

Reaching Movements With Similar Hand Paths But Different Arm Orientations. I. Activity of Individual Cells in Motor Cortex

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Scott, Stephen H. and John F. Kalaska. Reaching movements with similar hand paths but different arm orientations. I. Activity of individual cells in motor cortex. *J. Neurophysiol.* 77: 826–852, 1997. This study shows that the discharge of many motor cortical cells is strongly influenced by attributes of movement related to the geometry and mechanics of the arm and not only by spatial attributes of the hand trajectory. The activity of 619 directionally tuned cells was recorded from the motor cortex of two monkeys during reaching movements with the use of similar hand paths but two different arm orientations, in the natural parasagittal plane and abducted into the horizontal plane. Nearly all cells (588 of 619, 95%) showed statistically significant changes in activity between the two arm orientations [analysis of variance (ANOVA), $P < 0.01$]. A majority of cells showed a significant change in their overall level of activity (ANOVA, main effect of task, $P < 0.01$) between arm orientations before, during, and after movement. Many cells (433 of 619, 70%) also showed a significant change in the relation of their discharge with movement direction (ANOVA, task \times direction interaction term, $P < 0.01$) during movement, including changes in the dynamic range of discharge with movement and changes in the directional preference of cells that were directionally tuned in both arm orientations. Similar effects were seen for the discharge of cells while the monkey maintained constant arm postures over the different peripheral targets with the use of different arm orientations. Repeated data files from the same cell with the use of the same arm orientation showed only small changes in the level of discharge or in directional tuning, suggesting that changes in cell discharge between arm orientations cannot be explained by random temporal variations in cell activity. The distribution of movement-related preferred directions of the whole sample differed between arm orientations, and also differed strongly between cells receiving passive input predominantly from the shoulder or elbow. The electromyographic activity of most prime mover muscles at the shoulder and elbow was also strongly affected by arm orientation, resulting in changes in overall level of activity and/or directional tuning that often resembled those of the proximal arm-related motor cortical cells. A mathematical model that represented movements in terms of movement direction centered on the hand could not account for any of the arm-orientation-related response changes seen in this task, whereas models in intrinsic parameter spaces of joint kinematics and joint torques predicted many of the effects.

INTRODUCTION

There is considerable psychophysical evidence that the control of volitional movements such as reaching movements to a target involves a series of sensorimotor transformations proceeding from higher-level representations of the spatiotemporal form of movement to those specifying the causal details of its execution, culminating in signals that

generate the appropriate muscle activity patterns (Georgopoulos 1991; Kalaska 1991, 1995; Kalaska and Crammond 1992; Soechting and Flanders 1989, 1992). These processes are often described for heuristic purposes in terms of the convenient but arbitrary parameter spaces (hand path, joint angles, joint torques, etc.) and transformations (inverse kinematics, inverse dynamics) of newtonian mechanics. However, it is highly unlikely that the brain controls movement by explicitly solving the newtonian laws of motion. Instead, psychophysical studies are revealing the physiological parameters, reference frames, and transformations by which the motor system plans and implements movements (Flanders et al. 1992; Gordon et al. 1994; Hogan 1984; Karst and Hasan 1991a,b; Lacquaniti 1989; Lacquaniti et al. 1995; Shadmehr and Mussa-Ivaldi 1994; Soechting and Flanders 1989, 1992). For instance, a key step in this presumed sequence is the transformation from a representation related to the motion of the hand or the target location in space to a representation related to the mechanical details of its implementation by the arm (Karst and Hasan 1991a,b; Soechting and Flanders 1992). We refer to the latter class of representations as intrinsic and the former class as extrinsic to dissociate those representations that explicitly specify the geometry or mechanics of the limb from those that do not. For instance, hand path is an extrinsic representation because it does not provide explicit information about limb geometry, because a given hand path can be produced by a wide range of arm geometries and joint rotations. Psychophysical studies have also suggested that this transformation may not be directly from extrinsic coordinates to a representation of pure intrinsic coordinates (joint angles, muscle lengths, or joint torques), but rather to a hybrid reference frame reflecting the spatial orientation of limb segments relative to a body-centered origin (Soechting and Flanders 1989, 1992). We also refer to these hybrid coordinate systems as intrinsic frames, to signify that they specify the geometry of the limb.

How and indeed whether discrete sequential transformations between distinct representations of movement in different parameter spaces, as predicted by psychophysical models, are implemented within the widely interconnected network of cortical and subcortical movement-related populations remains a fundamental conceptual issue (Alexander et al. 1992; Fetz 1993; Georgopoulos 1991, 1995; Hogan 1984; Humphrey and Tanji 1991; Kalaska 1991, 1995; Kalaska and Crammond 1992; Kalaska and Drew 1993; Mountcastle 1995). For instance, whether primary motor cortex (MI) functions predominantly before or after

the putative transition from extrinsic to intrinsic coordinates is still controversial.

Early studies in which single-joint movements were used demonstrated that the discharge of many motor cortical cells covaried with kinetic parameters of movement, including force, torque, and muscle activation levels (Cheney and Fetz 1980; Evarts 1968; Fromm 1983; Humphrey 1972; Smith et al. 1975). The consensus of those single-joint studies implicated MI in the generation of signals that covaried with muscle activity in an intrinsic reference frame, that is, a late stage in the putative sequence of transformations.

However, a series of studies of MI activity during reaching movements challenged this conclusion (Georgopoulos et al. 1982, 1988). Those studies demonstrated that shoulder-related cells were broadly tuned with the direction of movement of the hand, centered on a preferred movement direction that varied from cell to cell. The pattern of activity of the total population covaried with the trajectory of hand movement. More recent studies of motor cortical discharge during continuous tracing motions of sinusoidal and spiral trajectories concluded more specifically that the MI population signaled the instantaneous movement direction and velocity along the hand path in a reference frame centered on the hand (Schwartz 1992, 1993, 1995). This suggested that MI generates a representation of movement in an extrinsic reference frame of hand motion in space, a higher level of representation than indicated by single-joint studies. However, Mussa-Ivaldi (1988) noted that cells signaling arbitrary intrinsic movement parameters, such as muscle length, would also show broad directional tuning during reaching movements, because intrinsic and extrinsic movement parameters were linked by simple trigonometric relations. Therefore the true nature of neuronal discharge can only be revealed by systematic experimental dissociation of different movement parameters.

Toward this goal, two studies attempted to dissociate various attributes of reaching movements. In the first, kinematic and kinetic parameters were dissociated by training monkeys to move the limb along similar reaching trajectories while compensating for loads that pulled the limb in different directions (Kalaska et al. 1989, 1990). The discharge of many single cells was modulated by the direction of external loads (Kalaska et al. 1989), and the directional signal generated by the sample population under different load conditions often deviated from the actual direction of movement (Kalaska and Crammond 1992). This implicated MI in the transformation from a representation of the spatiotemporal form of the movements to one that covaried with kinetic parameters of movement, but did not imply that the cells were explicitly signaling newtonian mechanical parameters such as joint torques or output forces (Kalaska et al. 1989, 1990). The design of the task in that study could not distinguish between an extrinsic or intrinsic representation.

In a second study, monkeys made movements in eight directions away from the centers to the corners of three adjoining work space cubes, thereby dissociating the extrinsic parameter of movement direction from intrinsic parameters that covaried with arm geometry (Caminiti et al. 1990, 1991). Many cells showed large and idiosyncratic changes in directional tuning during movements in the three cubes, even though the relative direction of movement from the

central start position to the targets in each was identical. This challenged the conclusion that the representation of movement in MI at the single-cell level was centered on the hand. The overall change in cell tuning across the cell sample was mainly a rotation about the vertical axis, corresponding reasonably well to the change in angle of the shoulder to place the hand at the central starting position in each cube. This implicated MI cells in the transformation from a representation of movement in extrinsic coordinates to one in intrinsic shoulder-centered coordinates.

A potential confounding factor in the study by Caminiti et al. (1990, 1991) is that each of the eight sets of parallel movement directions was performed in three different parts of space. Therefore it is still possible that the changes in directional tuning of single cells reflected the extrinsic spatial location of the trajectories, and not the changes in arm geometry. In the present study we attempt to clarify this issue. Monkeys were trained to make reaching movements of the arm along similar trajectories with the hand at shoulder level, while holding the arm in one of two different orientations. In the natural orientation, the upper arm and forearm formed a near-vertical plane with the elbow located below the line between the shoulder and hand. In the second orientation, the elbow was abducted nearly to shoulder level, so that the upper arm and forearm were oriented predominantly in the horizontal plane. If single MI cells represent movement exclusively in an extrinsic hand-centered reference frame, their activity should be insensitive to the change in arm orientation. In contrast, if their activity reflects to some degree attributes of movement that covary with arm geometry, their discharge should change in different arm orientations. A preliminary report of this work has been published (Scott and Kalaska 1995).

METHODS

Task apparatus and design

Two juvenile male rhesus monkeys (*Macaca mulatta*, 4–6 kg) were trained to make visually guided reaching movements from a central position to eight peripheral light-emitting diode targets. The basic apparatus and task have been described elsewhere (Kalaska et al. 1989). However, for this experiment, the position of the handle held by the monkey was 1 cm below shoulder height and ~12 cm from the free end of the pendulum (Fig. 1A). The monkey positioned a pointer at the free end of the manipulandum over the central light-emitting diode (target radius 1.0 cm) for 1–3 s, then moved the pointer to one of eight peripheral targets (target radius 1.5 cm) equally spaced on an 8-cm radius circle when the target was illuminated, and then held the pointer over the target for 2 s. The X-Y position of the manipulandum was measured to 0.1-mm resolution at 100 Hz (Science Accessories, model G/P-3). The eight target lights were presented five times in a randomized block design.

The monkeys made visually guided reaching movements with the use of two different arm orientations (Fig. 1). In the “natural” orientation, the monkey grasped the handle and moved the manipulandum with the use of its preferred, natural arm orientation with the elbow below a line joining the hand and shoulder. In the “abducted” orientation, a clear Plexiglas barrier was positioned immediately below the handle, so that the monkey had to abduct its arm to grasp the handle and move the manipulandum. The magnitude of abduction was ~80°, but varied slightly with the position of the manipulandum (see *Hand and joint kinematics*).

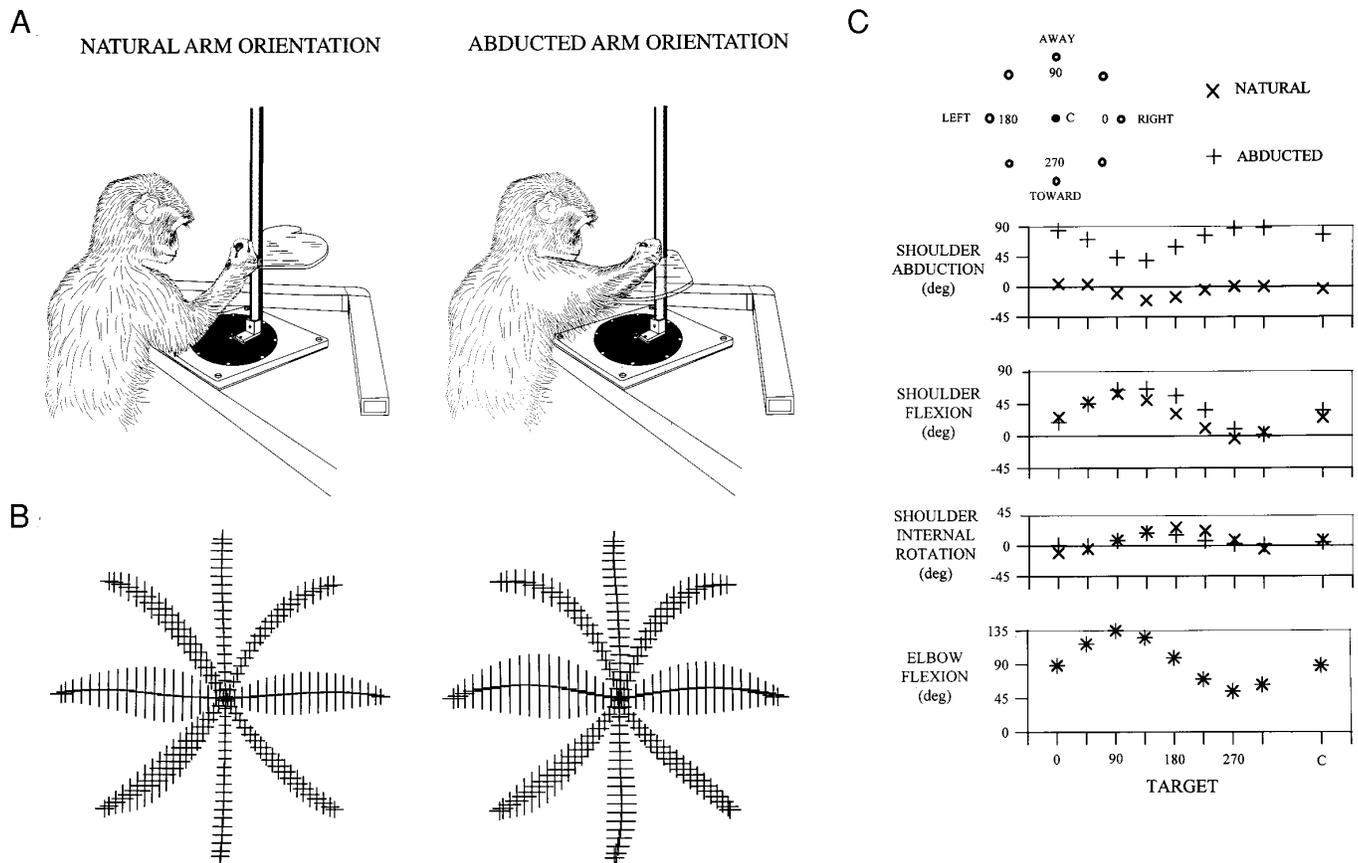


FIG. 1. *A*: task apparatus used in this study. In the natural orientation (*left*), the monkey grasped a handle on a pendulum-like manipulandum with the use of its preferred arm orientation with the elbow suspended below the line between the hand and shoulder. In the abducted orientation (*right*), a transparent plate was positioned just below the handle on the manipulandum, requiring the monkey to abduct its arm to shoulder level to grasp and move the handle. *B*: average hand trajectory to each target for the natural (*left*) and abducted (*right*) orientations for all trials recorded for this study. Each trajectory was divided into 20 equal-length segments and the mean (X - Y) position of each of the 20 segments was calculated. Crosses: X - Y position of the hand (mean \pm SD) for each segment. *C*: angles of the shoulder and elbow joints when the hand was at the central start position (C) and at each of the 8 peripheral targets for the 2 different arm orientations.

After training, standard aseptic surgical techniques were used to prepare the monkeys for recording in the precentral cortex (Kalaska et al. 1989).

Data collection

Standard recording methods were used to study the activity of individual cells in MI on the side contralateral to the arm used to make reaching movements (Kalaska et al. 1989). During each recording session, a microelectrode was advanced through MI while the monkey alternately used the natural or abducted arm orientation. Cells active during the motor task were isolated and examined for their response to passive movement of limb joints. Cells responding predominantly to shoulder or elbow movements were studied further, whereas cells responsive to trunk, wrist (including forearm supination/pronation), or hand movements were not included in the data sample. A scale from 1 to 5 was used to identify subjectively the relative response of each cell to passive movement of the shoulder and elbow joints. A score of 1 signified only elbow input, 5 only shoulder input. Cells without identified inputs were only recorded in the task if adjacent cells within that electrode penetration were related to shoulder and elbow movements. These latter cells were scored as 0, meaning no obvious passive input. Cells that were recorded in the two tasks, but for which a complete passive sensory exam

was not completed successfully, were not scored. The activity of each cell was recorded while the monkey performed five complete replications of eight movements first in one orientation and then in the other.

Because of the design of the apparatus, it was impractical to fully randomize the task for arm orientation within a data file. Instead, a given cell was recorded sequentially with one arm orientation and then the other. This leads to the possibility that changes in cell activity between data files in different arm orientations arose because of carryover effects between sequential arm orientations, or because of temporal variation in cell response properties independent of task manipulations. To counter these potential problems, several steps were taken. First, no fixed order of arm orientations was used while collecting data files, so that there were approximately equal numbers of cells recorded initially in each orientation. Second, the discharge level and directional tuning of cells was routinely tested in each arm orientation before collection of the actual data files. If there was any suspicion of alterations in cell responses between the preliminary tests and data collection sessions, the data files were deleted and the procedure was repeated. For a number of cells, a second duplicate set of data files was recorded, again in no fixed order, to evaluate quantitatively the degree of similarity of cell discharge seen in each arm orientation with repeated testing. Third, while the electrode was being advanced through the cortex to search for task-related cells, the mon-

key's arm orientation was frequently changed to avoid any inadvertent bias in our search procedure.

The task-related activity of most muscles acting about the shoulder and elbow was recorded after training was completed, and after termination of cell data collection. A pair of Teflon-insulated 50- μm stainless steel wires was inserted percutaneously into a muscle. The position of the wires within a given muscle was verified by passing current pulses through the wires and evoking localized contractions of the muscle (<1.5-mA, 30-Hz, 300-ms train). Two muscles at a time were recorded while the monkey performed the motor tasks. Electromyographic (EMG) signals were band-pass filtered (100–3,000 Hz), rectified, bin integrated, and sampled at 10-ms intervals. The muscles studied included latissimus dorsi, trapezius, rhomboids, infraspinatus, supraspinatus, subscapularis, teres major, dorsoepitrochlearis, deltoids (3 heads), pectoralis major, biceps (2 heads), brachialis, brachioradialis, and triceps (3 heads). Sixteen to 19 muscles were recorded in each arm of each monkey, resulting in a total sample of 70 muscle data sets (no duplicate muscles from the same arm).

Near the end of the experiment, electrolytic lesions (25 μA , 10 s) were made at several locations within each recording chamber to confirm the location of penetrations in MI. At the end of an experiment, monkeys were deeply anesthetized with barbiturates and perfused with buffered saline followed by Formalin. Pins were inserted at known grid map coordinates to identify the region where cell recordings were made.

Data analysis

Each trial was divided into three behavioral epochs: 1) center hold time (CHT), when the monkey remained at the central target before the illumination of the target light-emitting diode; 2) a combined reaction and movement time (RT+MT), from the illumination of the target light to the end of the arm movement; and 3) target hold time (THT), from the end of the movement to the end of the trial (Kalaska et al. 1989). The analyses in the present study were based on the average neuronal activity in each behavioral epoch. The temporal aspects of cell discharge will be studied in a future report (Kalaska 1996; Scott and Kalaska 1996).

Direction was defined by trigonometric convention, with 0° pointing to the right and angle increasing counterclockwise. Data (cell activity, hand trajectories, EMG) collected when the monkey performed the task with the left arm were mirror-image transposed.

