between the center target and *both* lateral target locations throughout the pre- and postinstruction intervals. The frequency of saccades was slightly higher in the postinstruction interval, but there was no directional preponderance associated with the location of the correct target. Despite the frequent saccades, gaze was fixed on the center target throughout most of the durations of the pre- and postinstruction intervals, and there were no consistent differences between the proportions of time in which the gaze was fixed on the correct versus the incorrect target. After the presentation of the lateral target(s) at the end of the pre- and postinstruction intervals, there was invariably a saccade to the correct target that preceded the corresponding limb movement in that direction.

Data base

Of the total sample of 741 neurons that showed task-related activity, 222 were located within the SMA, 202 within MC, and 317 within the putamen. Their distributions across the different monkeys and hemispheres are shown in Table 1. As indicated above (see METHODS), all neurons included within the database were located within a region of arm representation, as determined by the sensorimotor fields of local neurons and/or the loci of microstimulation-induced movements.

Neurons were classified as showing "preparatory" activity if their discharge rates during the postinstruction interval differed significantly from their preinstruction rates. Neurons whose discharge rates during the first and/or second movement interval (see Fig. 3) differed significantly

TABLE 1. *Database: cells sampled by region/hemisphere*

Subject/hemis.	A/R	B/L	B/R	C/L	D/L	D/R	E/L	Totals
SMA		47	60				115	222
MC		29	39	106			28	202
Putamen	44		56	83	35	81	18	317

A–E, subjects used in study; R and L, right and left hemisphere; SMA, supplementary motor area; MC, primary motor cortex.

TABLE 2. *Classification of cells according to PREP versus MVT discharge properties*

	SMA	MC	Putamen
PREP activity only	71 (32.0)	22 (10.9)	77 (24.3)
MVT activity only	101 (45.5)	127 (62.9)	212 (66.9)
PREP and MVT activity	50 (22.5)	53 (26.2)	28 (8.8)
Total	222 (100.0)	202 (100.0)	317 (100.0)
	[$P < 0.0001$]	[$P < 0.0001$]	
	[	$P < 0.0001$	]

Numbers in parentheses are percentages. PREP, preparatory; MVT, movement-related; other abbreviations, see Table 1.

from their preinstruction rates were classified as showing "movement-related" activity. The proportions of task-related neurons in each of the three motor areas that showed only preparatory activity, only movement-related activity, or both types of activity are shown in Table 2.

Each of the three motor areas was found to contain substantial proportions of neurons with preparatory activity, either alone or in combination with movement-related activity. The SMA contained a larger proportion of such cells (54.5%) than did MC (37.1%) or the putamen (33.1%). The apparent differences in proportions of different cell types among the three motor areas were all highly significant, as indicated by the results of a x^2 analysis that are shown in Table 2. Analysis of log odds ratios revealed that the relative proportion of cells that showed only preparatory activity (vs. combined preparatory and movement-related activity) was significantly higher both in SMA and putamen than in MC [MC vs. SMA: $\alpha = 0.29$; confidence interval (C.I.) = 0.54, 0.16; $P < 0.0001$; MC vs. putamen: $\alpha = 0.15$;

C.I. = 0.29, 0.08; $P < 0.0001$]. In this respect, the SMA and putamen differed only slightly ($\alpha = 1.94$; C.I. = 3.40, 1.10; $P = 0.021$).

Locations of task-related neurons

Along individual microelectrode penetrations through the SMA, MC, and putamen, neurons that showed preparatory activity were intermingled with those that showed movement-related activity. There were, however, significant tendencies in all three areas for cells with preparatory activity to be located *more rostrally* than those with movement-related activity.

The entry points for the microelectrode tracks through the two cortical areas are shown in Fig. 5. The SMA data were obtained primarily from the mesial wall of the hemisphere; only a small number of penetrations extended to the dorsal bank of the cingulate sulcus, and none to the ventral bank. Within the arm region of the SMA, the cells that showed preparatory activity, either alone or in combination with movement-related activity, tended to be located more rostrally than those that showed only movement-related activity (Table 3), although there was substantial overlap. This is illustrated in Fig. 6, in which it is also apparent that the sites from which arm movements could be evoked by microstimulation were concentrated caudally, in contrast to the more rostral distribution of preparatory cells. A x^2 analysis confirmed that the microexcitable sites were concentrated behind the genu of the arcuate sulcus ($x^2 = 76.1$, df = 1, $P < 0.0001$), a landmark that was found useful in several recent studies of the SMA (Dum and Strick 1990; Hummelsheim et al. 1986; Mitz and Wise 1987).

The locations of MC cells with preparatory and/or movement-related activity are shown in Fig. 7. Although
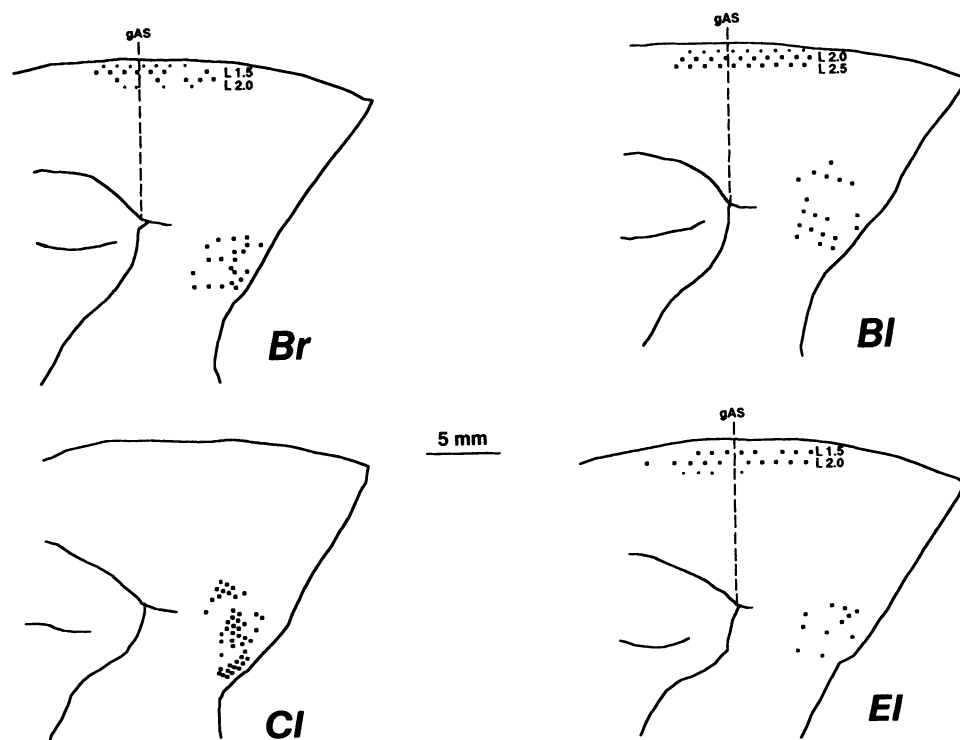