Variations in cell discharge with movement direction and/or arm orientation were evaluated with the use of several tests. A nonparametric "bootstrapping" test was used to identify whether a cell was directionally tuned (Crammond and Kalaska 1996; Georgopoulos et al. 1988). The directional bias of a cell during movement (RT+MT) and posture (THT) can be characterized by a mean vector whose orientation defines the cell's preferred movement direction (Batschelet 1981; Georgopoulos et al. 1982). The length of the mean vector (0–1) serves as a measure of the increasing sharpness of a cell's directional tuning (Batschelet 1981). The length of the mean vector was determined from a given cell's discharge across all movement directions, as recorded in the task. Then, a shuffling procedure randomly reassigned single-trial data to different "movement directions" and the length of the resulting mean vector of the shuffled data was determined. The cell was considered directionally tuned if the length of no more than 40 of 4,000 shuffled mean vectors exceeded the task-related mean vector length of the cell ($P < 0.01$).

A split plot analysis of variance (ANOVA) was used to evaluate whether changes in the overall level of cell discharge or its relationship to movement direction were significantly modulated by arm orientation ($P < 0.01$, Snedecor and Cochran 1980). This unbalanced ANOVA identifies those cells that show a main effect between the task conditions (i.e., a change in overall level of dis-

charge between the two arm orientations), a direction effect (a variation in cell activity with movement direction across task conditions), and a task \times direction interaction effect. A significant interaction effect is particularly important because it indicates that a cell shows a significant change in the nature of the relationship of its discharge with the movement direction of the hand. There are two principal ways that a cell could show a task \times direction interaction. In one case, the cell's tuning curve could retain the same preferred direction in both orientations but show a gain change, that is, a difference in amplitude (dynamic range) of the cell's directional tuning curve from its maximum to its minimum. At the extreme, a cell could be directionally tuned in one orientation but nondirectional (i.e., dynamic range of 0) in the other arm orientation. Alternatively, a cell's tuning curve could retain the same dynamic range in the two arm orientations but show a change in directional preference. Of course, these effects are not mutually exclusive and cells could potentially show combinations of both effects. Because the nature of the interaction effect, whether mainly a gain change or a directional shift, is of interest for understanding the nature of the influence of arm orientation on cell discharge, the following analyses were performed.

To test for a gain change, the difference between the maximum and minimum of each of the five replicated tuning curves of cell responses recorded during each of the five replicated blocks (1 trial for each of the 8 movement directions) was calculated for each data file, providing five measures of the dynamic range of the tuning curve in each arm orientation. A *t*-test was applied to test for a significant difference in the dynamic range between arm orientations.

To test for a direction shift, ideally one would like to be able to test for a significant change in the directional preference of the tuning curve of the cell between arm orientations independent of any other change in the tuning curves, such as a change in dynamic range or in overall activity level. A test that can reliably dissociate these factors does not appear to exist. As an alternative strategy, cells that were directionally tuned with movement in both arm orientations were tested further to identify whether there was a statistical change in their preferred direction between orientations (Watson-Williams test) (Batschelet 1981). For this test, repeated estimates of a cell's preferred direction are required for each arm orientation. Therefore a preferred direction was calculated separately for each of the five replication tuning curves of cell activity to provide five measures of the cell's preferred direction in each arm orientation. The Watson-Williams test determines whether or not there is a significant difference ($P < 0.01$) between the mean angles of the two distributions of five replication preferred directions for each arm orientation. It is important to emphasize that this is a robust test of only a shift in the distribution of replication preferred directions. The source of variability in this procedure is the temporal variability of the directional tuning curve of the cell measured in each replication of the eight movement directions and not the full directional variability of neural activity expressed in the underlying directional tuning curves from which the replication preferred directions were derived.

Muscle activity

Muscle activity patterns during the motor tasks were analyzed with the use of techniques similar to those used to analyze single-cell activity. For comparison of the tonic level of EMG of single muscles between two different arm orientations, the EMG for a given muscle was normalized to its largest value recorded for either arm orientation during any behavioral epoch.

Limb kinematics

The average trajectory of the hand to each target was calculated for each orientation. Each movement was divided into 20 equidis-

tant points along its trajectory. The mean and SD of the spatial locations of each of the 20 points along the trajectory to each particular target were calculated across all trials in which cell activity was recorded for each orientation ($n = 3,095$). Movements made with the left arm were mirror transposed about the midsagittal axis ($90\text{--}270^\circ$).

The joint kinematics for each movement was estimated for each arm orientation. The upper limb of the monkey was modeled as a two-segment appendage with a ball and socket joint at the shoulder providing three degrees of freedom (DOF), and a simple hinge joint (1 DOF) at the elbow. The lengths of the arm (distance from elbow to shoulder joints) and forearm/hand (distance from elbow joint to center of the palm of the hand) were measured on each monkey, as was the position of the shoulder joint relative to the central start position.

With the use of these measures, the spatial configuration of the arm was estimated at the central start position and for each of the target locations. The position of the hand was equated to the X - Y position of the manipulandum. Elbow position was defined with the use of three constraint equations based on simple geometric rules, the first two constraints being that the arm and forearm/hand were of fixed length. For the natural arm orientation, the third constraint equation was that the monkey maintained its arm in a vertical plane (as defined by the longitudinal axes of the arm and forearm). For the abducted orientation, the forearm of the monkey rested on the Plexiglas barrier and thus restricted movement of its elbow along a plane just above the surface of the barrier. Once the spatial locations of the hand and elbow were estimated, joint kinematics were defined on the basis of sequential rotations about the abduction(+)/adduction, flexion(+)/extension, and internal(+)/external rotation axes of the shoulder followed by rotation about the flexion(+)/extension axis of the elbow. Neutral position was defined as anatomic position (trunk erect, arm and forearm suspended vertically down at the side of the trunk). Visual inspection of the position of the elbow and corresponding shoulder and elbow joint angles was consistent with the computed values when the above technique was used. However, these reconstructions could not take into account the small translations of the shoulder girdle that accompany movements of the hand to different targets (Kalaska et al. 1990).

RESULTS

Hand and joint kinematics

The trajectory of the hand to each of the eight targets was similar when the monkey made reaching movements in the natural and abducted orientations (Fig. 1B). Hand paths were slightly curved and the variability in hand path trajectories for the abducted and natural orientations overlapped extensively. A detailed analysis of the trajectories along with the population signal of cell activity will be considered in a subsequent publication.

Joint angle changes varied approximately sinusoidally with the direction of movement (Fig. 1C). In the natural arm orientation, estimated joint angle changes were similar to those previously measured with the use of three-dimensional video analysis for a similar motor task (Kalaska et al. 1990).

The largest change in the joint kinematics between the two arm orientations was in shoulder abduction angle (Fig. 1C). In the natural arm orientation, abduction angle varied about the neutral anatomic position (i.e., 0°), whereas for the abducted orientation, shoulder abduction angle shifted by $\sim 80^\circ$. The next most important change was a reduction in the excursion of the shoulder joint in internal/external rotation by more than half. Slight variations in joint kinemat-

ics at each target were also seen for shoulder flexion/extension. Unlike the changing shoulder joint angles, elbow joint angles were similar for the two conditions.

There was one further subtle but important difference in the joint kinematics between arm orientations. In the natural arm orientation, maximal elbow and shoulder flexion/extension angle changes occurred for movements in the sagittal axis ($90\text{--}270^\circ$) that were nearly orthogonal to the directions of maximal shoulder internal/external rotation ($0\text{--}180^\circ$ axis). In the abducted orientation, elbow flexion/extension remained maximal along the $90\text{--}270^\circ$ axis, whereas maximum excursion of all three DOF of shoulder motion shifted toward the $135\text{--}315^\circ$ axis.

Note that calculated abduction angle dropped to $\sim 45^\circ$ for the most distant targets in the abducted orientation. This did not mean that the arm swung substantially out of the horizontal plane as the hand reached out to the distant targets. The elbow remained elevated close to the level of the shoulder at all times during movements in the abducted orientation. Instead, it is a result of the coordinate frame and sequence of rotations in which joint angles were measured.

Cell data base

The activity of 619 cells was recorded in MI in four hemispheres of two rhesus monkeys (*M. mulatta*, 4.0 and 5.5 kg). For the first monkey, 144 and 215 cells were recorded in the left and right hemispheres, respectively; for the second monkey, 165 and 95 cells were recorded in the left and right hemispheres, respectively. Penetrations were concentrated in or near the anterior bank of the central sulcus and were confined to the shoulder and elbow representations located medial to the distal arm representation (Kwan et al. 1978). Cells included in this study were unimodally tuned (Georgopoulos et al. 1982; Kalaska et al. 1989) in at least one of the behavioral epochs (RT+MT or THT) in one of the two arm orientations, and frequently for both epochs and orientations. Several hundred other cells were tested in the task but were not included in the data base because they were not active in the task or not related to movements of the proximal arm.

Arm orientation had a significant effect on one aspect or another of the discharge patterns of most cells (588 of 619, 95%; F test, $P < 0.01$, Table 1). Figure 2 illustrates the pronounced change in the activity of an individual cell when reaching movements were performed with the use of different arm orientations, even though the kinematics of the movements was similar. That cell showed a change in the level of overall activity before, during, and after arm movements to the targets (ANOVA, main effect of task, $P < 0.01$ for CHT, RT+MT, and THT), and changes in directional tuning both during and after the movements (ANOVA, task \times direction interaction, $P < 0.01$ for RT+MT and THT).

Variation in overall level of discharge with arm orientation

A common effect of arm orientation was a change in the overall level of activity of cells (Figs. 2 and 3A; ANOVA, main effect of task, $P < 0.01$). A significant task effect in different task epochs indicated a significant change in the

TABLE 1. Variation of motor cortical cell and proximal arm muscle activity during reaching tasks

	Motor Cortical Cells		Proximal Muscles	
	Between orientations (natural vs. abducted)	Repeated files	Between orientations (natural vs. abducted)	Repeated files
<i>n</i>	619	55	70	59
Level of activity (task main effect)				
CHT	356 (58)	8 (14)	35 (50)	17 (29)
RT+MT	327 (53)	4 (7)	46 (66)	6 (10)
THT	316 (51)	6 (11)	48 (68)	13 (22)
Any epoch	501 (81)	13 (24)	62 (88)	21 (36)
Movement direction (task × direction interaction)				
RT+MT	433 (70)	1 (2)	64 (91)	6 (10)
THT	489 (79)	5 (9)	63 (90)	13 (22)
Any epoch	562 (91)	5 (9)	68 (97)	17 (29)
Level of activity or movement direction				
RT+MT	497 (80)	5 (9)	66 (94)	11 (19)
THT	531 (86)	9 (16)	64 (91)	20 (34)
Any epoch	588 (95)	15 (27)	69 (99)	30 (51)

F test, $P < 0.01$. Values in parentheses are percentages. *n*, number of cells. CHT, center hold time; RT+MT combined reaction time and movement time; THT, target hold time.

level of tonic discharge of cells between the two arm orientations when the monkey maintained its hand at the central start position (CHT), or in the grand mean of the movement-related activity averaged across all eight directions during RT+MT, or in the posture-related activity during holding of the hand at the eight outer targets during THT (Table 1). Tonic discharge during CHT changed between control and abducted conditions in 356 of 619 cells (58%; *F* test, $P < 0.01$). Average absolute change in tonic activity during CHT between natural and abducted arm orientations for all cells was 7.2 spikes/s. However, the change in tonic activity of the sample was distributed randomly about zero (Fig. 3A), and the mean discharge rate of cells in the two arm orientations was similar (13.7 and 14.2 spikes/s for natural and abducted orientations; paired *t*-test, $P > 0.10$). Similar percentages of cells showed a significant main task effect of arm orientation on the grand mean of activity measured across all eight directions during RT+MT (53%) and THT (51%) between the two orientations (Table 1).

Although the change in activity appeared to be random across the population, an important finding was that there was a strong tendency for the change in the level of discharge of a given cell to be similar in both sign (increase or decrease) and in magnitude in the three behavioral epochs of the trial (Fig. 4). As a result, cells that showed a large change in discharge between arm orientations in one of the behavioral epochs also tended to show large changes in the other two epochs (Fig. 4; CHT vs. RT+MT, $r = 0.77$; CHT vs. THT, $r = 0.76$; RT+MT vs. THT, $r = 0.83$; $P < 0.01$ for all). Therefore the shift in arm orientation produced a change in pre-movement tonic rate during CHT that tended to be sustained during the subsequent movements to the targets (RT+MT) and during holding of the arm over the peripheral targets (THT).

Variation in directional tuning with arm orientation

A majority of cells (433 of 619, 70%) showed a significant task × direction interaction effect during RT+MT (*F*

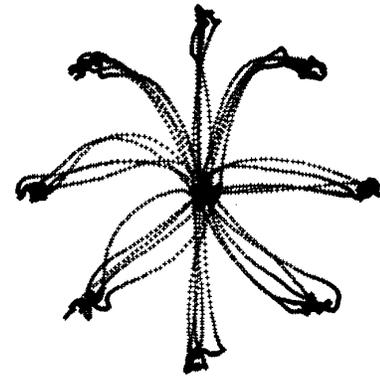
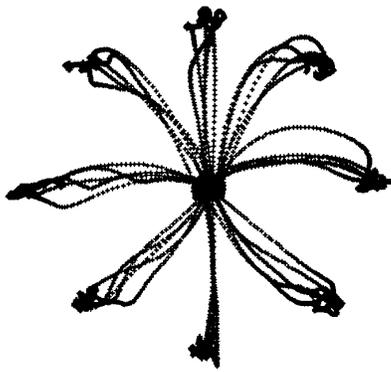
test, $P < 0.01$, Table 1), indicating a change in the nature of the relationship between cell activity and movement direction between arm orientations that is independent of the shifts in overall level of activity (main task effect) described in the previous section. Similarly, 489 of 619 cells (79%) showed a significant task × direction interaction effect during THT (Table 1).

At least two factors can produce a significant task × direction interaction. The first is a change in the dynamic range of the task-related tuning curve of the cell in the two arm orientations. At the extreme, cells could be directionally tuned in one arm orientation but not in the other. A majority of cells (422 of 619, 68%) were directionally tuned in both arm orientations during RT+MT (bootstrap test for directionality, $P < 0.01$), but 80 and 88 cells were tuned only in the natural or abducted orientation, respectively (Fig. 3B). The remaining 29 cells were not directionally tuned during RT+MT in either orientation. Of the cells directionally tuned in both orientations during RT+MT, 303 of 422 (72%) showed a significant task × direction interaction. Finally, 139 of 303 (46%) of the cells that were directional in both arm orientations and showed a significant task × direction interaction also showed a significant difference in the dynamic range of the five replicated tuning curves between the two arm orientations (*t*-test, $P < 0.01$, see METHODS). The mean absolute (i.e., unsigned) change in dynamic range for the 303 cells with a significant task × direction interaction during RT+MT was 13.9 spikes/s, and the median change was 11.2 spikes/s. Similar alterations were seen in the dynamic range of cell tuning curves during THT. For instance, 53 cells were directionally tuned only in the natural orientation and 56 only in the abducted orientation. Of the 495 cells that were directionally tuned during THT in both orientations, 395 (80%) showed a significant task × direction interaction, and 207 of 395 cells (52%) showed a significant change in absolute dynamic range between arm orientations (*t*-test, $P < 0.01$; mean absolute dynamic range 10.9 spikes/s, median change 8.4 spikes/s).

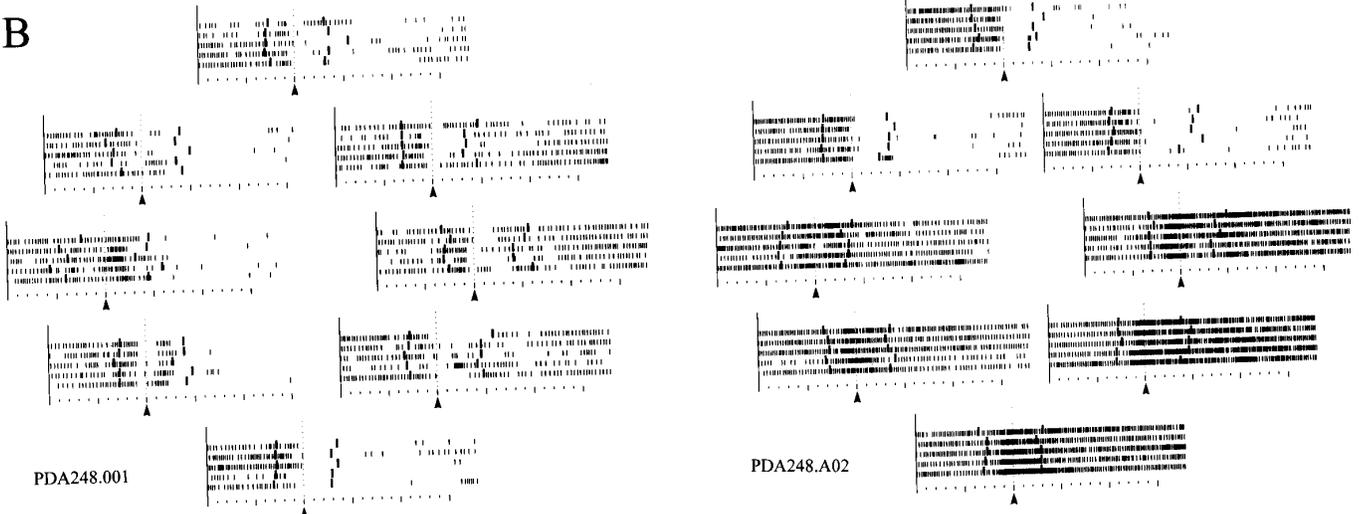
NATURAL

ABDUCTED

A



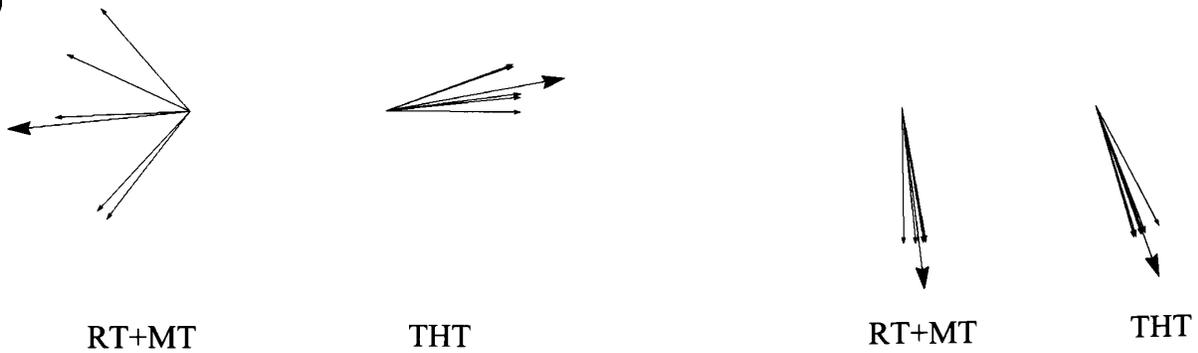
B



C



D



A second possible origin of a significant task \times direction interaction is a shift in the directional preference of the cell tuning curve between arm orientations. This was also a prominent characteristic of the cell responses in this study. Although many cells that were directionally tuned in both arm orientations during RT+MT showed only a small directional shift between arm orientations, the directional preference of others was altered dramatically, in a few cases by almost 180°, and the average absolute (unsigned) shift in preferred direction was 45.6° (Fig. 3B). However, the distribution of differences in preferred direction in the two arm orientations was centered on zero [arithmetic (signed) mean difference 0.7° clockwise, Fig. 3B], indicating that there was no systematic rotation of the directional tuning of the total cell sample between arm orientations.

These directional shifts were a major contributing factor in the probability of a significant task \times direction interaction effect during RT+MT. As is evident in Fig. 3B, right, cells without a significant interaction term tended to show smaller shifts in directionality. This was confirmed when the distributions of directional shifts were plotted separately for cells with and without a significant task \times direction interaction (Fig. 5A). The distributions for cells with a significant interaction were highly significantly skewed toward larger directional changes (nonparametric test for dispersion, $P < 0.01$).

A valid question is how many of these directional shifts are statistically significant. As discussed in METHODS, a rigorous test of this question that accounts for the full directional variance (spread of the tuning curve) of a cell does not exist. Instead, we used the Watson-Williams test to identify significant changes in the distribution of the preferred directions of the five replication tuning curves of a cell recorded in each arm orientation. This test determined that 203 of 422 cells (48%) showed a significant shift in the distribution of replication preferred directions between arm orientations.

Again, similar effects were found during holding of the arm over the targets during the THT epoch (Figs. 3C and 5B). The mean absolute shift in directional tuning between arm orientations was 37.6°, but the arithmetic mean was only 2.4° counterclockwise (Fig. 3C). Cells that were directionally tuned in both orientations during THT and had a significant task \times direction interaction showed a much larger range of changes in preferred directions than did cells without a significant interaction (Figs. 3C and 5B; $P < 0.01$, nonparametric test for dispersion). Finally, 255 of 495 cells (51%) showed a significant difference in their distribution of replication preferred directions between arm orientations (Watson-Williams test, $P < 0.01$).

As was the case for the overall level of activity, there was

a correlation in both the magnitude and direction (clockwise or counterclockwise) of the orientation-related directional shift between RT+MT and THT for cells that were directionally tuned in both epochs ($r = 0.45$, $P < 0.01$) (Batschelet 1981). In other words, a change in directional tuning of a given cell during movement between the two arm orientations tended to be sustained after movement, while constant arm postures were maintained at the peripheral targets.

Distribution of preferred directions for different arm orientations

The distribution of preferred directions of the total sample of cells was very broad but not statistically random for either RT+MT or THT epochs in either arm orientation (Fig. 6). According to the Rayleigh test, the distributions for the natural and abducted orientations during the RT+MT epoch were best described as bimodal ($P < 0.001$) with major axes oriented at 98–278° and 104–284°, respectively. During THT, the distribution for the abducted orientation was also bimodal ($P < 0.001$) with its major axis oriented at 129–309°. In contrast, the distribution of preferred directions for the natural orientation during THT was best described as unimodal ($P < 0.01$) and oriented at 79.7°.

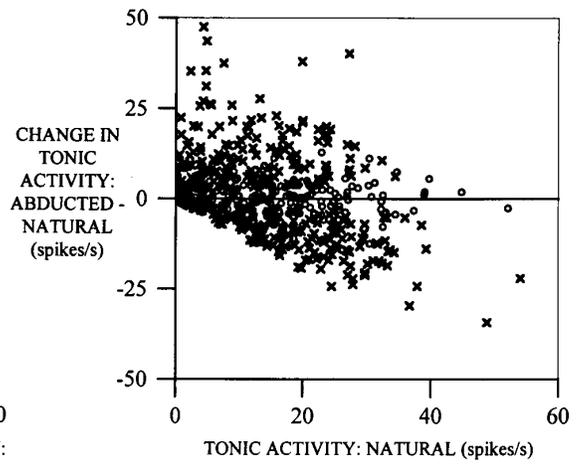
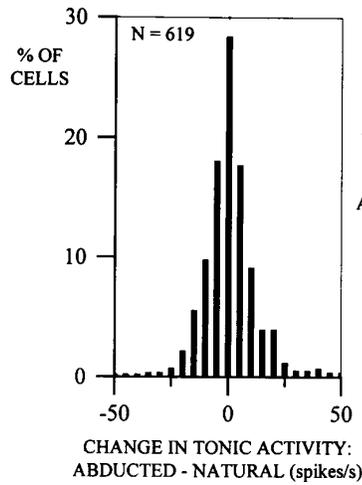
Response properties of cells with passive input from the periphery

A total of 534 cells responded to passive movement of the shoulder and/or elbow joints. Although some cells (43%) responded only to passive movement of one of the two joints (classes 1 and 5, Fig. 7A), the majority of cells (57%) responded to varying degrees of passive movement at both joints. A larger proportion of cells was related to passive movement of the shoulder compared with the elbow. This partially reflects a sampling bias: among other factors, many elbow-related cells were also strongly responsive to forearm pronation/supination or wrist movements and so were rejected from our sample.

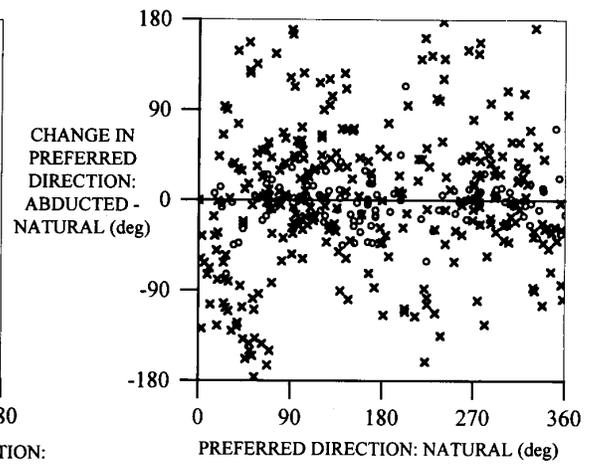
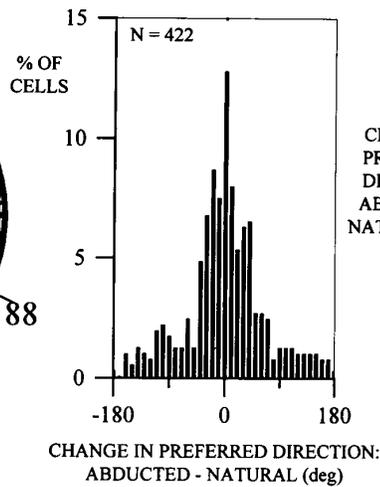
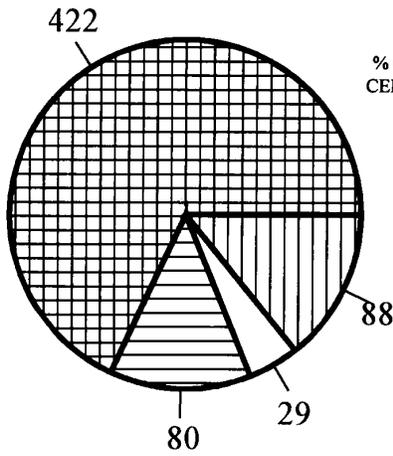
To compare the behavior of cells that received passive inputs predominantly from the shoulder or elbow, cells with passive scores of 4 or 5 were classified as shoulder-related cells, whereas cells with passive scores of 1 or 2 were classified as elbow related (see METHODS). The distribution of preferred directions of elbow-related cells was dramatically different from that of shoulder-related cells (Fig. 7B). For the RT+MT epoch, the preferred directions of elbow-related cells were strongly bimodally distributed close to the 90–270° axis for both arm orientations (Rayleigh test, $P < 0.001$), consistent with the movement direction requiring maximal motion at the elbow joint (Fig. 1C). In contrast, the preferred directions of shoulder-related cells were uniformly

FIG. 2. Comparison of the activity of a motor cortical cell during reaching movements with the use of the natural and abducted arm orientations. *A*: path of the hand at 10-ms intervals during movements to the 8 peripheral targets in the 2 arm orientations. *B*: response of the cell during reaching movements in the 2 arm orientations. Each raster illustrates the discharge pattern of the cell during 5 repeated trials to each target. Arrowheads: start of movement. Thicker bars before and after the arrowhead on each raster line: time of appearance of the target light and the end of movement, respectively. *C*: velocity profiles of the hand movement to the lower target (270°) with the use of the natural and abducted orientations. *D*: preferred direction of the cell discharge calculated for each replication of 8 movements to each target (short vectors) and the mean preferred direction for the 5 replications (long vectors). RT+MT, combined reaction time and movement time; THT, target hold time.

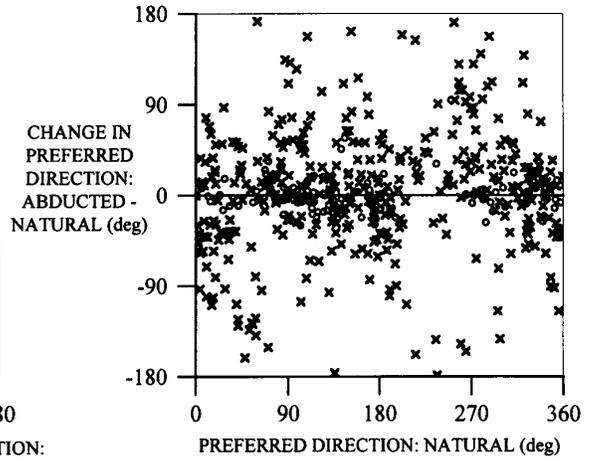
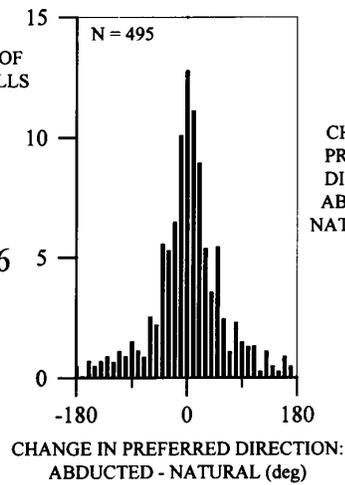
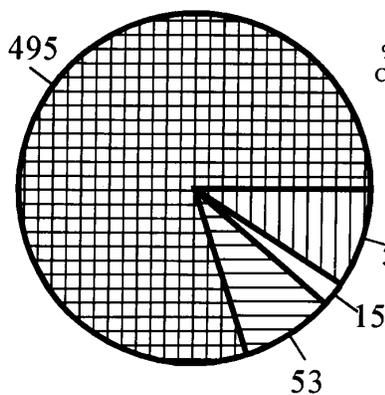
A TONIC ACTIVITY: CHT



B DIRECTIONAL TUNING: RT+MT



C DIRECTIONAL TUNING: THT



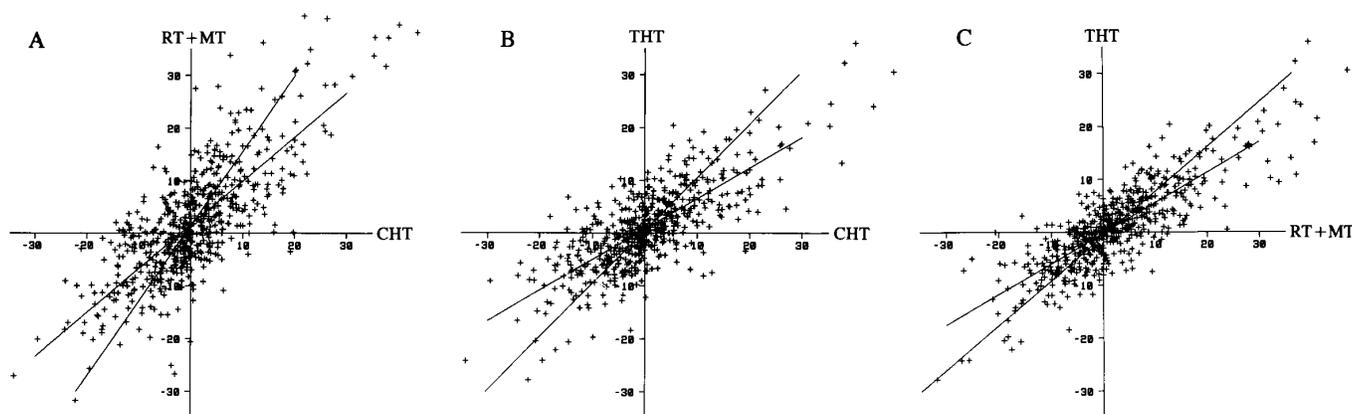


FIG. 4. Comparison of the change in the overall level of discharge between arm orientations across the 3 behavioral epochs. Changes in arm orientation resulted in correlated changes in cell discharge before, during, and after movement. The 2 intersecting diagonal lines are the regression lines for ordinate on abscissa and abscissa on ordinate.

distributed in the natural orientation ($P > 0.05$). In the abducted arm orientation, the shoulder-related cells' preferred directions were significantly bimodally distributed with a bias oriented along the $115\text{--}295^\circ$ axis ($P < 0.001$).

Although data related to the left arm (cells recorded in right motor cortex) have been mirror transformed in Fig. 7, the bimodal distributions of preferred directions remained when shoulder-related cells were analyzed for each arm separately, and appeared to be mirror opposites in nature (Fig. 8). For example, during the THT epoch in the abducted arm orientation the distributions for both the left and right arms were bimodal ($P < 0.01$). As well, the major axis of the distribution of shoulder-related cells for the right arm was at $148\text{--}328^\circ$ (i.e., 58° counterclockwise from the $90\text{--}270^\circ$ direction), whereas the major axis of the non-mirror-reversed distribution related to the left arm was at the $70\text{--}240^\circ$ (i.e., 60° clockwise from the $90\text{--}270^\circ$ direction), and thus the major axis for the left arm was a mirror image of the axis for the right arm. Furthermore, there was a significant difference between the distribution for the right shoulder-related cells and the nontransposed distribution for the left shoulder-related cells (Kuiper's test and Watson U^2 test, $P < 0.01$) (Batschelet 1981). In contrast, no significant difference was found when the right arm distribution was compared with the left arm distribution when the latter was mirror transposed ($P > 0.10$), so that the two distributions could be pooled without distorting the data. Similar trends were evident for the shoulder-related cells during RT+MT (Fig. 8). For instance, the principal axes for the left (non-

mirror reversed) and right arms were 58.4 and 110.3° , respectively.

The proportion of shoulder-related cells with significant changes in directional tuning (Watson-Williams test, $P < 0.01$) between arm orientations was higher than the proportion of elbow-related cells during the THT epoch (55 and 47.7%, respectively, $P < 0.05$, difference between proportions) (Freund 1984). Correspondingly, the average absolute shift in directional tuning for this epoch was slightly larger for shoulder-related cells (37.6°) than for elbow-related cells (33.8°). This trend of shoulder-related cells being more sensitive to changes in arm orientation than elbow-related cells was also seen during the RT+MT epoch.

In summary, there were important differences in the behavior of cells receiving passive input predominantly from the shoulder or elbow joints, and the directionality of shoulder-related cells tended to be more strongly modulated by changes in arm orientation than the directionality of elbow-related cells. Cells receiving about equal inputs from the shoulder and elbow were intermediate in their behavior to shoulder- and elbow-related cells in all response properties tested (data not shown).

Variation in cell activity between repeated data files

Because data in the two orientations were collected in separate sequential files, any systematic temporal variability in the activity of a cell will be confounded with any arm orientation effect on the cell's discharge. To determine the

FIG. 3. Changes in the activity of motor cortical cells during reaching movements in different arm orientations. A: change in the level of tonic discharge of cells during center hold time (CHT). Frequency histogram (left) of difference in cell discharge between abducted and natural orientations. Bin size: 5 spikes/s. Middle bin represents activity change of ± 2.5 spikes/s. Scatter plot (right) shows the relationship between the level of discharge of each cell during CHT in the natural arm orientation vs. the magnitude of change in discharge between orientations. Crosses: cells with a significant difference in discharge ($P < 0.01$, F test). Circles: cells with no significant difference ($P > 0.01$). B and C: diagrams at left show the proportion of cells directionally tuned in the natural orientation only (horizontal lines), abducted orientation only (vertical lines), and both (hatched), as well as those not directionally tuned in either arm orientation (unfilled). The number of cells in each group is indicated beside each pie slice. The frequency histograms (middle) illustrate the change in directional tuning of cells between natural and abducted orientations (bin size: 10° , central bin: $\pm 5^\circ$, positive value denotes a counterclockwise rotation in preferred direction from natural to abducted orientations). Scatter plots (right) show the relationship between the preferred direction of movement of each cell in the natural orientation vs. the magnitude of change in the preferred direction between orientations. Symbols denote statistical significance (F -test, task \times direction interaction, $P < 0.01$) as in scatter plot in A.