FIG. 5. Locations of entry points for microelectrode penetrations in which cells that showed task-related activity were found within the arm region of the SMA and MC. For each of the 3 hemispheres in which the SMA was studied, data from 2 adjacent parasagittal planes were selected for illustration of the histological reconstructions of the recording/stimulation sites, as shown in Fig. 6. The entry points for penetrations in these planes (Br: L 1.5, L 2.0; Bl: L 2.0, L 2.5; El: L 1.5, L 2.0) have been designated by large dots, as with the penetrations through MC. Small dots designate the other SMA tracks from which comparable data were obtained but which were not included in Fig. 6 for clarity of exposition.

TABLE 3. *Relative rostrocaudal location of cells with PREP vs. MVT activity*

	PREP Only	PREP + MVT	MVT Only
SMA*	1.5 ± 2.4	0.1 ± 3.2	−1.2 ± 2.7
	[$P < 0.1$]	[$P = 0.01$]	
	[$P < 0.001$		]
MC†	3.4 ± 1.7	3.0 ± 1.8	2.5 ± 1.7
	[NS]	[NS]	
	[$P = 0.02$		]
Putamen‡	17.4 ± 2.0	16.9 ± 2.2	16.3 ± 2.1
	[NS]	[NS]	
	[$P < 0.001$		]

Values are means ± SD. The number of cells in each category is indicated in Table 2. NS, not significant; other abbreviations, see Tables 1 and 2. *Distance in millimeters rostral (+) or caudal (−) to the coronal plane through the genu of the arcuate sulcus. †Perpendicular distance in millimeters rostral to the central sulcus. ‡Anteroposterior level in standard stereotaxic coordinates relative to the interaural plane.

the distributions of the various functional classes appear relatively uniform in that figure, *t* tests revealed that the cells that showed only preparatory activity tended to be significantly more distant from (rostral to) the central sulcus than those that showed only movement-related activity (Table 3).

The locations of putamen neurons with preparatory and/or movement-related activity are indicated in Fig. 8. There was a significant tendency for cells that showed only preparatory activity to be located more rostrally than those with only movement-related activity (Table 3), although the two classes overlapped to a considerable degree.

Sensorimotor fields of cells with preparatory activity

Cells with task-related activity were classified according to their sensorimotor fields, as determined by the results of sensorimotor examinations conducted outside the computer-controlled behavioral paradigm. The results are summarized in Table 4. Each cell that was tested with a sensorimotor examination was classified according to whether it could be shown to discharge consistently in relation to active and/or passive movements of a specific body part. If a cell appeared to be related to active arm movements, but the sensorimotor field could not be localized specifically to the elbow, the shoulder, or "distal" (wrist and/or fingers) structures, it was classified as "active arm." Although many of the preparatory cells in each motor area had discrete sensorimotor fields or could at least be classified as active arm (Table 4), most of these were cells with combined preparatory and movement-related activity. Few of the cells that showed *only* preparatory, without accompanying movement-related activity, had discrete somatosensory or motor fields restricted to a single joint (SMA, 7 cells, all "elbow"; MC, 7 cells, including 4 elbow, 2 shoulder, and 1 distal; putamen, 3 cells, including 2 elbow and 1 shoulder).

Directionality of preparatory activity

In all three motor areas, task-related preparatory activity was in most cases directionally selective (Table 5). Examples of directional preparatory activity in SMA, MC, and putamen are shown in Figs. 9–11. For these cells the selective activations during the postinstruction interval were manifested by a preponderance of activity in anticipation of one direction of movement (flexion or extension). The SMA neuron whose activity is illustrated in Fig. 9, for ex-
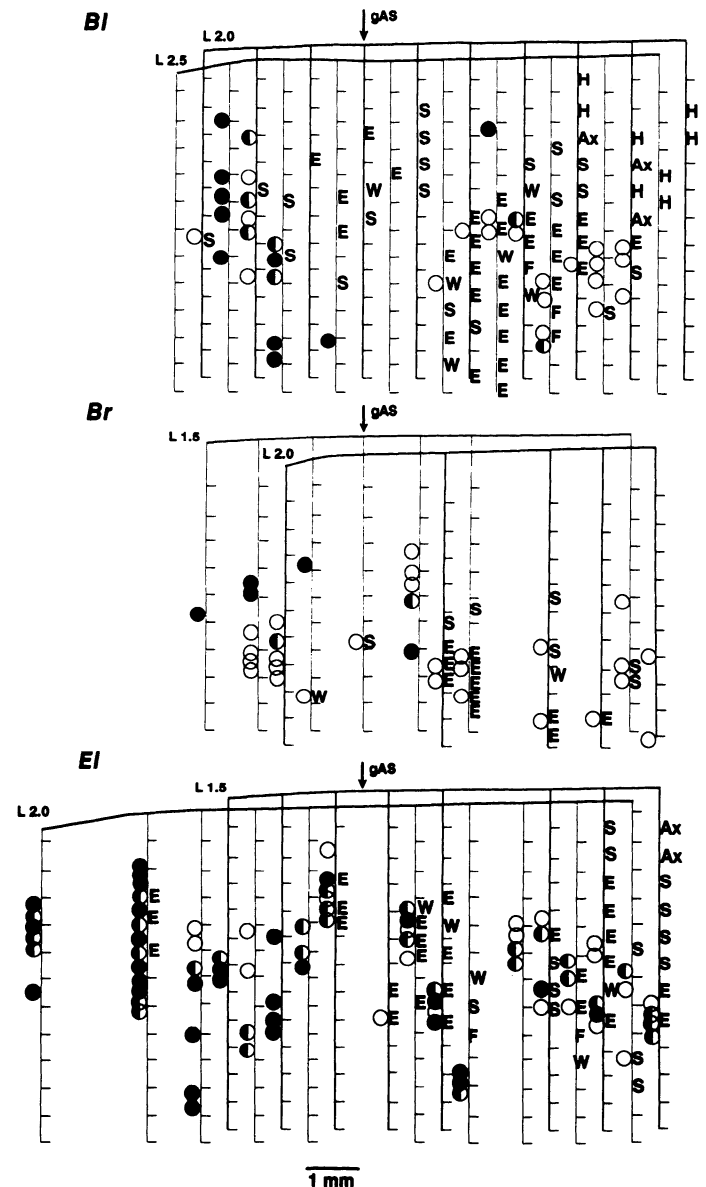