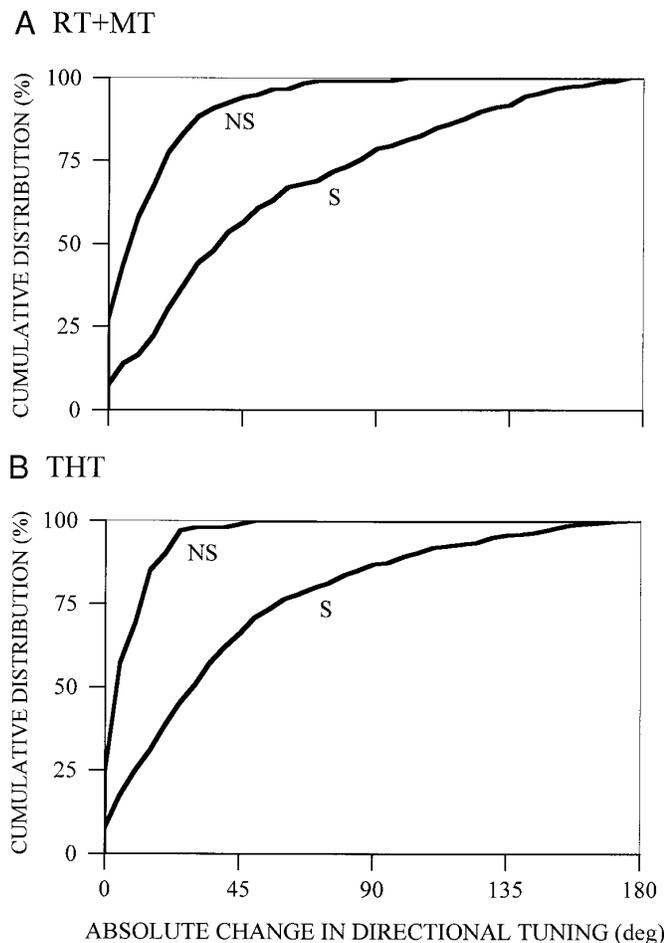


FIG. 5. Cumulative frequency histograms of the distribution of changes in directional tuning of cells that were directional in both arm orientations, but showed a significant (S) or nonsignificant (NS) task \times direction interaction effect during the RT+MT (A) or THT (B) epochs.

stability of the cell responses for movements in a given arm orientation over an extended period of time, a second set of data files was collected for some cells and the responses in the repeated data files in the same arm orientation were compared. To control for possible carryover effects between arm orientations, the repeated data files were collected in no fixed order and not necessarily in the same order as in the original data set. A total of 55 repeated files (24 natural and 21 abducted) was recorded from 30 different cells. There was a significant change in the level of discharge during CHT for only 8 of 55 (14%) repeated files (F test, main effect, $P < 0.01$, Table 1, Fig. 9A). Moreover, the average absolute change in cell discharge was only 2.3 spikes/s and only two (4%) pairs of repeated files showed a change in cell discharge >10.0 spikes/s (Fig. 9B). The magnitude of change in discharge for these cells between replicated files was statistically smaller than their observed change in discharge between arm orientations (8.5 spikes/s; $P < 0.001$; paired t -test), and also statistically smaller than the change in discharge between arm orientations for the entire cell sample (7.2 spikes/s, $P < 0.001$, Wilcoxon-Mann-Whitney test). Main effects were correspondingly rare and weak between replicated files during RT+MT and THT (Table 1).

For the RT+MT epoch, a significant repetition \times direction interaction effect was observed only once ($P < 0.01$, Table 1), only one cell showed a significant change in the distribution of replicated preferred directions between repeated files (Watson-Williams test, $P < 0.01$), and the average absolute shift in directional tuning was only 8.0° (Fig. 9B). In contrast, 23 of 30 (77%) of these cells showed a significant task \times direction interaction between natural and abducted orientations, 16 of 30 (53%) showed a significant change in the distribution of replication preferred directions (Watson-Williams test, $P < 0.01$), and the average magnitude of directional change was 49.2° . The magnitude of change in directional tuning for these cells between replicated files was statistically smaller than their observed change in discharge between arm orientations (nonparametric test for dispersion, $P < 0.001$), and also statistically smaller than the change in tuning between arm orientations observed for the entire cell sample (45.6° , $P < 0.001$, nonparametric test for dispersion) (Batschelet 1981). Similar stability of directional preferences was seen during the THT epoch of repeated files (Fig. 9C).

In summary, the responses of cells recorded in repeated data files in the same arm orientation showed much smaller changes in their overall level of activity and in their directional tuning than were seen for those same cells when recorded with the use of different arm orientations. Because the response changes of these cells between arm orientations are similar to those of the sample population as a whole, they are representative of that sample and not a group of cells that showed relatively small response alterations with arm orientation. This suggests that temporal variations in the activity of cells could explain, at best, only a small portion of the response variability between data files in different arm orientations. Further, the pairs of data files in different arm orientations that make up the body of this study were recorded consecutively with very little time between the completion of one file and the initiation of the next. In contrast, repeated data files for a given arm orientation were always recorded after one or more intervening files, and often after still further delays to test the cell for passive inputs. Therefore even the modest changes in tonic activity and directionality of cells between repeated files with the use of the same arm orientation likely overestimates the contribution of temporal variability in cell discharge to the changes in cell responses reported in this study during movements in different arm orientations.

EMG activity during reaching movements in different arm orientations

The EMG activity from the major muscles spanning the elbow and shoulder was recorded in both monkeys. Sixteen to 19 muscles were recorded in each arm of each monkey, resulting in a total sample of 70 muscle data sets. Most muscles were unimodally tuned during the motor task (Fig. 10) (Kalaska et al. 1989, 1990), and most elbow muscles were more active in the present paradigm than previously observed (Georgopoulos et al. 1982; Kalaska et al. 1989).

The effect of arm orientation on EMG activity showed a number of similarities to the changes in the response of

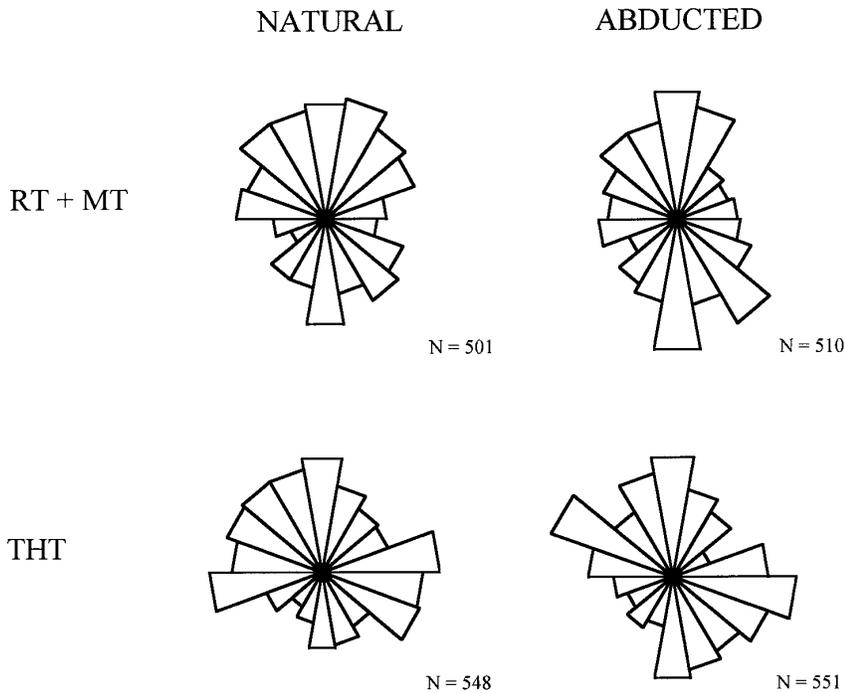
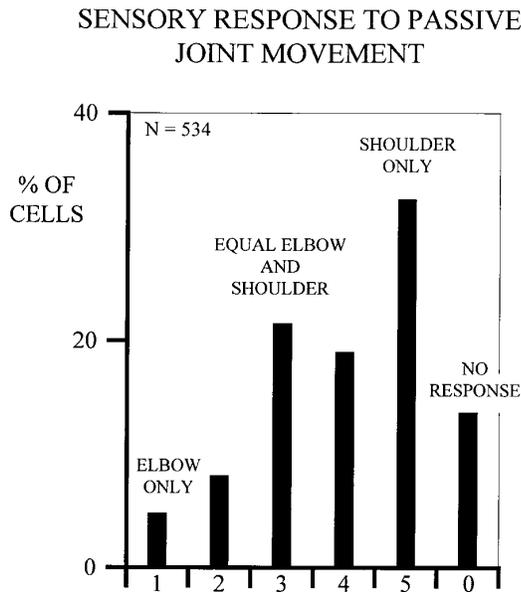


FIG. 6. Frequency distribution of the preferred directions of cells that were directionally tuned during movement (RT+MT) or posture (THT), in the natural and abducted orientations. The length of each segment is proportional to the number of cells with a preferred direction within the corresponding 20° segment.

A



B

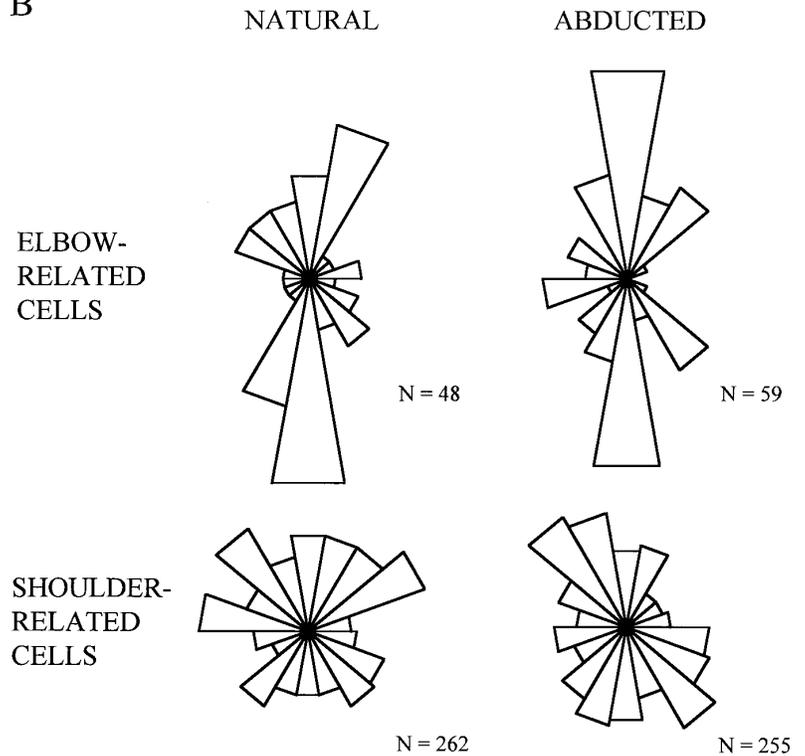


FIG. 7. A: frequency distribution of motor cortical cells with differing degrees of response to passive movement of the shoulder and elbow. B: distribution of preferred directions of elbow-related (scored 1 or 2) and shoulder-related (scored 4 or 5) cells for RT+MT in natural and abducted orientations.

motor cortical cells. There was a statistically significant change in EMG activity between the two arm orientations in at least one of the three trial epochs in virtually all EMG records (*F* test, *P* < 0.01, Table 1). Half of the EMG records (50%) showed changes in tonic activity

(main task effect) during CHT between the two orientations (Table 1, Fig. 11A), with the frequency of main task effects increasing to 66 and 68% in RT+MT and THT, respectively (Table 1).

The large majority of EMG records showed a significant

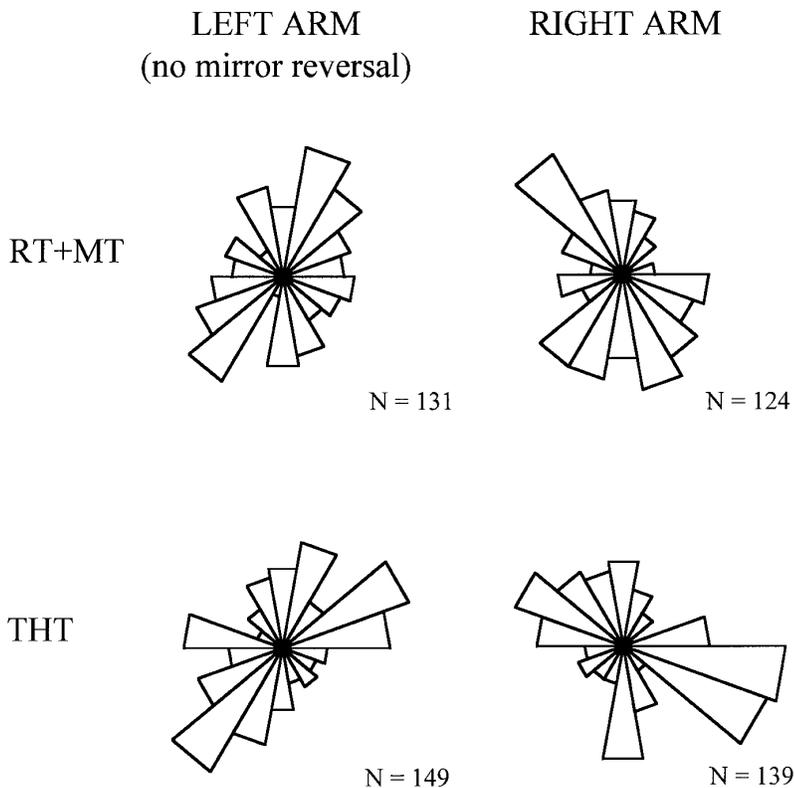


FIG. 8. Frequency distribution of the preferred directions of shoulder-related cells in the abducted arm orientation for the left and right arms (cells recorded in contralateral motor cortex). Note that major axes for the nontransposed distributions related to the left arm are mirror images of the distributions related to the right arm (see text).

task \times direction interaction effect in either the RT+MT (91%) or THT (90%) epochs. As was the case for motor cortex cells, this interaction effect manifested itself as either a change in the dynamic range of activity or a shift in directional preference or both. For instance, although most EMG records (52 of 70, 74%) were directionally tuned in both orientations during RT+MT (bootstrap test, $P < 0.01$), 5 EMG records were tuned in only the natural orientation and 11 only in the abducted orientation (2 muscles not tuned in either arm orientation). Whereas some of the 52 EMG records that were directionally tuned in both orientations showed little change in directional preference between arm orientations during RT+MT, including all of the records without a significant task \times direction interaction, others showed changes of $\geq 45^\circ$ (Fig. 11B). The average absolute change in directional tuning was 29.8° , which was less than that observed for the motor cortex population (Fig. 14, $P < 0.05$, nonparametric test for dispersion), and the distribution of changes was centered near 0° . Similar to the motor cortex cell sample, slightly less than half of the EMG records (21 of 52, 40%) showed a significant shift in the distribution of replication preferred directions between arm orientations during RT+MT (Watson-Williams test). Corresponding effects in the dynamic range and directionality of EMG activity were seen during the THT epoch (Fig. 11C, Table 1).

The distribution of preferred directions for all EMG records was irregular but statistically uniform for both arm orientations and both epochs (Rayleigh test, $P > 0.01$; Fig. 12). However, when muscles were separated according to the joint they span, the distribution of preferred directions was bimodal for all conditions (Rayleigh test, $P < 0.01$). Elbow muscles were active maximally for movements ap-

proximately along the $90\text{--}270^\circ$ axis in the natural orientation, with a small clockwise rotation toward the $45\text{--}225^\circ$ axis in the abducted orientation. Shoulder muscles were generally active approximately along the $0\text{--}180^\circ$ axis.

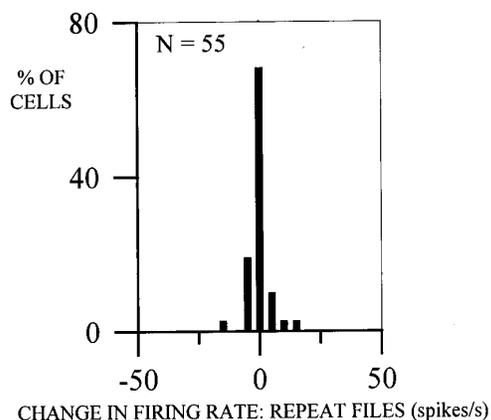
The stability of the muscle responses for movements in a given arm orientation was tested by recording repeated files of muscle activity in a given orientation. A total of 59 repeated files (30 control and 29 abducted) was collected. The incidence of significant main task effects and task \times direction interactions was far lower in the repeated file data sets in the same arm orientations than was the case for data sets between arm orientations (Table 1). The average absolute change in preferred direction between repeated files was only 8.2° . The variability of the directional tuning of muscles between repeated files was similar to the variability observed for the tuning of motor cortical cells between repeated files (see Fig. 9) and much lower than the changes in directional tuning of muscles and MI cells between arm orientations.

Mathematical models

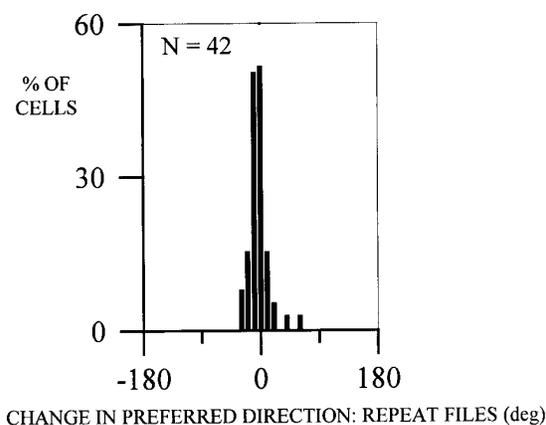
A number of models were developed to aid in the interpretation of the response properties of cells during the motor task (see APPENDIX). Three different populations of units are presented here: 1) units that encode the direction of hand movement in space (H units); 2) units that encode the direction of angular movement at the shoulder and elbow joints (K units); and 3) units that encode the torque at the shoulder and elbow joints (T units).

HAND-CENTERED COORDINATES. A key feature of this model was that unit activity reflected the intertrial variability in the path of the monkey's hand both within and between different

A TONIC ACTIVITY: CHT



B DIRECTIONAL TUNING: RT+MT



C DIRECTIONAL TUNING: THT

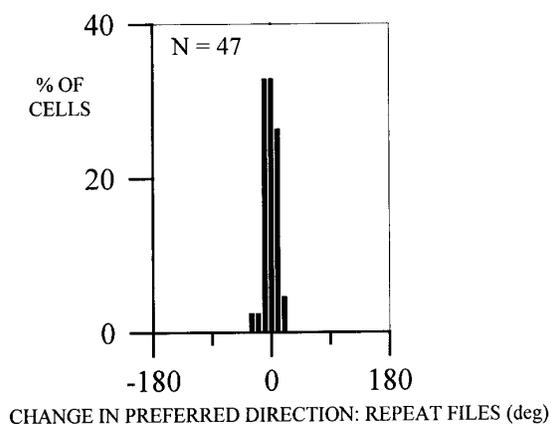


FIG. 9. Change in activity of motor cortical cells between repeated files with the use of the same arm orientation. *A*: change in tonic discharge during CHT. *B* and *C*: change in directional tuning of cells between repeated files during RT+MT and THT, respectively. Format same as Fig. 3. Note the relatively consistent activity between repeated files, compared with the changes in cell activity for reaching movements with the use of different arm orientations (Fig. 3).

arm orientations, on the basis of the observed mean and SD of the hand path at the midpoint of the movement to each peripheral target (see Fig. 1*B* and APPENDIX). The directional shift of these H units between arm orientations was

usually small (Fig. 13), unlike the response of motor cortical cells. Most H units (56%) showed a change of $<5^\circ$ in preferred direction between the natural and abducted orientations, and the average absolute change between orientations was only 5.2° . The directional tuning of motor cortical cells was more sensitive to changes in arm orientation than was the directional tuning of this population of H units (Fig. 14; nonparametric test for dispersion, $P < 0.001$) (Batschelet 1981). Therefore observed variations in hand path between arm orientations result in only minor changes in the directional tuning of units that encode the extrinsic kinematics of hand movement.