FIG. 6. Locations of SMA neurons with preparatory activity (●), movement-related activity (○), and combined preparatory and movement-related activity (◉). The 3 panels show data from the 3 hemispheres explored in this study. In each case, data from 2 adjacent parasagittal planes are presented. The more lateral plane is displaced slightly downward. The location of each set of tracks relative to surface landmarks is shown in Fig. 5. In the present figure, rostral is to the left, regardless of whether data are from the right or left hemisphere. The coronal plane through the genu of the arcuate sulcus is indicated (gAS). Horizontal dashes indicate negative microstimulation sites. Letters denote the movements evoked at threshold where microstimulation was effective: E, elbow; S, shoulder; W, wrist; F, fingers; H, hip; Ax, axial.
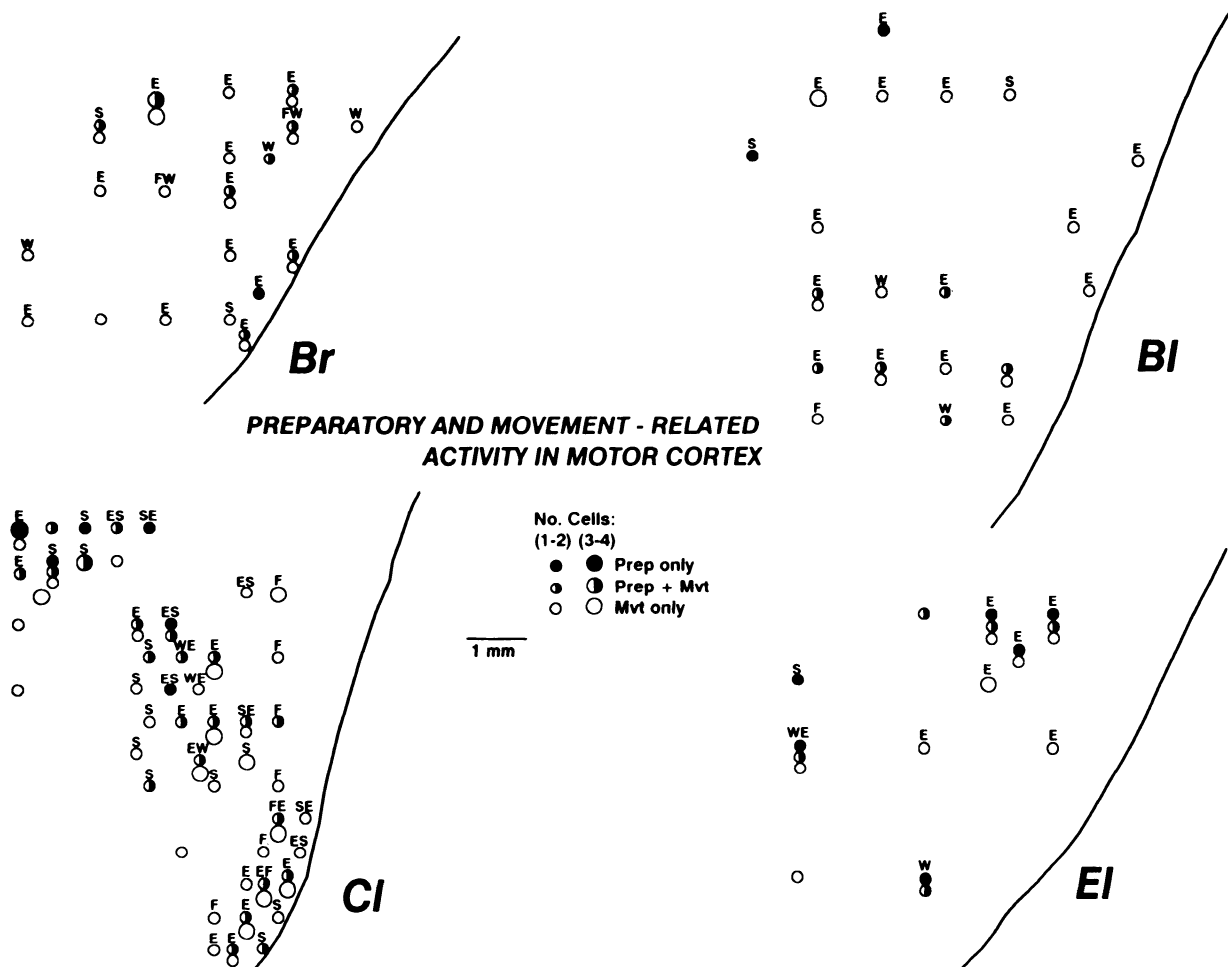
FIG. 7.   Locations of MC neurons with preparatory, movement-related, and combined preparatory and movement-related activity. Locations are indicated in terms of the cortical entry points of the microelectrode penetrations. The separate panels show data from the 4 hemispheres explored in this study. The central sulcus is indicated, and rostral is to the left (regardless of whether data are from the right or left hemisphere). Locations of the recording areas relative to other surface landmarks are shown in Fig. 5.

ample, showed a sustained increase in discharge rate throughout the postinstruction interval prior to preplanned extension movements, irrespective of the loading conditions, and a corresponding reduction in activity on flexion trials. Such reciprocal directional effects were seen commonly in all three motor areas. Figure 10 shows the directionally selective, load-independent activation of an MC neuron during the postinstruction interval on flexion trials.

The same pattern of activity is seen in Fig. 11, which shows the task-related discharge of a putamen neuron.

As indicated in Table 5, the proportion of preparatory activity related to flexion movements was roughly equivalent to that related to extension movements in each of the three motor areas examined in this study. X^2 analyses revealed that there were no significant differences between SMA, MC, and putamen in terms of their relative propor-

TABLE 4.   *Sensorimotor fields of cells with preparatory activity**

	SMA	MC	Putamen
Elbow	9 (24)	23 (41)	17 (27)
Shoulder	4 (11)	9 (16)	1 (1)
Distal	1 (3)	5 (9)	0 (0)
Active arm	17 (46)	16 (29)	17 (27)
Negative	6 (16)	3 (5)	29 (45)
Total tested	37 (100)	56 (100)	64 (100)
Not tested	84	19	41
Grand total	121	75	105

Numbers in parentheses are percentages. Abbreviations, see Table 1. *Includes cells with combined preparatory and movement-related activity.

TABLE 5.   *Directional selectivity of preparatory activity*

	SMA	MC	Putamen
Discharge precedes			
Flexion movements	55 (45)	38 (51)	39 (37)
Extension movements	49 (41)	27 (36)	43 (41)
Both movements	17 (14)	10 (13)	23 (22)
Total	121 (100)	75 (100)	105 (100)
	[NS]	[NS]	
	[NS]		

Numbers in parentheses are percentages. Abbreviations, see Table 1.

FIG. 8. Recording sites of cells that showed preparatory activity (●), movement-related activity (○), or both (◉) within the arm region of the putamen. The microelectrode tracks from all subjects are shown in this schematic representation of the left putamen (regardless of whether data are from the right or left hemisphere). The monkey/hemisphere designation for each track is indicated at the left margin of each coronal plane. Recording sites are plotted along the different tracks in anteroposterior planes at 1-mm intervals extending from A10 to A21. The scale is in millimeters.

PRE-INSTRUCTION INTERVAL

POST-INSTRUCTION INTERVAL

FIG. 9. Raster display of an SMA neuron that showed directional preparatory activity. Each small tick indicates the occurrence of a single action potential, and each row represents the neuronal activity recorded during 1 trial. The large ticks indicate the times of occurrence of the target shifts that triggered the first and second center-to-side movements of each trial. The activity associated with the first half of each trial is aligned on the onset of the first lateral movement of the forearm, and that of the second half of the trial is aligned on the onset of the second lateral movement. The rasters are sorted according to class and reaction time, with the use of the same conventions as in Fig. 4. This cell showed a sustained increase in discharge throughout the postinstruction interval on extension trials, irrespective of the loading conditions, and a corresponding reduction in activity during the postinstruction interval on flexion trials.

tions of "flexion" versus "extension" versus "bidirectional" preparatory neurons.

In all three motor areas, the preparatory activity observed in this study showed no evidence of temporal patterning, and there was no indication in any of the cells of an anticipatory build up in activity prior to the second lateral movement. Rather, the discharge rates of cells with preparatory activity remained relatively constant throughout the postinstruction interval.

For each cell that showed both preparatory and movement-related discharge, we compared the directionality of the two types of activity. Of the cells in which both the preparatory and the movement-related discharge were unidirectional, most showed the same directionality for both types of activity (SMA 81%, 35/43; MC 70%, 33/47; putamen 87%, 20/23). The task-related discharge of an MC neuron that showed this pattern of activity is illustrated in Fig. 12. This cell showed maximal discharge related to the preparation and execution of extension movements and corresponding reductions in activity on flexion trials. The activity of an MC neuron whose preparatory and movement-related responses had opposite directionalities is il-