The distribution of preferred directions of these units encoding the direction of hand movement was uniform for each arm orientation (Rayleigh test for uni- or bimodal distribution, $P > 0.10$; Fig. 13), unlike the bimodal distribution observed for the total sample of motor cortical cells.

JOINT KINEMATIC COORDINATES. This model was designed to predict how cells specifying motor commands about shoulder and elbow joint angle changes would behave during whole arm reaching movements in different directions with the use of different arm orientations. The effect of arm orientation on the activity of K units during reaching movements (Fig. 15) showed many similarities to that of motor cortical cells. The directional tuning of many units showed a pronounced change between arm orientations, whereas other units did not show any change in directional tuning. Average absolute change in their preferred directions was 33.3° (Fig. 15), which was less than observed for the cell population in motor cortex during the RT+MT epoch (Fig. 14; nonparametric test for dispersion, $P < 0.01$), and the arithmetic mean change in the preferred direction was only 1.2° clockwise. This suggests that changes in arm orientation had a greater effect on the directional tuning of individual motor cortical cells than on a simulated population of units that explicitly encode joint angular movement at the shoulder and elbow.

The distribution of preferred directions of these K units was bimodal for both arm orientations (Rayleigh test, $P < 0.01$), with an increased skewing of the distribution for the abducted orientation (Fig. 15). The major direction of the distribution was along the $107\text{--}287^\circ$ axis for the natural orientation and along the $117\text{--}297^\circ$ axis for the abducted orientation. Similar trends were seen for motor cortical cells, although they were not as pronounced (Fig. 6).

There was a dramatic difference in the distribution of preferred movement directions between elbow- and shoulder-related K units (Fig. 15). The preferred directions of elbow-related units were strongly bimodally distributed (Rayleigh test, $P < 0.01$) close to the $90\text{--}270^\circ$ axis in both arm orientations. In contrast, shoulder-related K units were uniformly distributed in the natural arm orientation ($P > 0.01$), but were bimodally distributed in the abducted orientation ($P < 0.01$), with the principal axis oriented at $138\text{--}318^\circ$ (Fig. 15). These shifts in the preferred directions of K units reflect changes in the size and directional orientation of the maximum excursions of the four DOF of shoulder and elbow joint angle changes (Fig. 1*C*). Again, similar trends were seen in the behavior of elbow- and shoulder-related MI cells (Fig. 7), although they were more modest in degree.

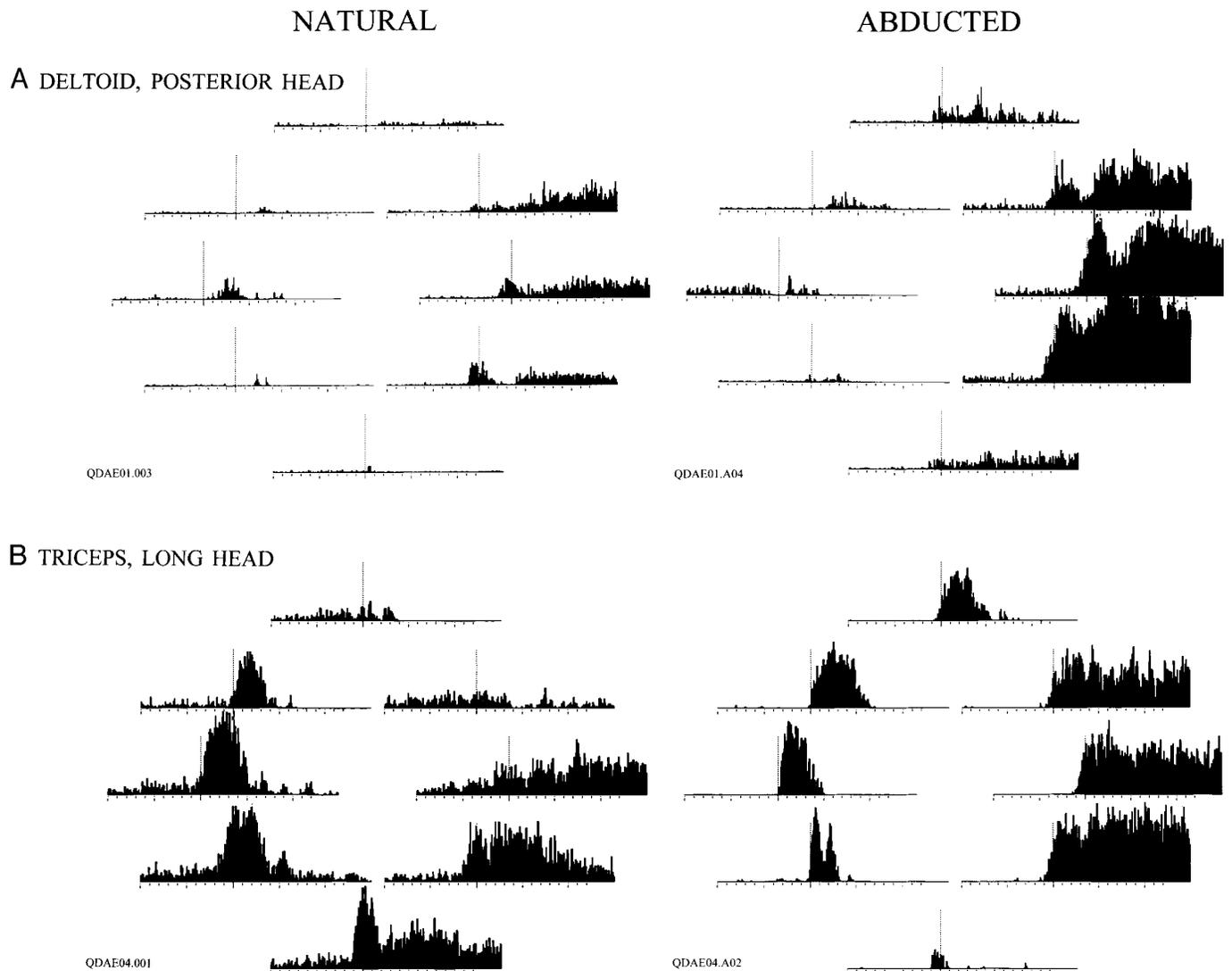


FIG. 10. Activity of posterior deltoid (*A*) and long head of the triceps (*B*) during reaching movements in the natural and abducted arm orientations. Each histogram is the sum of rectified electromyographic (EMG) activity recorded for 5 repetitions of movements to each target. Vertical dotted lines: start of movement.

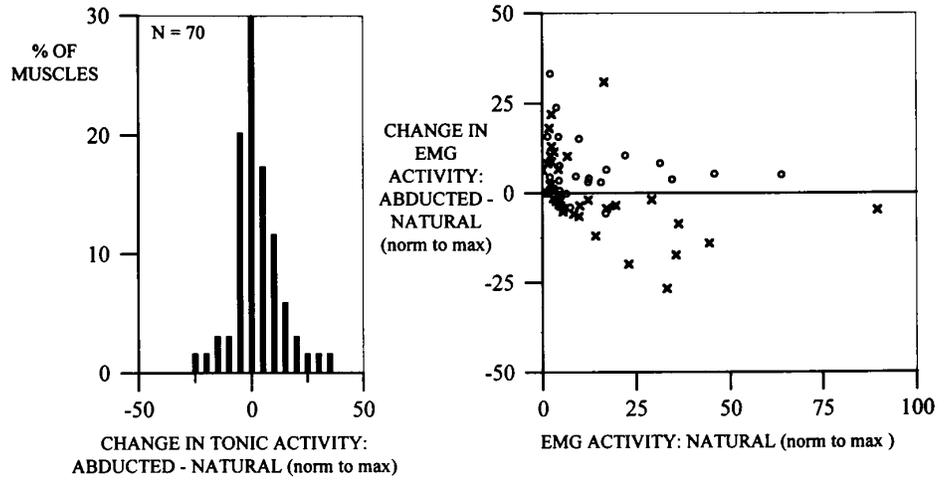
There is another interesting parallel to note between the model and the neuronal data. In the model, the coefficients for the four DOF of joint motion were randomly selected for each K unit in the population (see APPENDIX). Predominantly shoulder-related units composed 63% of the population and elbow-related units composed 11.5%, because of the greater number of DOF available at the shoulder. Although it may only be coincidental, this ratio is similar to that seen in the actual data sample (Fig. 7).

JOINT TORQUE COORDINATES. The behavior of T units also showed some similarities to that of motor cortical cells and EMG activity. For instance, variations in arm orientation had little effect on the preferred direction of movement of some T units, whereas others showed large changes in directional tuning (Fig. 16). The average absolute directional shift was 63.5° between orientations and the arithmetic mean change in preferred direction for the entire population between abducted and natural arm orientations was 16° clockwise. This population of units encoding torque at the shoul-

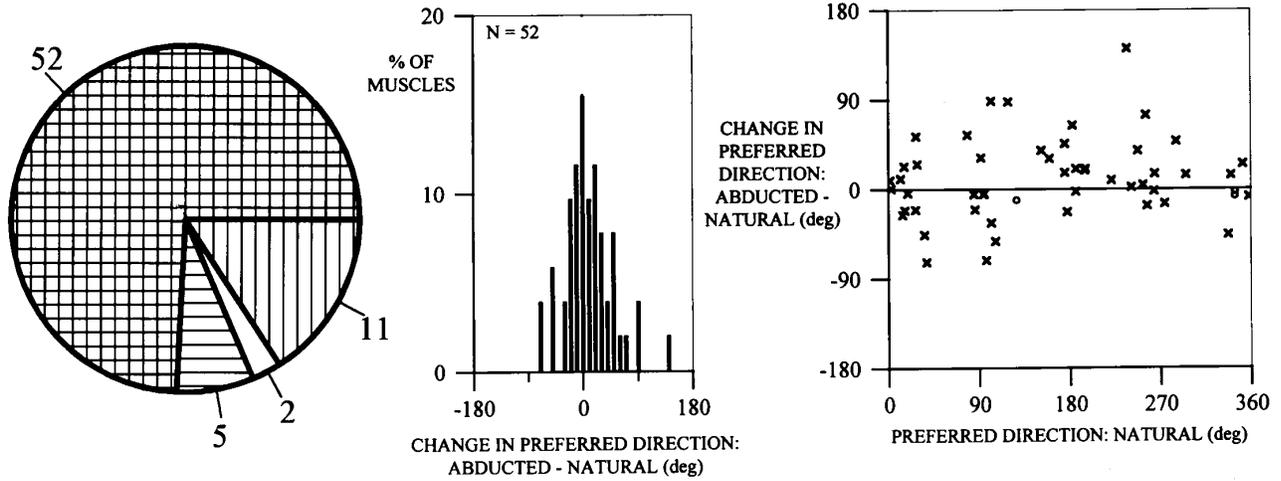
der and elbow was more sensitive to changes in arm orientation than motor cortical cells (Fig. 14; nonparametric test for dispersion, $P < 0.01$). There was a relatively systematic relationship between the change in the preferred direction of these T units and their preferred direction of hand movement in the natural arm orientation (Fig. 16). Changes in the preferred direction were limited to a 180° band that shifted systematically with the preferred direction of movement for the natural arm orientation. There was some evidence for a similar but less sharply defined cyclical relation between cell preferred direction in the natural orientation and the change in directional tuning in the abducted orientation in both motor cortical cells (Fig. 3) and in the K units of the joint kinematics model (Fig. 15).

The preferred directions of T units were distributed bimodally, approximately along the 0 – 180° axis (Rayleigh test, $P < 0.01$, Fig. 16). The orientation of the major axis of the distribution shifted between arm orientations, and the distribution was somewhat more eccentric in the natu-

A TONIC MUSCLE ACTIVITY: CHT



B DIRECTIONAL TUNING: RT+MT



C DIRECTIONAL TUNING: THT

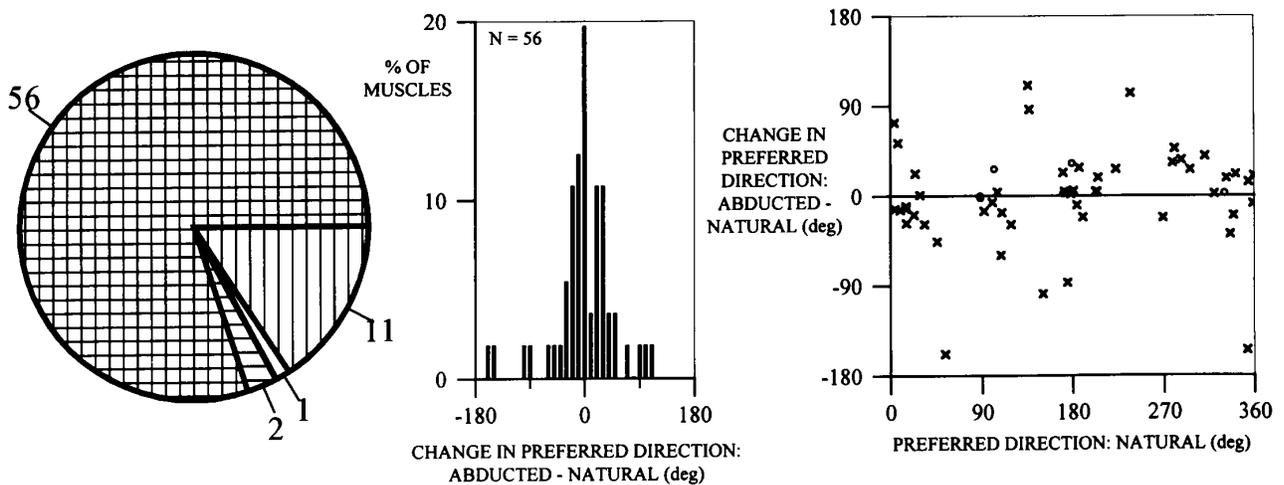


FIG. 11. Changes in the EMG activity of proximal arm muscles during reaching movements in different arm orientations. *A*: change in the tonic level of EMG during CHT between orientations. Level of EMG normalized to maximal value recorded in any behavioral epoch. *B* and *C*: changes in the directional tuning of EMG during RT+MT and THT, respectively, between orientations. Format of diagram same as in Fig. 3.

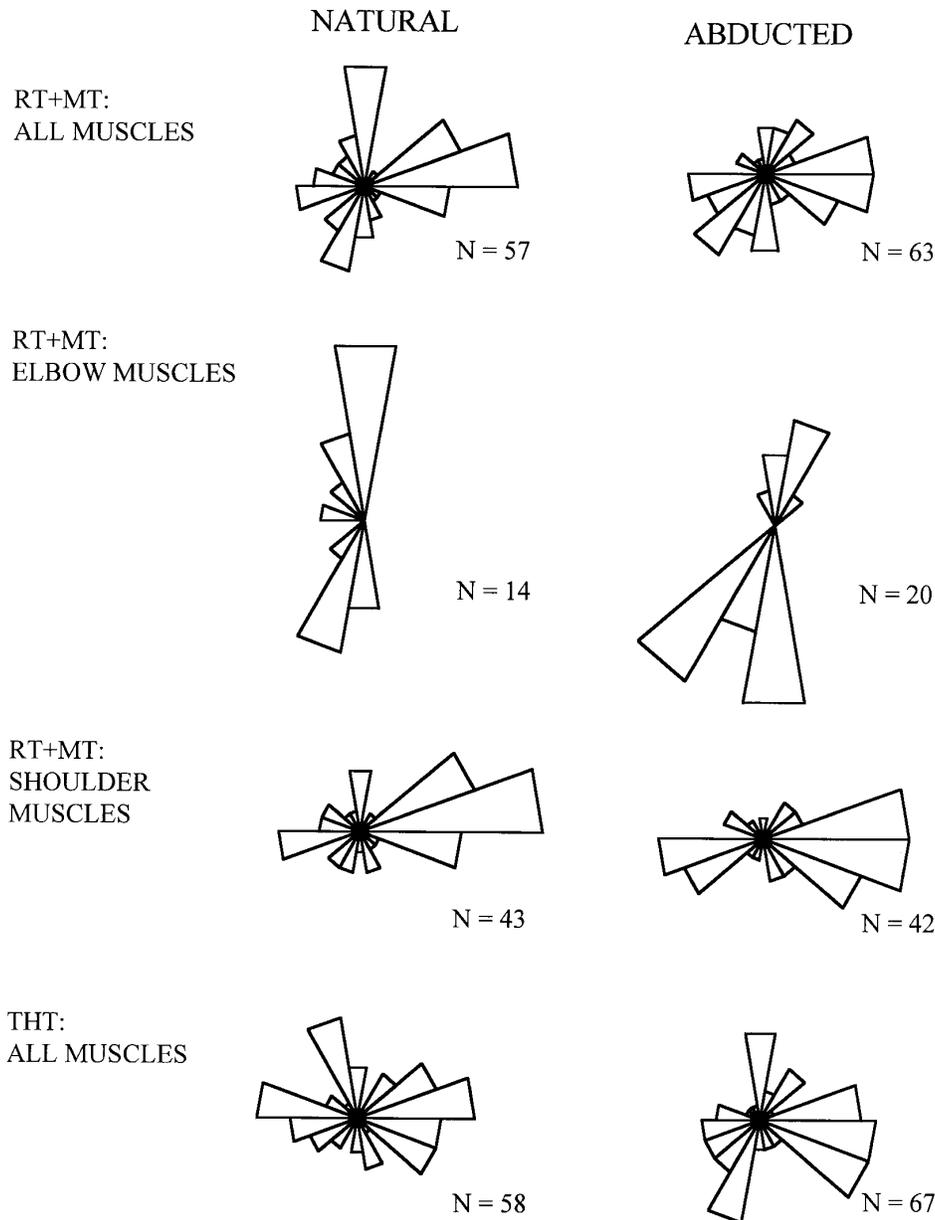


FIG. 12. Frequency distribution of preferred directions for EMG of proximal arm muscles in natural and abducted orientations during RT+MT and THT epochs.

ral than in the abducted orientation. The preferred directions of elbow and shoulder-related T units were also bimodally distributed for both arm orientations (Rayleigh test, $P < 0.01$), but showed different directional biases. Shoulder-related T units were preferentially distributed approximately close to the $0-180^\circ$ axis in both arm orientations, and did not change much between orientations (the apparent lack of units with optimal shoulder torques close to the $90-270^\circ$ axis arises because the hand and shoulder are at the same horizontal level, so that output forces exerted at the hand along that axis are generated by net torques at the elbow and not at the shoulder). Elbow-related T units, in contrast, were oriented along the $94-274^\circ$ axis in the natural orientation, and rotated clockwise to the $45-225^\circ$ axis in the abducted orientation. Overall, these patterns of distributions of preferred directions of shoulder- and elbow-related T units showed more

similarity to those of shoulder- and elbow-related EMG activity than to those of motor cortical cells.