PRE-INSTRUCTION INTERVAL
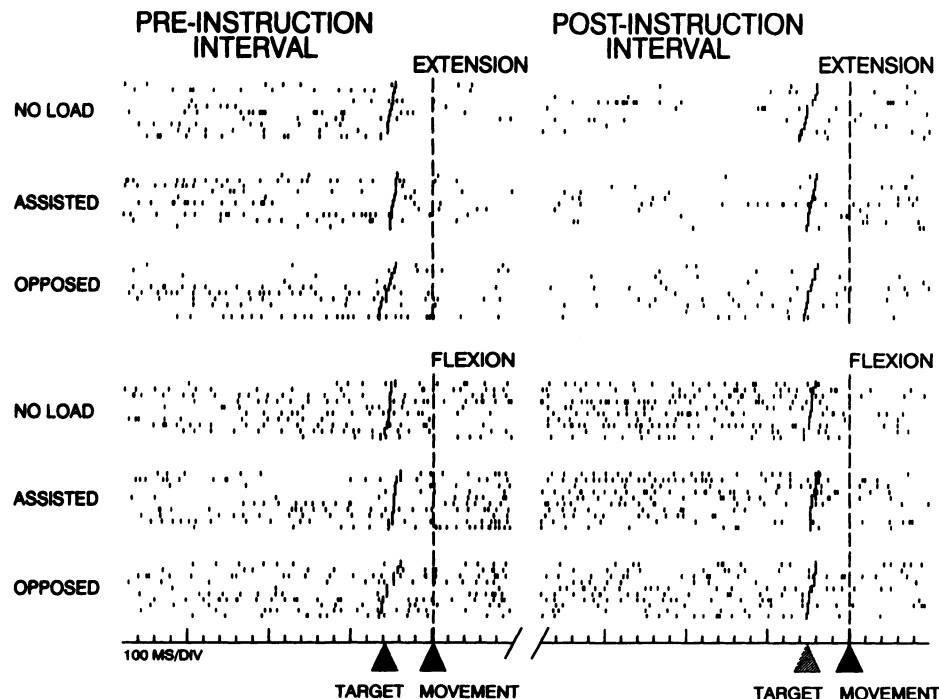
POST-INSTRUCTION INTERVAL

FIG. 10. Directional preparatory activity of a neuron in the arm region of motor cortex. This cell showed a selective increase in activity throughout the postinstruction interval on flexion trials. Conventions are the same as in Fig. 9.
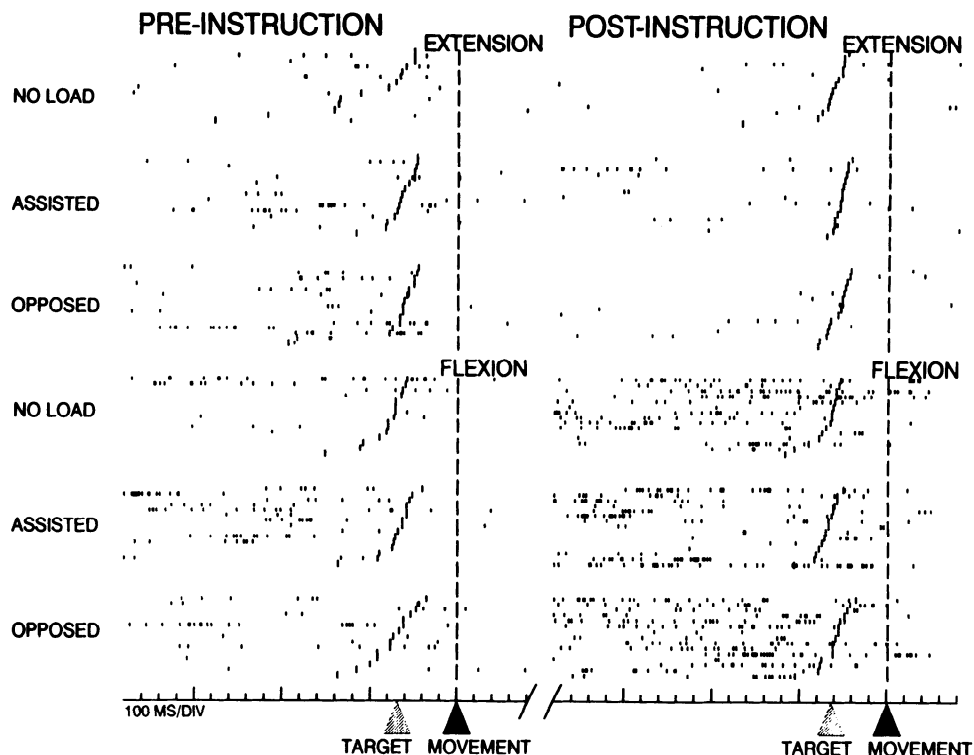
PRE-INSTRUCTION

POST-INSTRUCTION

FIG. 11. Directionally selective preparatory activity recorded from a putamen neuron, which showed a sustained increase in discharge rate throughout the postinstruction interval preceding flexion movements. Conventions are the same as in Fig. 9.

lustrated in Fig. 13. This cell showed preparatory activity preceding preplanned (second lateral) flexion movements and movement-related discharge associated with extension movements. x^2 analyses revealed that the relative proportions of cells with the same directionality versus those with opposite directionality did not differ significantly among the three motor areas.

Effects of loading on preparatory activity

In each of the three motor areas, most of the cells with preparatory activity that were tested with continuous torque loads (that opposed or assisted the task-related movements) showed no loading effects during either the pre- or postinstruction intervals (SMA 80%, 28/35; MC

PRE-INSTRUCTION INTERVAL
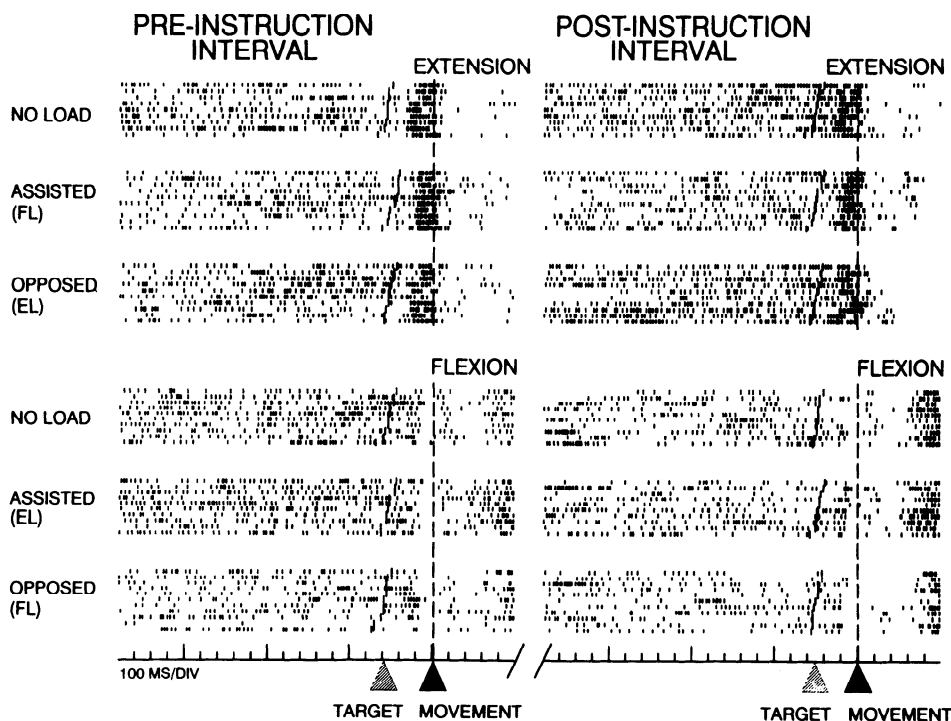
POST-INSTRUCTION INTERVAL

FIG. 12. A motor cortex neuron that showed both preparatory and movement-related activity. Both types of activity showed the same directional selectivity; i.e., both were seen only on extension trials. The preparatory activity seemed to be slightly reduced on trials in which the flexors were loaded, but this was not statistically significant. Conventions are the same as in Fig. 9.
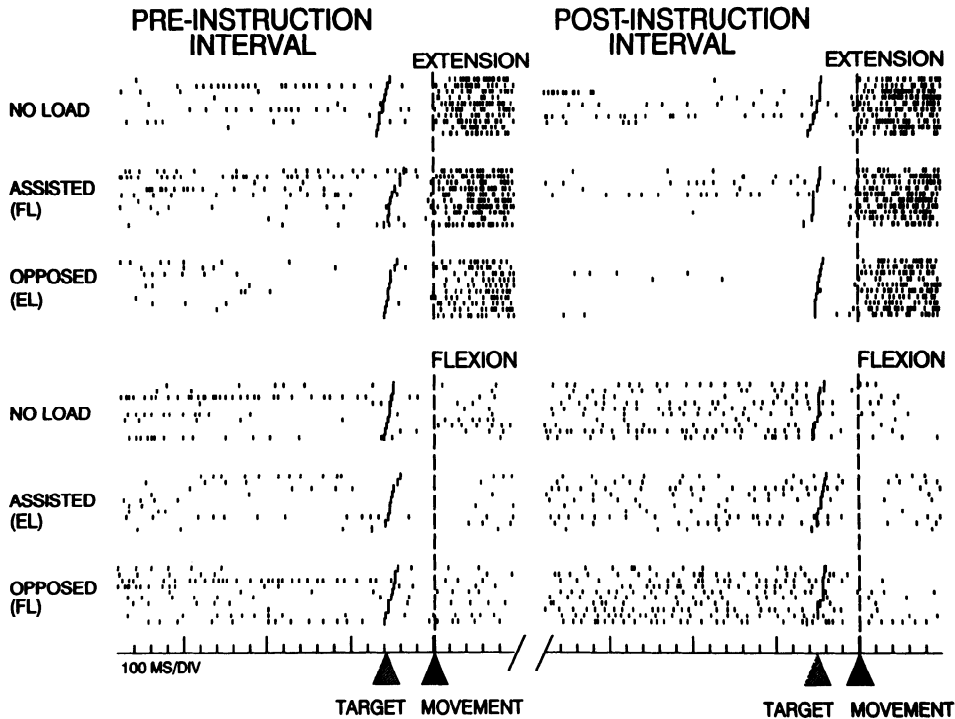
FIG. 13. Motor cortex neuron whose preparatory and movement-related responses had opposite directionalities. This cell showed selective preparatory activity preceding the second (preplanned) lateral movement on flexion trials and movement-related discharge on extension trials. Both types of activity appeared to be slightly reduced on trials in which the extensors were loaded (EL), but this was only significant ($P < 0.001$) for the preparatory activity (as well as the preinstruction activity). Conventions are the same as in Fig. 9.