DISCUSSION

It is a truism that to reach to a visual target, the CNS must transform the image of the target on the retina into contractions of motor units in arm muscles. Understanding how the CNS generates a reaching movement therefore requires knowledge of the nature and number of intervening sensorimotor transformations and how they might be realized explicitly or implicitly by neuronal circuits (Feldman and Levin 1995; Flanders et al. 1992; Georgopoulos 1991, 1995; Kalaska 1991, 1995; Kalaska and Crammond 1992; Karst and Hasan 1991a,b; Lacquaniti 1989; Lacquaniti et al. 1995; Soechting and Flanders 1992). The present study was designed to test whether

3-D HAND-CENTERED MODEL

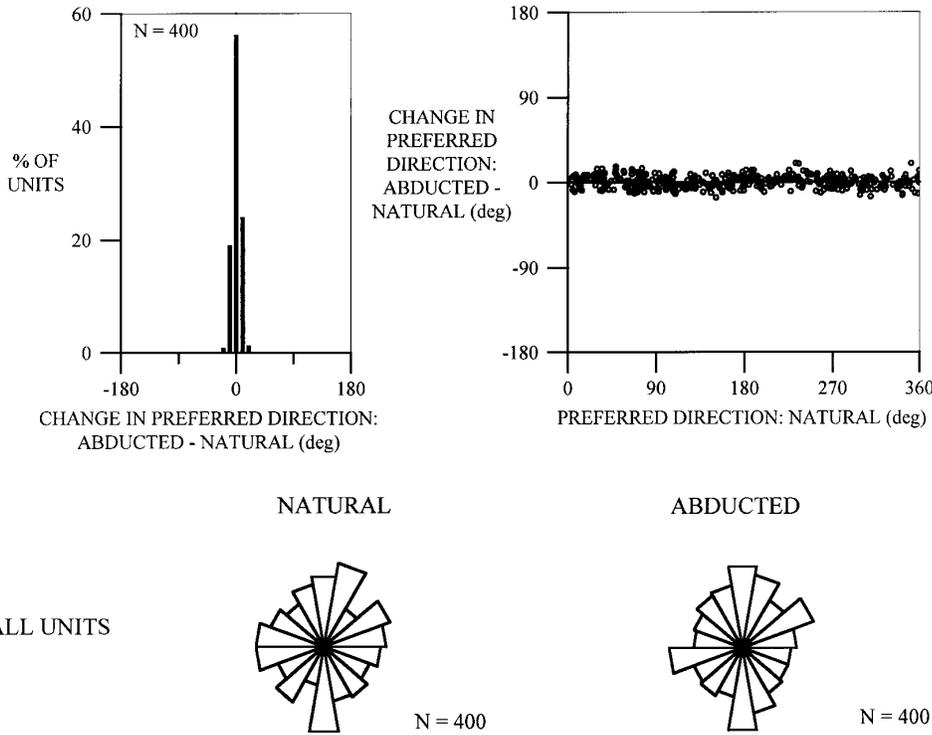


FIG. 13. Changes in directional tuning for a simulated population of units encoding the direction of hand movement. Variability in directional tuning reflected the observed trial-to-trial variability and systematic differences in the hand path between arm orientations (see Fig. 1B). Top: same format as in Fig. 3. Bottom: distributions of preferred directions, same format as in Fig. 6.

single cells in MI contributed to the control of reaching movements at a stage before or after a putative transformation from an extrinsic representation related to the path of the hand or target location in space to an intrinsic representation related to the properties of the proximal arm motor apparatus. If the activity of neurons explicitly signaled information in an extrinsic space, as defined

here, their activity would not be altered when reaching movements were made with the use of similar hand trajectories but with different arm orientations. In contrast, changes in arm orientation during reaching will alter the activity of neurons signaling movement in an intrinsic parameter space.

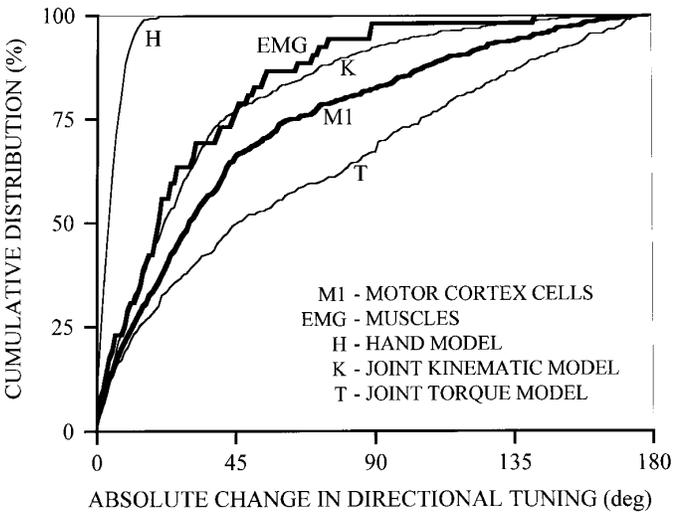


FIG. 14. Cumulative frequency distribution of the change in directional tuning between arm orientations observed during RT+MT for motor cortical cells and muscles, and predicted for populations of units encoding different movement parameters. H, units encoding direction of hand movement in space; K, units encoding direction of angular movement at shoulder and elbow joints; T, units encoding torque at shoulder and elbow joints.

There are several major observations in this study. First, almost all cells showed a significant change in task-related activity, either in their overall level of discharge or directional tuning or both, as a function of different arm orientations while monkeys made reaching movements along similar hand paths to fixed target locations. Second, these changes occurred during both static (CHT, THT) and dynamic (RT+MT) epochs of the task, and for a given cell, the nature of the changes tended to be correlated between static and dynamic task conditions. Changes in cell activity between arm orientations could not be explained by variability in the response of cells over time (Fig. 9), nor do the small differences in the path of the hand to each target between arm orientations appear to account for the large changes in the activity seen in many cells (Figs. 2 and 13). Third, the distribution of preferred directions of cells was not uniform, particularly when movements were performed in the abducted arm orientation. Fourth, differences were found in the task-related responses of subpopulations of cells with sensory input predominantly from either the shoulder or elbow. Fifth, there were greater similarities between the arm-orientation-related changes in activity of motor cortical cells and those observed for muscles and predicted for populations of simulated units encoding joint-centered parameters of movement than there were with simulated units encoding hand-centered movement parameters.

4-D JOINT KINEMATIC MODEL

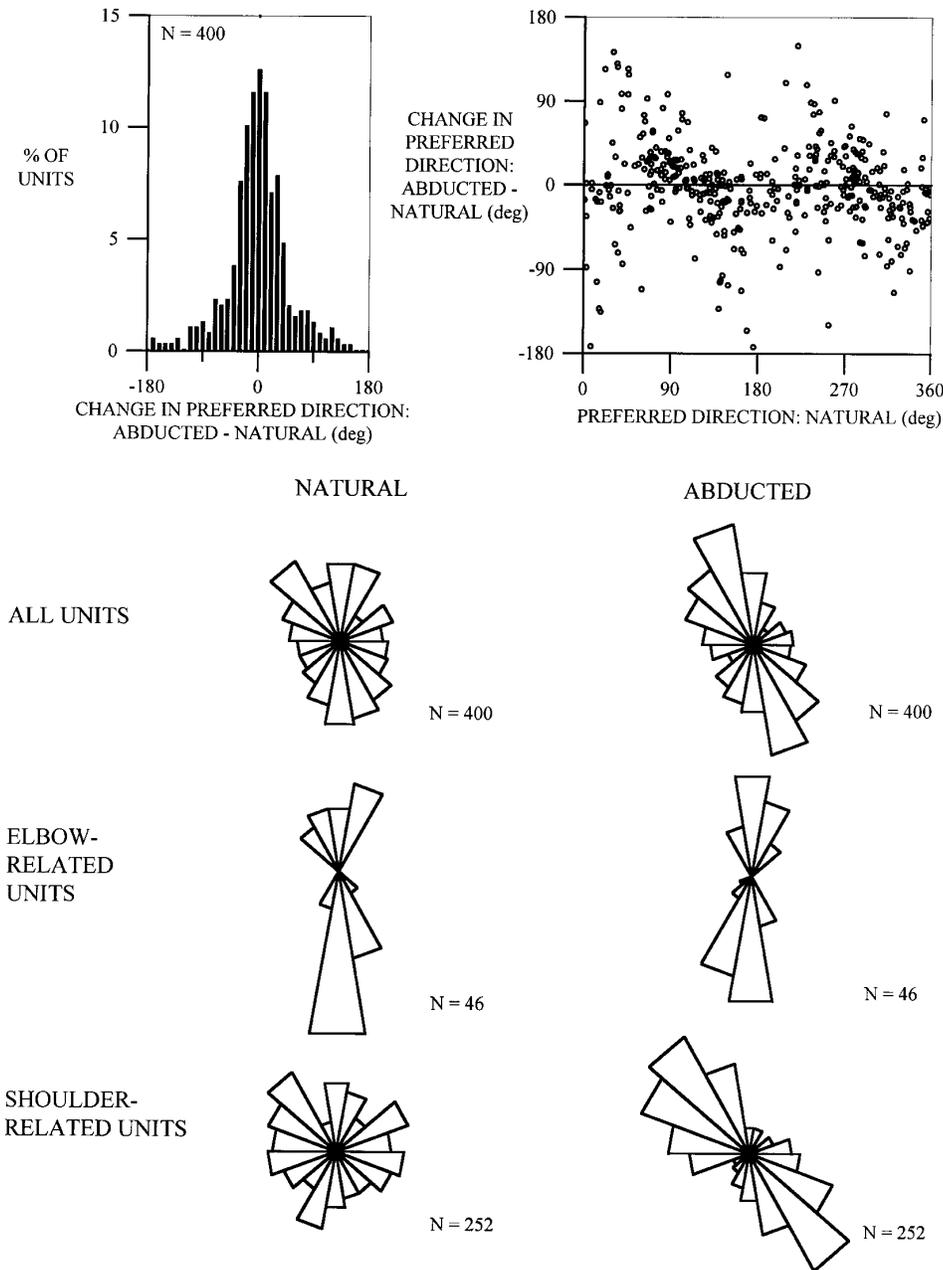


FIG. 15. Changes in directional tuning for a simulated population of units encoding joint angles at the shoulder and elbow. *Top*: same format as in Fig. 3. *Bottom*: distributions of preferred directions, same format as in Fig. 6.

Do single motor cortical cells explicitly encode intrinsic variables of movement?

The present findings reveal that the discharge of many single MI neurons located in the bank of the central sulcus covaried with arm orientation during planar reaching movements. Mathematical models of units encoding intrinsic joint-centered kinematic or kinetic parameters predicted a complex relationship between changes in arm orientation and changes in directional tuning that had many similarities to those observed for motor cortical cells, whereas the extrinsic hand space model predicted very little change of directional tuning of single cells with arm orientation. Therefore

this study shows that motor cortical discharge during reaching movements is influenced by arm geometry, and any coordinate system proposed for the movement representation in motor cortex that does not take into account the geometry of the arm provides an inadequate description of the activity of most single MI cells. However, the results are not proof that MI neurons encode movement either explicitly or exclusively in an intrinsic parameter space related directly to kinesiological features of movement.

The extrinsic hand space model as formulated in this study does not make a distinction between the activity of cells related to different parts of the arm. In contrast, the responses of cells responding preferentially to pas-

4-D JOINT TORQUE MODEL

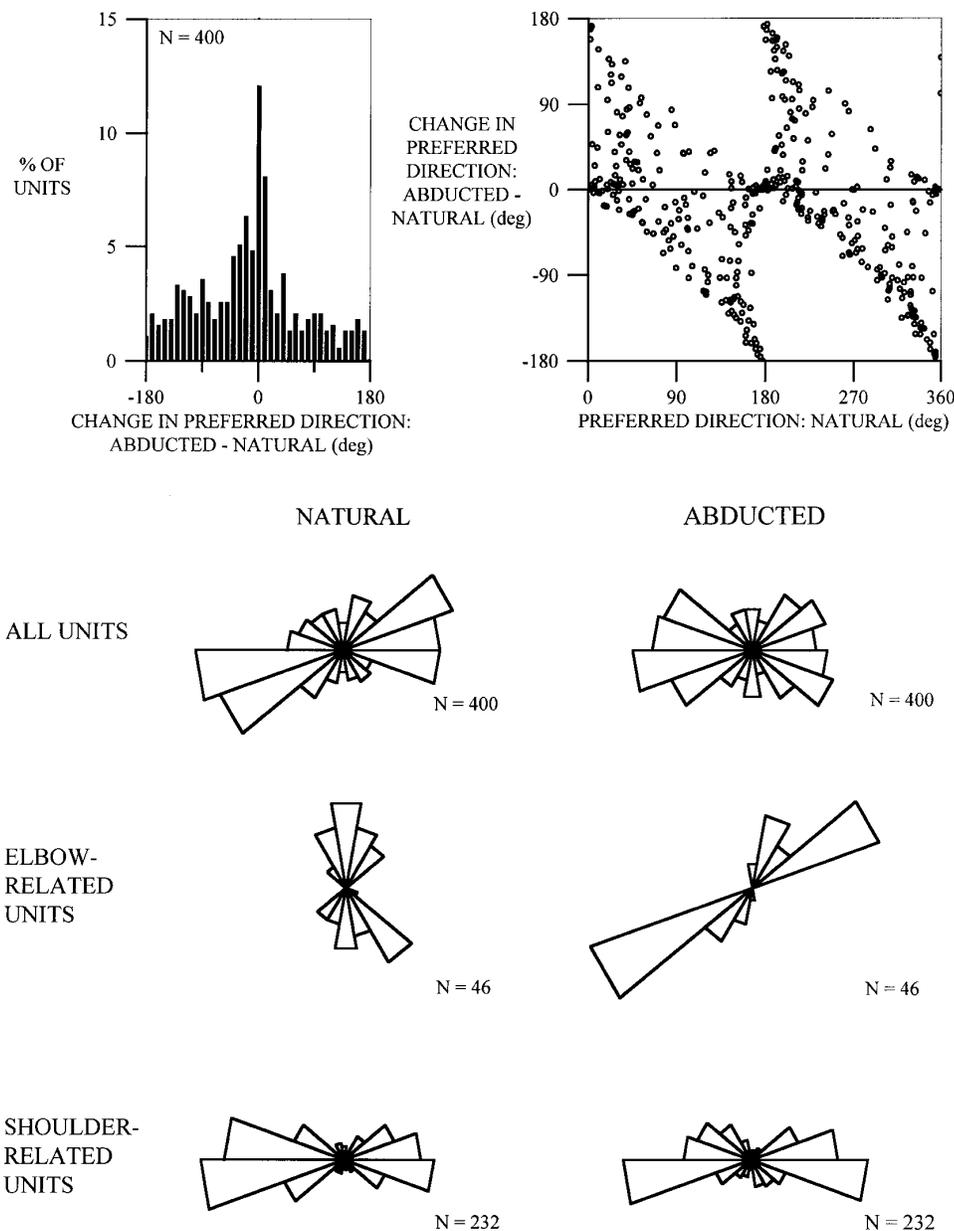


FIG. 16. Changes in directional tuning for a simulated population of units encoding joint torque at the shoulder and elbow. *Top*: same format as in Fig. 3. *Bottom*: distributions of preferred directions, same format as in Fig. 6.

sive motions of the shoulder or elbow joints were different and appeared to reflect the different contributions of their respective peripheral motor fields to the performance of the arm movements in the two arm orientations, as predicted by the joint-centered models. This provided some of the most compelling evidence of the influence of intrinsic movement attributes on MI cell discharge found in this study.

For instance, although single elbow-related cells and muscles were broadly tuned with movement direction, their preferred movement directions were strongly concentrated along the 90–270° movement axis in the natural arm orientation (Figs. 7 and 12). In contrast, the distribution of preferred directions of shoulder-related cells was uniform. This reflects a number of important differences in the action of

the shoulder and elbow during multijoint reaching movements. In the natural arm orientation, the greatest change in elbow joint angle and elbow torques both occurred along the 90–270° axis. In contrast, movements in different directions involved large changes in shoulder joint angle in all three principal DOF of motion, and the directions of movement producing the largest changes in shoulder angle were widely different for each DOF (Fig. 1). Furthermore, the kinematic and kinetic features of movement were less coupled at the shoulder than at the elbow: the directions of movement requiring the largest change in shoulder angle were different from the directions requiring the largest joint torque (~90–270° and 0–180° axes, respectively). Because MI cell activity appears to covary with both kinetic and kinematic parameters of movement (Kalaska et al. 1989; Thach 1978), this

would produce a broad distribution of tuning properties for shoulder-related cells in the natural arm orientation.

Moreover, reaching movements in which the different arm orientations were used resulted in large changes in angular motions at the shoulder but minimal changes at the elbow. In the abducted arm orientation, the directions of movement that produced the largest change in joint angle for all three DOF of shoulder motion tended to shift toward the 135–315° axis, and this was accompanied by a decrease in excursion of shoulder joint internal/external rotation from natural to abducted conditions. As a result, the joint kinematics model predicted that the distribution of shoulder-related cell preferred directions should become bimodal and oriented toward the 135–315° axis, whereas the directional preferences of elbow-related cells should remain strongly bimodally distributed along the 90–270° axis, as was observed.

The joint torque model predicted the opposite trend, that the distribution of elbow cell preferred directions would shift more than that for the shoulder. Overall, the joint kinematics model predicted some aspects of the behavior of motor cortical cells better than the joint torque model. We would not conclude, however, that motor cortical cells signal the intrinsic kinematics of reaching movements. Many experimental results contradict that conclusion (Evarts 1968; Fromm 1983; Humphrey 1972; Humphrey and Tanji 1991; Kalaska et al. 1989; Smith et al. 1975; Thach 1978). One must also consider the simple nature of the mathematical models developed for this study. In particular, the joint torque model only considered the forces exerted at the hand to initiate movement of the manipulandum to each target and not the forces to move the limb itself, nor any forces exerted by the monkey on the manipulandum out of the plane of motion. It is difficult to predict how inclusion of these other joint torques would affect the behavior of the model units. Moreover, a model that expresses the kinetics of the task in a more physiological muscle-based space may yield different predictions than did the joint torque model. Nevertheless, the fact that there were some similarities between the behavior of T units and muscle activity suggests that even this very simple model has some utility.

The present study complements the findings of Caminiti et al. (1990, 1991), who also showed that the directional preference of cells was influenced by the starting posture of the arm and was not fixed to the absolute spatial direction of hand movement. Furthermore, they found a systematic rotation in tuning across the population of cells that followed the angular rotation at the shoulder about the vertical axis necessary to make the movements in each region of the work space. We observed no such systematic shift in the directional tuning of the sample population. This reflects a fundamental difference in task design. In the study by Caminiti et al. (1990), movements were made in three-dimensional space and the arm orientation rotated predominantly about one of the three orthogonal axes (vertical). As a result, any rotation of the tuning function of a cell about any of the three spatial axes with the change in arm geometry would be expressed and observed in the task of Caminiti et al. In contrast, in the present study, hand movements were confined to the horizontal plane, so that we could only observe that part of the tuning function of each cell expressed within

that plane. However, the arm rotation in our task occurred about an axis in the plane of the task, not orthogonal to it. As a result, the directional tuning functions of most cells, if coupled to arm orientation in an arm- or body-centered coordinate system, will rotate mainly into or out of the plane of hand movements and not within it and would result in no net rotation of their distribution, as was observed. It is also noteworthy that the distribution of shifts in directionality of EMG activity, which is strongly coupled to arm geometry (Buchanan et al. 1986; Buneo et al. 1995; Flanders and Soechting 1990; Karst and Hasan 1991a,b), likewise did not show any systematic bias.

Lacquaniti et al. (1995) described a regression analysis of area 5 activity in the same task apparatus used for the study by Caminiti et al. (1990). Consistent with the present results, Lacquaniti et al. concluded that a body-centered coordinate frame accounted better for the discharge across all three cubic work spaces than did a hand-centered directional reference frame in each cube separately. However, Lacquaniti et al. could not distinguish between coordinate systems that specified only the location of the hand relative to the body and those that partly or completely specified intrinsic parameters (joint or limb segment angles). This resulted because movement variables in different parameter spaces were all highly correlated (Lacquaniti et al. 1995; Mussa-Ivaldi 1988). Our results suggest that for many MI cells, any attempt to account for their activity in a parameter space that only specifies hand location and movement direction, without reflecting the intervening limb geometry, is untenable. For instance, the finding that the distributions of preferred directions of shoulder-related cells recorded with the left and right arms in the abducted orientations were bilobed with a directional bias that was mirror reflected about the sagittal plane presumably paralleled the mirror-reflected geometry and mechanics of the two arms. This mirror-image symmetry provides further evidence that an important component of the discharge of MI cells during reaching movements can be best described by a body-centered or even a limb-centered coordinate framework (Caminiti et al. 1990, 1991).

Do single motor cortical cells explicitly encode extrinsic variables of movement?

The summed activity of MI cell populations has been shown to covary with the direction and path of the hand in space (Georgopoulos et al. 1982, 1983, 1988; Schwartz 1993). Subsequent studies have extended this finding by relating the discharge of single motor cortical cells simultaneously with several different extrinsic kinematic parameters, such as the direction, velocity, amplitude, and target location of straight-line movements (Ashe and Georgopoulos 1994; Fu et al. 1993, 1995), and the instantaneous direction and speed of continuously curved trajectories (Schwartz 1992, 1993, 1995).

However, the results of the present study argue strongly that many individual motor cortical cells neither explicitly nor exclusively “encode” the direction of movement of the hand or its spatial location, per se, but rather reflect at least in part the covariation of intrinsic movement attributes at their peripheral motor fields with the desired direction of

hand movement, or the force required to hold the hand at a particular location. However, they are not proof that single-cell discharge expressed only intrinsic attributes of the movement, or that no neuronal correlate of extrinsic spatial parameters exists in MI at either the single-cell or population level.

Although the hand paths traversed by the monkeys in the two arm orientations in this task were very similar, they were not identical (Fig. 1). It is possible therefore that the effects of arm orientation on cell activity in this study could all be caused by small changes in the extrinsic kinematics of motor performance in the two arm orientations. However, the hand space model took into account the directional variability of hand paths within and between arm orientations to predict the resulting directional changes that would be expected of cells signaling extrinsic kinematics, but failed to reproduce any of the major effects on cell activity observed in the task (Fig. 13). This suggests that hand path variability, at least as concerns its direction, cannot explain the cell response patterns in this study, many of which were captured by very simple joint-centered intrinsic models. Admittedly, there were also small changes in movement velocities between arm orientations (Fig. 2) that could account for more of the task-related changes in activity than the hand space model currently does. However, the relation with velocity may be strongest near the cell's preferred direction (Schwartz 1992, 1993), so that there would have to be large changes in velocity for movements away from the cell's preferred direction to significantly alter its directional tuning. Velocity changes of that magnitude were not seen (Fig. 2). Moreover, the regression studies reported that movement direction was typically the single most important factor determining cell activity and that velocity and other extrinsic parameters were less important, suggesting that the addition of other factors will have a minor impact on the predictions of the hand space model.

Even more difficult to explain with the use of a hand-centered extrinsic kinematics model are the changes in activity of single cells between arm orientations during the static epochs of the trial, specifically, the changes in tonic activity during CHT, and the changes in both overall activity level and spatial tuning during THT. In those epochs, the hand was being held steadily in the same spatial locations over the targets and the only difference was in the orientation of the arm. A strictly extrinsic hand-centered model that signaled hand location would predict no changes in activity in those conditions. The response changes between arm orientations could have a different origin during the dynamic and static parts of the task if, for instance, the nature of the relation of motor cortex activity to motor output parameters is fundamentally different between static and dynamic conditions (Georgopoulos et al. 1992; Soechting and Flanders 1992). However, the changes in discharge level and directional tuning observed during the dynamic (RT+MT) and static (CHT, THT) epochs of the present task were statistically correlated. This is readily explained if the orientation-related response changes in the static and dynamic epochs had a common causal origin related to a stable relation between cell activity and motor performance during dynamic and static epochs of the task (Crammond and Kalaska 1996).

Conversely, the observation that the changes in directional tuning of a number of motor cortical cells were relatively

small or that 30% of the cells directional in both orientations did not show a significant task \times direction interaction during RT+MT could be interpreted as evidence that a distinct subpopulation of motor cortical cells encodes hand trajectory. However, those neurons represented only part of a continuum of changes in the discharge patterns of cells, not a distinct group (Fig. 3). Furthermore, the mathematical models also predicted that the directional tuning of many units will not be altered by changes in arm orientation even when they explicitly encode intrinsic features of movement. For those units, the change in arm orientation did not produce a sufficient change in the mapping between hand trajectory confined to the plane of the task and their preferred combination of intrinsic movement parameters to result in a large variation in apparent directional tuning. That lack of change does not alter the underlying mathematical basis for these simulations: they encoded intrinsic features of movement and not the direction of hand movement.

Similarly, some EMG records from muscles spanning the shoulder and elbow showed no significant task \times direction interaction or significant shifts in the distribution of replication preferred directions. This does not mean that the contractile activity of those muscles was directly related to the extrinsic kinematic parameter of movement direction in anything other than the most general descriptive sense. Instead, the activity of a given muscle during reaching is related to its ability to contribute to the performance of the motor task as a function of skeletomuscular geometry and mechanics (Buchanan et al. 1986; Buneo et al. 1995; Flanders and Herrmann 1992; Flanders and Soechting 1990; Karst and Hasan 1991a,b; Kuo 1994; Zajac and Gordon 1989). In a number of cases, the change in arm orientation did not produce a sufficient change in those factors to cause an alteration in the covariation of muscle activity with hand movement direction in the horizontal plane of the task.

In summary, it is predictable that a sizeable population of cells encoding intrinsic movement attributes such as joint angle changes, joint torques, or even single-muscle activity levels will show no change in directional tuning in the task used in this study. Therefore the finding that some cells in motor cortex show minor changes in direction is at best equivocal evidence of an explicit representation of hand trajectory at the single-cell level.

Nature of the parameter space for motor cortical discharge

What parameter space best describes the activity of MI cells remains a formidable technical and conceptual problem. The present observations emphasize that the well-established broad directional tuning of motor cortical neurons (Fu et al. 1993, 1995; Georgopoulos 1995; Georgopoulos et al. 1983; Kalaska et al. 1989; Schwartz 1992, 1993, 1995; Schwartz et al. 1988) is not of itself sufficient to favor one alternative over others. Mathematical models here (Fig. 17) and elsewhere (Lacquaniti et al. 1995; Mussa-Ivaldi 1988; Sanger 1994; Tanaka 1994) have demonstrated that units encoding either extrinsic or intrinsic features of movement can be broadly tuned to the direction of hand movement in each arm orientation. The directional tuning of model units signaled the desired change in state in their particular parameter

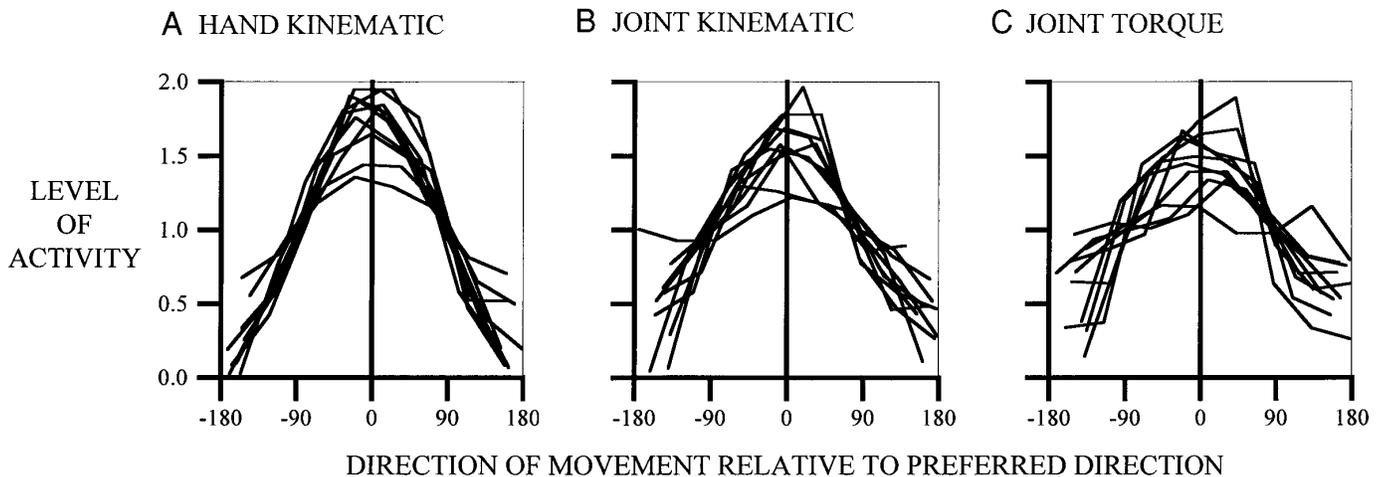


FIG. 17. Directional tuning curves of 10 randomly chosen units encoding movement in 3 different parameter spaces, illustrating the variation of their activity level as a function of the direction of planar hand movements in the natural arm orientation. The tuning curve of each unit is centered on its "preferred direction," identified during the planar hand movements.

space as a function of movement direction. Moreover, broad directional tuning is a property of cells in every structure studied with reaching movements, and the discharge of these cell populations covaries to different degrees with a wide range of movement parameters (Kalaska and Crammond 1992). The significance of this finding is subject to two very different interpretations.

On the one hand, this may indicate that the motor system might perform sensorimotor transformations by encoding movement-related information in terms of their covariation with intended movement direction (Georgopoulos 1991, 1995; Kalaska and Crammond 1992; Kalaska et al. 1989, 1990). Furthermore, the discharge of a single cell may not express movement in a single distinct reference frame. Instead, cell activity usually shows partial correlations to a number of different movement attributes from different parameter spaces, as if expressing weighted combinations of signals in different reference frames (Alexander et al. 1992; Fetz 1992, 1993; Kalaska 1991, 1995; Kalaska and Crammond 1992; Thach 1978). Rather than representing the movement explicitly in a distinct parameter space, single cells may be signaling the covariation of movement attributes in different reference frames, and so implicitly affect a sensorimotor transformation. The representation of a given parameter space would be found in the partial correlations distributed across a heterogeneous population of cells.

On the other hand, these partial correlations with multiple movement parameters may be an epiphenomenon resulting from the inescapable fact that movement variables in different parameter spaces are tightly coupled through the laws of motion and skeletomuscular mechanics (Kalaska 1991, 1995). Most studies have failed to dissociate them adequately, and the problem is exacerbated by the highly stereotyped motor behavior of overtrained monkeys. As a result, should cells encode movement in a particular reference frame, they will inevitably also show strong partial correlations with many different movement parameters in other reference frames. According to this point of view, demonstration of multiple partial correlations in cell activity reveals less about underlying central mechanisms than about the fact

that extrinsic and intrinsic kinematic and kinetic parameters are all inextricably coupled through the laws of motion and skeletomuscular mechanics.

Motor cortex and the selection of coordinated multimuscle recruitment patterns

Whatever the nature of the parameter space(s) in which MI cells are functioning, it is informative to consider the implications of their response properties in terms of motor output. Ultimately, the desired movement is produced by generating the appropriate coordinated pattern of activity of a large number of muscles in the arm. The powerful effect of direction on the activity of muscles is well established and produces directional tuning functions that typically bear considerable similarity to those of MI cells (Buchanan et al. 1986; Flanders and Herrmann 1992; Flanders and Soechting 1990; Kalaska et al. 1989, 1990; Karst and Hasan 1991a,b; Turner et al. 1995; Wadman et al. 1980). EMG patterns are also strongly dependent on mechanical factors that vary with limb posture (Buchanan et al. 1986; Flanders and Soechting 1990; Karst and Hasan 1991a,b). For instance, Karst and Hasan (1991a,b) found that the patterns of recruitment of muscle activity at the shoulder and elbow during planar pointing movements were less related to the absolute direction of hand movement than to the direction of the target relative to the angle of the forearm, i.e., its initial posture. Furthermore, the specific multimuscle coordination pattern appears to be highly dependent on specific task conditions, implying that fixed multimuscle "synergies" applicable over a broad range of task conditions cannot be a major mechanism to facilitate multimuscle coordination (Buchanan et al. 1986; Karst and Hasan 1991a,b; MacPherson 1991; Soechting and Lacquaniti 1989). The CNS must have other means to specify the requisite coordinated multimuscle pattern for each task condition.

Many MI cells have been shown to be strongly modulated by all major parameters, including the direction of movement, the direction and size of output forces and external loads, and now the geometry of the limb, that influence

muscle activity patterns. This suggests that a critical role for the motor cortex is to transform directional aspects of motor tasks into the appropriate coordinated multimuscle recruitment patterns (Georgopoulos 1991, 1995; Kalaska and Drew 1993). Consistent with this hypothesis, the discharge of corticomotoneurons is often highly specific to the nature of the fractionated muscle activity patterns within which their target muscles are being recruited (Bennett and Lemon 1996; Muir and Lemon 1983).

It is now widely recognized that the divergent projections of a given corticospinal axon onto spinal interneuronal networks or directly into motoneuron pools will tend to establish a graded pattern of activation of a set of muscles, its so-called muscle field. The broadly tuned discharge of MI cells could reflect the orderly gradation of the level of activation of their muscle field related to the direction of reaching movement (Georgopoulos et al. 1983, 1988) and of external loads (Kalaska et al. 1989). The modulations of single-cell activity reported here and by Caminiti et al. (1990, 1991) reveal that this process does not reflect only extrinsic directional requirements, but is also influenced by the arm geometry by which the movement is accomplished. This places at least part of the multimuscle specification process at the cortical level, rather than relegating it entirely to the spinal level (Kalaska and Drew 1993). Single MI cells can only alter the level of activation of their particular muscle field as a unit. The overall muscle recruitment pattern is shaped by the global pattern of activity of the MI population, by the subsequent pattern of termination of corticospinal and other descending axons on spinal interneurons and motoneurons, and by the distribution of activity within those spinal circuits. The possible contribution of MI to the selection of muscle recruitment patterns is further supported by the similarities in the patterns of variation of onset times and initial response magnitudes as a function of movement direction for activity of both MI neurons and proximal arm muscles before the onset of reaching movements (Scott 1996). This does not mean that MI specifies the precise level and temporal pattern of activity of each muscle. This is produced by the interplay between many convergent descending signals and local spinal processes (Kalaska and Drew 1993). Furthermore, we do not suggest that the changes in directional tuning of MI cells explicitly signal the changes in the directionality of EMG activity as a function of arm orientation (Buneo et al. 1995). However, the present results suggest that the motor cortex might contribute to the mechanisms required to specify muscle recruitment patterns as a function of arm orientation. To what degree MI activity parallels arm-posture-related changes in muscle recruitment patterns and how it might contribute to the specification of coordinated muscle patterns during reaching movements requires testing of cell responses over a broader range of arm postures.

A striking finding was that cells sorted into shoulder- and elbow-joint-centered classes solely on the basis of their responses to passive peripheral inputs demonstrated quite different response properties in the task, consistent with the contributions of their respective peripheral motor fields to movements in the different arm orientations. Besides indicating the degree of correspondence between the sensory inputs and motor output signals in MI, this finding provides circum-

stantial support for the role of reafferent proprioceptive input into MI in this transformation process. Peripheral feedback has often been relegated to the role of the feedback loop of error detection or servo-control mechanisms, such as the transcortical reflex model of MI organization (Evarts 1981; Phillips 1969). However, the reafferent input converging onto a single MI cell will alter its activity, and thus the level of activation of its muscle field, as a function of joint angles, muscle lengths, external perturbations, and loads. Repeated across all the cells composing the motor output map in MI, reafferent input will continually modulate activity across MI, thereby changing the output of MI to other input signals such as the desired direction of movement or target location as a function of the current status of the peripheral skeletal-muscular system.

This discussion illustrates a key issue. It may not be appropriate to discuss MI function in terms of generating a single specific movement representation in a particular parameter space. It may be better to think of MI function in terms of an operation, such as the sensorimotor transformations required to produce the desired motor act. The sensorimotor transformation from the MI representation of the movement to the intrinsic muscle-centered representation of coordinated multimuscle recruitment patterns of motoneurons in the spinal cord is realized in part by neuronal events within MI, and is embedded in part in the pattern of descending projections from MI to the spinal apparatus and to other components of the motor system. The idea that MI contributes actively to a sensorimotor transformation is supported by the finding that the size of the directional change in the activity of MI cells between arm orientations increases progressively with time before the onset of movement (Scott and Kalaska 1996).

Whatever the nature of that operation and the role it might play in determining multimuscle activity patterns, it is also simplistic to regard MI as only a muscle controller composed of cells encoding only muscle space variables related directly to spinal motoneuron activity levels and spindle sensory feedback (Georgopoulos 1991, 1995). Neuronal correlates of movement attributes and higher-order planning processes completely independent of causal muscle activity have been documented in MI in many studies (Alexander et al. 1992; Georgopoulos 1991, 1995; Humphrey and Tanji 1991; Kalaska and Crammond 1992; Thach 1978). Their presence provides further circumstantial evidence that MI is implicated in the sensorimotor transformations required to control movement, and is not just responsible for generating a homogenous representation of movement in a single well-defined parameter space.