83%, 48/58; putamen 84%, 80/95). A small proportion of preparatory cells in each area showed weak effects of such loads throughout both the pre- and postinstruction intervals (SMA 17%, MC 15%, putamen 12%). An example is shown in Fig. 14. This putamen neuron showed increased preparatory activity prior to extension movements and decreased activity prior to flexion movements. Superimposed on this was a decrease in activity with extensor loads during both the preinstruction and postinstruction intervals. Such

"additive" load effects, although statistically significant ($P < 0.001$ main effect for load in ANOVAs; see METHODS), were difficult to discern in the visual displays (rasters and histograms) of neuronal activity. Moreover, as these effects were not confined to the postinstruction interval, they did not appear to be preparatory in nature. Rather, these additive load effects appeared merely to reflect the current loading conditions.

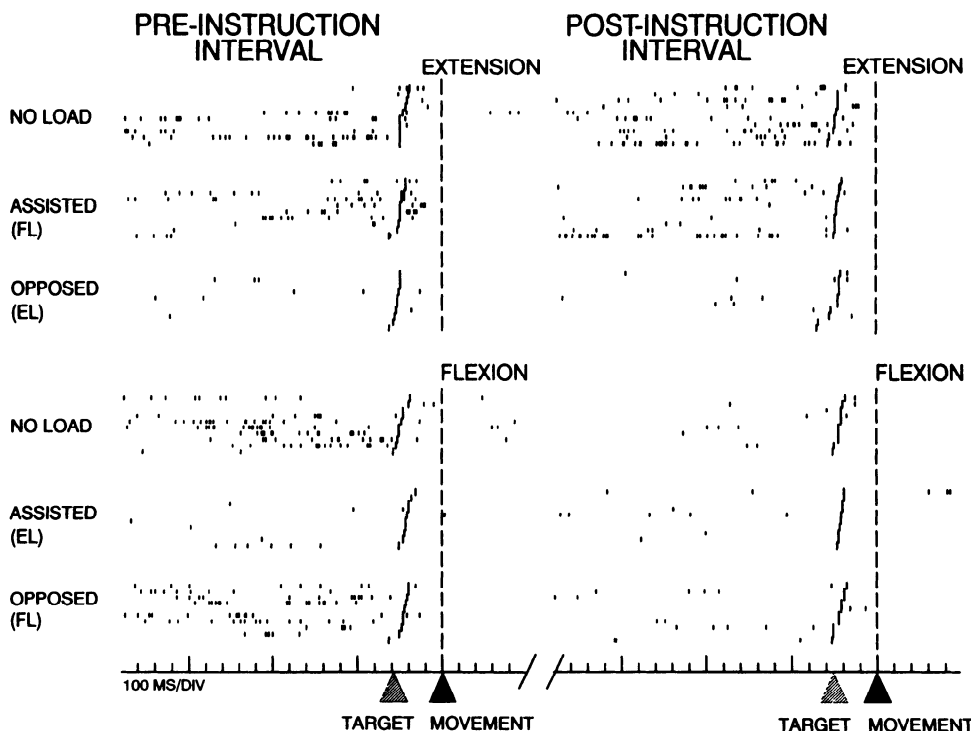One cell each in the SMA and MC and four cells in the

FIG. 14. Additive load effects in a putamen neuron with directional preparatory activity. The preparatory activity that occurred on extension trials was combined with a tonic decrease in activity throughout trials in which the extensor muscles were loaded. FL, flexors loaded throughout trial; EL, extensors loaded. Other conventions as in Fig. 9.

putamen showed significant "nonadditive" load effects that *were* confined to the postinstruction interval. These rare effects, which did appear to be preparatory in nature, were even more difficult to discern in the raster displays than their additive counterparts (and are therefore not illustrated).

Relative timing of preparatory activity

The times of onset and offset of preparatory activity were computed on a trial-by-trial basis, with the use of the algorithms described in the following paper (Crutcher and Alexander 1990). The median values for each cell were then computed. The onset latency was measured from the end of the preceding centering movement, after the first return-to-center target shift (see Fig. 3). The offset latency was measured from the time of the second center-to-side target shift (i.e., the time at which both side targets were presented, which marked the end of the postinstruction interval). For some cells with associated movement-related activity, the precise time of offset of the preparatory activity could not be computed accurately (i.e., when there was little or no pause between the end of the preparatory activity and the onset of movement-related activity).

The distributions of median onset and offset latencies for the three motor areas are presented in Figs. 15 and 16, respectively. Although the overlap of the distributions was extensive, the average onset of directional preparatory activity in the SMA was significantly earlier than that in MC, which in turn was earlier than that in the putamen (Table 6). The average offset latency for directional preparatory activity was significantly earlier in both the SMA and MC than in the putamen.
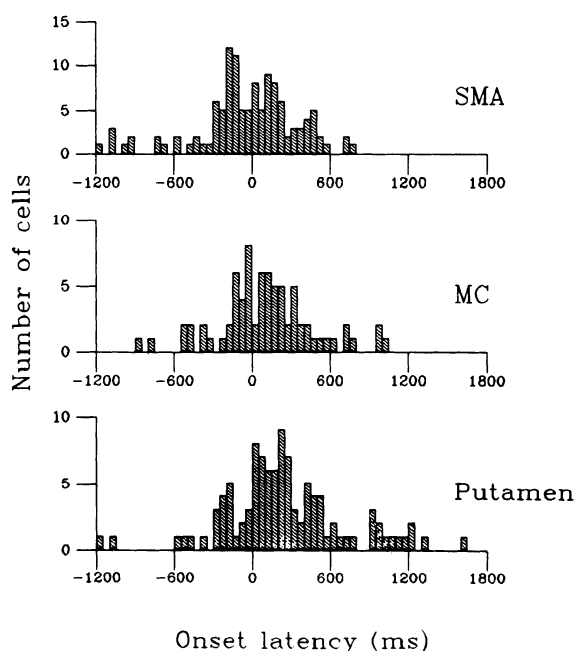

Onset latency (ms)

FIG. 15.   Distributions of preparatory onset latencies observed in each of the 3 motor areas. Time 0 is the time of the beginning of the postinstruction period (the end of the first return-to-center movement).
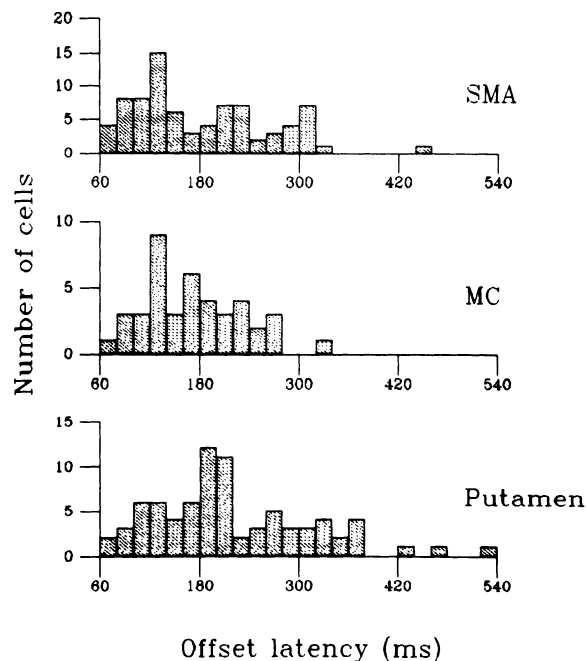

Offset latency (ms)

FIG. 16.   Distributions of preparatory offset latencies observed in each of the 3 motor areas. The latencies are relative to the end of the postinstruction period (the time of presentation of both side targets).

DISCUSSION

Preparatory activity coding movement direction independent of loading conditions

Neurons that showed directionally selective preparatory discharge were found to be distributed across the SMA, MC, and putamen, with substantial proportions of such neurons in all three areas. Of cells showing only preparatory activity, the largest proportion was seen in the SMA and the lowest in MC. This is consistent with previous reports indicating more set-related activity in SMA than MC (Tanji 1985; Tanji and Kurata 1985; Tanji et al. 1980).

TABLE 6.   *Timing of preparatory activity*

	SMA	MC	Putamen
Onset latencies[e]			
Median, ms[b]	−25	90	205
Mean ± SE, ms[c]	−40 ± 34	95 ± 43	243 ± 44
n[d]	121	75	205
	[$P = 0.02$]	[$P = 0.02$]	
	[	$P < 0.001$	]
Offset latencies[e]			
Median, ms[b]	154	168	200
Mean ± SE, ms[c]	180 ± 9	173 ± 9	219 ± 11
n[d]	80	42	79
	[NS]	[$P = 0.002$]	
	[	$P = 0.007$	]

Abbreviations, see Tables 1 and 3. [a]Latencies of onset of preparatory discharge measured from the end of the preceding centering movement; [b]median value of the median latencies for all cells; [c]mean value of the median latencies for all cells; [d]cells for which the time of onset or offset of preparatory activity could be clearly identified; [e]latencies of offset of preparatory activity measured from the end of postinstruction hold period.

The preparatory activity appeared to be related primarily to the preplanned *direction* of upcoming cursor/forelimb movements that were used to capture visual targets. This observation is consistent with previous studies in the SMA (Tanji and Kurata 1985; Tanji et al. 1980), MC (Georgopoulos et al. 1989; Kubota and Funahashi 1982; Lecas et al. 1986; Tanji and Evarts 1976; Thach 1978), and putamen (Alexander 1987) that showed set-related (preparatory) discharge after presentation of instructional stimuli that specified the directions of forthcoming stimulus-triggered movements.

In the present study the dissociation of movement direction from the accompanying pattern of muscle activity [a technique that was first employed for the study of preparatory activity by Thach (1978)] revealed that most of the preparatory activity in all three motor areas was unrelated to the current or anticipated loading conditions. The near absence of "loading effects" that could be considered preparatory (i.e., effects that were confined to the postinstructional interval) suggests that directional preparatory activity, at least in these three motor areas, may not play a significant role in coding for either the dynamics or the muscle activation patterns of preplanned movements. Instead, such activity may be coding for the intended direction of movement at a more abstract level of processing (e.g., trajectory and/or kinematics), independent of the forces that the movement will require.

Organization of the basal ganglia–thalamocortical motor circuit

Overall, the results indicate that neural representations of relatively high-level motor behavioral variables related to planning of the direction of visually guided limb movements occur within the SMA, MC, and putamen. Most of the preparatory neurons in the putamen showed no evidence of associated movement-related activity. This raises the possibility that corticostriatal inputs to the putamen may be functionally segregated, with preparatory neurons in the putamen receiving corticostriatal inputs only from purely preparatory neurons. There is considerable evidence, both anatomic and physiological, that the basal ganglia–thalamocortical motor circuit is somatotopically organized throughout, i.e., at cortical (Mitz and Wise 1987; Muakkassa and Strick 1979; Murphy et al. 1978; Strick and Preston 1982a,b; Tanji and Kurata 1982), striatal (Alexander and DeLong 1985a; Crutcher and DeLong 1984; Kunzle 1975; Liles 1975, 1979), pallidal (DeLong et al. 1985; Szabo 1967), and thalamic levels (DeVito and Anderson 1982; Hedreen et al. 1988; Kuo and Carpenter 1973; Strick 1976). The functional segregation of preparatory and movement-related neurons within the putamen suggests that within the somatotopically organized pathways of the motor circuit there could be further differentiation into parallel, functionally segregated channels that separately mediate preparatory versus executive motor processes.

Comparisons of the onsets and the offsets of preparatory activity in the three different motor areas suggested that, on average, such activity both begins and ends earlier in the SMA and MC than in the putamen. This would be compatible with the suggestion that some of the preparatory activity in the putamen may arise from corticostriatal inputs to this nucleus from either or both of these precentral motor fields. On the other hand, there was considerable overlap of both the onset latencies and the offset latencies among the three structures. Thus, given that influences from the putamen are eventually returned to the SMA and rostral MC via intermediate connections in the ventrolateral thalamus, it is also possible that some of the "latest" preparatory activity in these two cortical areas might be driven by some of the "earliest" preparatory activity in the putamen. Moreover, despite the above-mentioned differences in average onsets and offsets among the three areas studied, the fact remains that the preparatory neurons in the SMA, MC, and putamen were active *simultaneously* throughout most of the postinstruction interval. This is consistent, of course, with the general concept of parallel, distributed processing (Rumelhart and McClelland 1986).

Spatial distribution of preparatory activity

Within all three motor areas examined in this study, there was a significant tendency for preparatory activity to be located more rostrally than movement-related activity. It is conceivable that the spatial distributions of preparatory activity in the two cortical areas may be responsible, at least in part, for the similar distribution of such activity in the putamen. Corticostriatal projections to the putamen from the SMA and MC are each distributed throughout the rostrocaudal axis (Kunzle 1975, 1978; Liles and Updyke 1985), although their respective territories are confined to relatively nonoverlapping zones distributed in the mediolateral and dorsoventral dimensions (Alexander et al. 1988; Martino and Strick, personal communication). The rostrocaudal topography of these corticostriatal projections has not yet been determined, but the present finding of similar rostrocaudal distributions of preparatory activity in the SMA, MC, and putamen could be explained by topographic mapping of corticostriatal projections along the rostrocaudal axis of the putamen.

Within the SMA, we found that whereas cells with preparatory activity were concentrated rostrally, the sites from which arm movements could be evoked by microstimulation were concentrated caudally, behind the genu of the arcuate sulcus. Previous reports of set-related activity in the SMA have not indicated whether there was a rostral predominance of this type of response (Tanji and Kurata 1985; Tanji et al. 1980). However, the present finding of a caudal predominance of microexcitable zones within the SMA is consistent with two previous reports (Hummelsheim et al. 1986; Macpherson et al. 1982). A third report (Mitz and Wise 1987) presented similar findings from one of two monkeys in whom the SMA was explored with microstimulation. The caudal concentration of arm-related microexcitable zones within the SMA might be explained by anatomic studies that have shown that SMA neurons with corticospinal projections [as demonstrated by retrograde labeling with horseradish peroxidase (HRP) injected into cervical levels of the spinal cord] are concentrated within the same territory, behind the genu of the arcuate sulcus (Biber et al. 1978; Dum and Strick 1990; Macpherson et al. 1982; Murray and Coulter 1981).

Alternative explanations for preparatory activity

Several lines of evidence indicated that the preparatory activity observed in this study could not be accounted for by activity changes in eye, limb, or axial muscles associated with anticipation of the upcoming movement. Neurons showing preparatory activity typically ceased discharging during the monkey's movements, contrary to what would be expected if the preparatory discharge reflected anticipatory activity in muscles to be employed in the upcoming movement. Extensive EMG surveys of limb and axial musculature during task performance failed to reveal evidence of any muscles with activity patterns comparable to those of preparatory neurons. Moreover, few of the cells that showed only preparatory activity, without accompanying movement-related activity, were found to have discrete motor or somatosensory fields, despite the extensive manipulations comprised in a detailed sensorimotor examination (although all preparatory neurons were recorded within regions that were identified as containing arm representations, based on the sensorimotor fields properties of surrounding neurons and/or the movements evoked by local microstimulation).

Additional explanations for the preparatory activity were also excluded for various reasons. For example, there was no basis for attributing preparatory activity that was directionally selective to such factors as arousal, motivation, or the task-related sensory conditions, as these should have been the same for both flexion and extension trials. Moreover, the lack of correlation between preparatory discharge and eye position also appeared to rule out any simple relationship to this variable.

Significance of preparatory processes

One possible interpretation of the preparatory activity observed in this study is that it represented the neural substrate of motor set, i.e., the covert biasing of downstream motor systems with respect to some specific aspect of the planned movement (e.g., the direction of movement or the pattern of muscle activations required) (Evarts et al. 1984). This has been the most common interpretation of directionally selective preparatory activity observed in motor and premotor areas (Alexander 1987; Godschalk et al. 1985; Tanji and Evarts 1976; Tanji and Kurata 1985; Tanji et al. 1980; Thach 1978; Weinrich and Wise 1982; Weinrich et al. 1984; Wise and Mauritz 1983, 1985). If related to motor set, most of the preparatory activity observed in the present study would appear to represent possible biasing of downstream structures in terms of the intended direction of movement, irrespective of the required force or pattern of muscle activations.

Some of the preparatory activity observed in this study might have been related to the expectation of target appearance, a form of "perceptual set" (Evarts et al. 1984). Tonic, set-related activity that appeared to be related to the expectation of target appearance has been reported previously in the SMA (Tanji and Kurata 1985) and in premotor cortex (Mauritz and Wise 1986). It is not clear whether, or how, this type of process might differ from that which is frequently referred to as "spatial memory" (e.g., see Funaha-

shi et al. 1989). It is conceivable that some of the directionally selective preparatory cells might also have been involved in the process of selective *spatial attention*, although this process is usually invoked only to explain task-dependent modulations of phasic sensory responses, rather than tonic, set-related activity (e.g., see Goldberg and Bruce 1985). The activity of some preparatory neurons might have represented a high-level form of motor set involving the intention to *capture the target* (with the cursor), as opposed to the intention to move the arm in a certain direction. Such activity would essentially represent a process of movement planning in terms of the target or goal of the movement rather than the movement itself.

The frame of reference for these last four types of preparatory processes (perceptual set, spatial memory, spatial attention, target-level planning) is that of *external space*, whereas the frame of reference for motor set (at least as traditionally conceived) is that of *body-centered space*. Thus one way to differentiate the former processes from motor set would be to dissociate these two frames of reference, as was done in the experiments described in the third paper of this series (Alexander and Crutcher 1990).

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