Movement representations at the single-cell and population levels

Although the present data argue against explicit coding of the direction of hand movement at the single-cell level for all MI cells, it is possible that a representation of hand trajectory is coded at the population level (Georgopoulos et al. 1982, 1983, 1988; Schwartz 1993, 1995). Caminiti et al. (1990, 1991) reported that despite the changes in directional tuning of single cells in different parts of the work space, the summed population vector signals continued to covary

with movement direction, suggesting a dissociation of the nature of the representation of reaching movements at single-cell and population levels. We will address this important issue in a subsequent paper.

APPENDIX: MATHEMATICAL MODELS OF POPULATIONS OF UNITS ENCODING MOTOR COMMANDS IN DIFFERENT PARAMETER SPACES

A number of models were developed to aid in the interpretation of the response properties of cells during the two motor tasks. As in many previous studies, our analysis of cell activity in MI during whole arm reaching movements described the relationship between cell activity and the direction of hand movement. To interpret the significance of these findings, it is important to understand how the activity of cells specifying motor commands in different parameter spaces would covary with the direction of hand movement during reaching movements in two different arm orientations. Two types of models were developed: one in which populations of single units specified the extrinsic kinematics of hand movement in three-dimensional space, and another in which units specified the intrinsic joint kinematics (change in joint angles) or kinetics of movement (change in joint torques) at the shoulder and elbow joints.

Hand-centered coordinates

This model used a population of 400 units that each encoded hand trajectory (H units) along a preferred direction in three-dimensional space, in a Cartesian coordinate frame (X , Y , Z). A preferred direction of hand movement was chosen randomly for each unit on the basis of direction cosines l_1 , m_1 , and n_1 relative to the positive X -, Y -, and Z -axes, respectively. The direction of hand movement was defined by direction cosines l_2 , m_2 , and n_2 , where $n_2 = 0$ because hand movement was limited to the horizontal plane. Unit activity $H(A)$ during movement was proportional to the cosine of the angle between its preferred and the actual directions of movement

$$H(A) = l_1 l_2 + m_1 m_2 + n_1 n_2 + 1 \quad (A1)$$

Therefore unit activity ranged from 0 to 2. The start and finish position of the hand were identical when movements were made with the use of different arm orientations. Therefore, no change in the response of these H units would be expected with changes in arm orientation if only the direction of movement between initial and final postures was considered. However, the trajectory of the hand was not always identical; trial-to-trial variability in the path of the hand for a given target and arm orientation may result in variations in the neuronal activity related to the control of these movements for a given arm orientation. Moreover, small differences in the trajectory of the hand between arm orientations may also contribute to the observed changes in the response of motor cortical cells. We included both of these factors in this hand-centered model by selecting movement direction randomly from a Gaussian distribution matching the mean and SD of the recorded position of the hand at the midway point of movements to each of the eight targets for each arm orientation individually. For a given movement target and arm orientation, the directions of movement for five repeated trials were randomly selected and the response of the cell was calculated for each trial and then averaged to estimate the response of the unit for a given target. The unit's task-related "preferred direction" in each orientation was then computed with the use of trigonometric moments (Georgopoulos et al. 1982; Mardia 1972). Note that although each unit had a preferred direction of movement in three-dimensional space, this exercise calculated the projection of the unit's three-dimensional directional tuning function onto the horizontal plane of the motor task. Figure

17A illustrates the predicted variation of activity level of 10 H units with planar movement direction relative to their preferred direction defined in the plane. All the units are unimodally related to the direction of hand movement.

Joint kinematic coordinates

This model used a population of 400 units that specified joint kinematics (K units), with each unit encoding a preferred direction of angular movement at the shoulder and elbow. The monkey's arm was modeled with three DOF at the shoulder [a , abduction(+)/adduction; b , flexion(+)/extension; c , internal(+)/external rotation] and one DOF at the elbow [d , flexion(+)/extension: see *Limb kinematics*). For each unit, a preferred direction of angular movement at the joints was chosen randomly on the basis of direction cosines a_1 , b_1 , c_1 , and d_1 relative to the a , b , c , and d axes, respectively. This preferred direction defined a specific combination, or proportion, of angular movement at the shoulder and elbow, and thus each unit encoded movement in four-dimensional joint-angle space. For a given direction of movement, the angular excursions at the shoulder and elbow joints necessary to the move the hand from the start to the target position were defined with the use of direction cosines a_2 , b_2 , c_2 , and d_2 . Note that while the direction cosines defining the direction of joint movement during reaching vary with arm orientation, the preferred direction of each unit remains constant in joint-angle space. Unit activity $K(A)$ was proportional to the cosine of the angle between its preferred direction of joint movement and the actual direction of joint movement

$$K(A) = a_1 a_2 + b_1 b_2 + c_1 c_2 + d_1 d_2 + 1 \quad (A2)$$

and thus unit activity ranged from 0 to 2. Equation 2 calculates the activity for a unit as a function of the difference between its preferred direction vector and the actual movement direction in joint-angle space. Unit activity was computed with the use of Eq. 2 for each of the eight movement directions in each arm orientation. Subsequently, the activity of each unit for a given arm orientation (natural or abducted) was then related to the direction of hand movement, as was performed for cells in MI (Georgopoulos et al. 1982; Mardia 1972). For each arm orientation, the unit's task-related preferred direction was computed with the use of trigonometric moments. This model illustrates how the activity of units encoding joint space kinematics covaries with the direction of hand movements in the two arm orientations. Units encoding different combinations of angular rotation at the shoulder and elbow joints during reaching movements were broadly tuned to the direction of hand movement (Fig. 17B).

All units in this population encoded reaching movements on the basis of the change in joint angles at the shoulder and elbow joints. However, the relative weighting of a given unit's activity to the four DOF of joint motion varied. The behavior of the subpopulations of units whose directional vector predominantly signaled angular movement at one of the two joints was also informative. Units were classified as elbow related if the absolute magnitude of the elbow flexion/extension component of the preferred direction vector was 50% larger than that of each of the three shoulder components (flexion/extension, abduction/adduction, internal/external rotation). Units were classified as shoulder related if the absolute value of any of the three shoulder components of the preferred direction vector was 50% larger than that of the elbow flexion/extension component. This separation between elbow- and shoulder-related units approximated the criteria we used to identify sensory input to motor cortical cells in the present experiment.

Joint torque coordinates

A second joint-centered model was developed to consider how units involved in controlling joint dynamics (torques) would be-

have during the reaching tasks. The actual muscular torques at the elbow and shoulder cannot be calculated with the present experimental paradigm because the direction and the magnitude of the force applied by the monkey to the manipulandum was not monitored. However, the relative magnitude of the joint torques necessary to initiate movement of the manipulandum toward the targets can be estimated simply by transforming a spatial vector (oriented from the center start position to the peripheral target) into joint space. This model used a population of 400 units that each encoded a preferred direction of joint torque (T units). The shoulder was again modeled with three DOF [p , abduction(+)/adduction; q , flexion(+)/extension; r , internal(+)/external rotation] and one DOF at the elbow [s , flexion(+)/extension]. For each T unit, a preferred direction of joint torque was chosen randomly on the basis of direction cosines p_1 , q_1 , r_1 , and s_1 relative to the p , q , r , and s axes, respectively. This preferred direction defined a specific combination, or proportion, of joint torque at the shoulder and elbow, and thus encoded movements in four-dimensional joint-torque space. For a given direction of movement, the torques necessary to move the manipulandum from the central start to the peripheral target were defined with the use of direction cosines p_2 , q_2 , r_2 , and s_2 . Note that although the direction cosines for the joint torques required to move the handle vary with arm orientation, the preferred direction of each T unit remains constant in joint-torque space. Unit activity $T(A)$ was proportional to the cosine of the angle between its preferred combination of joint torques and the actual combination of joint torques

$$T(A) = p_1 p_2 + q_1 q_2 + r_1 r_2 + s_1 s_2 + 1 \quad (\text{A3})$$

and thus, unit activity ranged from 0 to 2. Unit activity was computed for each of the eight movement directions in each arm orientation. Subsequently, the activity of each unit for a given arm orientation was then related to the direction of hand movement, as was performed for cells in MI (Georgopoulos et al. 1982; Mardia 1972). For each arm orientation, the unit's task-related preferred direction was estimated with the use of trigonometric moments. This model therefore illustrates how the activity of units that signal the joint torques required to initiate displacement of the pendulum toward the targets would covary with the direction of planar hand movements in the two arm orientations. Most T units were unimodally tuned to the direction of hand movement (Fig. 17C). As was the case for K units, the T units of this model could be sorted into predominantly shoulder- or elbow-related classes with the use of similar criteria.

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REFERENCES

- ALEXANDER, G. E., DELONG, M. R., AND CRUTCHER, M. D. Do cortical and basal ganglionic motor areas use "motor programs" to control movement? *Brain Behav. Sci.* 15: 644–655, 1992.
- ASHE, J. AND GEORGOPOULOS, A. P. Movement parameters and neural activity in motor cortex and area 5. *Cereb. Cortex* 6: 590–600, 1994.
- BATSCHLEET, E. *Mathematics in Biology: Circular Statistics in Biology*. London: Academic, 1981.
- BENNETT, K. M. B. AND LEMON, R. N. Corticomotoneuronal contribution to the fractionation of muscle activity during precision grip in the monkey. *J. Neurophysiol.* 75: 1826–1842, 1996.
- BUCHANAN, T. S., ALMDALE, D. P. J., LEWIS, J. L., AND RYMER, W. Z. Characteristics of synergic relations during isometric contractions of human elbow muscles. *J. Neurophysiol.* 56: 1225–1241, 1986.
- BUNEO, C. A., SOECHTING, J. F., AND FLANDERS, M. Muscle torque directions at the human shoulder. *Soc. Neurosci. Abstr.* 21: 423, 1995.
- CAMINITI, R., JOHNSON, P. B., GALLI, C., FERRAINA, S., AND BURNOD, Y. Making arm movements in different parts of space: the premotor and motor cortical representation of a coordinate system for reaching to visual targets. *J. Neurosci.* 11: 1182–1197, 1991.
- CAMINITI, R., JOHNSON, P. B., AND URBANO, A. Making arm movements within different parts of space: dynamic aspects in the primate motor cortex. *J. Neurosci.* 10: 2039–2058, 1990.
- CHENEY, P. D. AND FETZ, E. E. Functional classes of primate corticomotoneuronal cells and their relation to active force. *J. Neurophysiol.* 44: 773–791, 1980.
- CRAMMOND, D. J. AND KALASKA, J. F. Differential relation of discharge in primary motor cortex and premotor cortex to movements versus actively maintained postures during a reaching task. *Exp. Brain Res.* 108: 45–61, 1996.
- EVARTS, E. V. Relation of pyramidal tract activity to force exerted during voluntary movement. *J. Neurophysiol.* 31: 14–27, 1968.
- EVARTS, E. V. Transcortical reflexes and servo control of movement. *Can. J. Physiol. Pharmacol.* 59: 757–775, 1981.
- FELDMAN, A. G. AND LEVIN, M. F. Positional frames of reference in motor control. The origin and use. *Behav. Brain Sci.* 13: 737–804, 1995.
- FETZ, E. E. Are movement parameters recognizably coded in the activity of single neurons? *Behav. Brain Sci.* 15: 679–690, 1992.
- FETZ, E. E. Cortical mechanisms controlling limb movement. *Curr. Opin. Neurobiol.* 3: 932–939, 1993.
- FLANDERS, M. AND HERRMANN, U. Two components of muscle activation: scaling with the speed of arm movement. *J. Neurophysiol.* 67: 931–943, 1992.
- FLANDERS, M. AND SOECHTING, J. F. Arm muscle activation for static forces in three-dimensional space. *J. Neurophysiol.* 64: 1818–1837, 1990.
- FLANDERS, M., TILLERY, S. I. H., AND SOECHTING, J. F. Early stages in a sensorimotor transformation. *Behav. Brain Sci.* 15: 309–320, 1992.
- FREUND, J. E. *Modern Elementary Statistics* (6th ed.). Englewood Cliffs, NJ: Prentice-Hall, 1984.
- FROMM, C. Changes of steady state activity in motor cortex consistent with the length-tension relation of muscle. *Pfluegers Arch.* 398: 318–323, 1983.
- FU, Q. G., FLAMENT, D., COLTZ, J. D., AND EBNER, T. J. Temporal encoding of movement kinematics in the discharge of primate primary motor and premotor neurons. *J. Neurophysiol.* 73: 836–854, 1995.
- FU, Q. G., SUAREZ, J. I., AND EBNER, T. J. Neuronal specification of direction and distance during reaching movements in the superior precentral premotor area and primary motor cortex of monkeys. *J. Neurophysiol.* 70: 2097–2116, 1993.
- GEORGOPOULOS, A. P. Higher order motor control. *Annu. Rev. Neurosci.* 14: 361–377, 1991.
- GEORGOPOULOS, A. P. Current issues in directional motor control. *Trends Neurosci.* 18: 506–510, 1995.
- GEORGOPOULOS, A. P., ASHE, J., SMYRNIS, N., AND TAIRA, M. The motor cortex and the coding of force. *Science Wash. DC* 256: 1692–1695, 1992.
- GEORGOPOULOS, A. P., CAMINITI, R., KALASKA, J. F., AND MASSEY, J. T. Spatial coding of movement: a hypothesis concerning the coding of movement direction by motor cortical populations. *Exp. Brain Res. Suppl.* 7: 327–336, 1983.
- GEORGOPOULOS, A. P., KALASKA, J. F., CAMINITI, R., AND MASSEY, J. T. On the relations between the direction of two-dimensional arm movements and cell discharge in primary motor cortex. *J. Neurosci.* 2: 1527–1537, 1982.
- GEORGOPOULOS, A. P., KETTNER, R. E., AND SCHWARTZ, A. B. Primate motor cortex and free arm movements to visual targets in three-dimensional space. II. Coding of the direction of arm movement by a neural population. *J. Neurosci.* 8: 2928–2937, 1988.
- GORDON, J., GHILARDI, M. F., AND GHEZ, C. Accuracy of planar reaching movements. I. Independence of direction and extent variability. *Exp. Brain Res.* 99: 97–111, 1994.

- HOGAN, N. An organising principle for a class of voluntary movements. *J. Neurosci.* 4: 2745–2754, 1984.
- HUMPHREY, D. R. Relating motor cortex spike trains to measures of motor performance. *Brain Res.* 40: 7–18, 1972.
- HUMPHREY, D. R. AND TANJI, J. What features of voluntary motor control are encoded in the neuronal discharge of different cortical motor areas? In: *Motor Control: Concepts and Issues*, edited by D. R. Humphrey and H.-J. Freund. Chichester, UK: Wiley, 1991, p. 413–444.
- KALASKA, J. F. Reaching movements to visual targets: neuronal representations of sensori-motor transformations. *Semin. Neurosci.* 3: 67–80, 1991.
- KALASKA, J. F. Reaching movements: implications of connectionist models. In: *The Handbook of Brain Theory and Neural Networks*, edited by M. A. Arbib. Cambridge, MA: MIT Press, 1995, p. 788–793.
- KALASKA, J. F. External loads in different directions produce minor changes in primate motor cortex (MI) directional tuning. *Soc. Neurosci. Abstr.* 22: 1829, 1996.
- KALASKA, J. F., COHEN, D. A. D., HYDE, M. L., AND PRUD'HOMME, M. A comparison of movement direction-related versus load direction-related activity in primate motor cortex, using a two-dimensional reaching task. *J. Neurosci.* 9: 2080–2102, 1989.
- KALASKA, J. F., COHEN, D. A. D., PRUD'HOMME, M., AND HYDE, M. L. Parietal area 5 neuronal activity encodes movement kinematics, not movement dynamics. *Exp. Brain Res.* 80: 351–364, 1990.
- KALASKA, J. F. AND CRAMMOND, D. J. Cerebral cortical mechanisms of reaching movements. *Science Wash. DC* 255: 1517–1523, 1992.
- KALASKA, J. F. AND DREW, T. Motor control and visuomotor behaviour. *Exer. Sports Sci. Rev.* 21: 397–436, 1993.
- KARST, G. M. AND HASAN, Z. Initiation rules for planar two-joint arm movements: agonist selection for movements throughout the work space. *J. Neurophysiol.* 66: 1579–1593, 1991a.
- KARST, G. M. AND HASAN, Z. Timing and magnitude of electromyographic activity for two-joint arm movements in different directions. *J. Neurophysiol.* 66: 1594–1604, 1991b.
- KUO, A. D. A mechanical analysis of force distribution between redundant, multiple degree-of-freedom actuators in the human: implications for the central nervous system. *Hum. Mov. Sci.* 13: 635–663, 1994.
- KWAN, H. C., MACKAY, W. A., MURPHY, J. T., AND WONG, Y. C. Spatial organization of precentral cortex in awake primates. II. Motor outputs. *J. Neurophysiol.* 41: 1120–1131, 1978.
- LACQUANITI, F. Central representations of human limb movement as revealed by studies of drawing and writing. *Trends Neurosci.* 12: 287–291, 1989.
- LACQUANITI, F., GUIGON, E., BIANCHI, L., FERRAINA, S., AND CAMINITI, R. Representing spatial information for limb movement: role of area 5 in the monkey. *Cereb. Cortex* 5: 391–409, 1995.
- MACPHERSON, J. M. How flexible are muscle synergies? In: *Motor Control: Concepts and Issues*, edited by D. R. Humphrey and H.-J. Freund. Chichester, UK: Wiley, 1991, p. 33–47.
- MARDIA, K. V. *Statistics of Directional Data*. London: Academic, 1972.
- MOUNTCASTLE, V. B. Feature article: the parietal system and some higher brain functions. *Cereb. Cortex* 5: 377–390, 1995.
- MUIR, R. B. AND LEMON, R. Corticospinal neurons with a special role in precision grip. *Brain Res.* 261: 312–316, 1983.
- MUSSA-IVALDI, F. A. Do neurons in the motor cortex encode movement direction? An alternative hypothesis. *Neurosci. Lett.* 91: 106–111, 1988.
- PHILLIPS, C. G. Motor apparatus of the baboon's hand. *Proc. R. Soc. Lond. B Biol. Sci.* 173: 141–174, 1969.
- SANGER, T. D. Theoretical considerations for the analysis of population coding in motor cortex. *Neural Comput.* 6: 12–21, 1994.
- SCHWARTZ, A. B. Motor cortical activity during drawing movements: single-unit activity during sinusoid tracing. *J. Neurophysiol.* 68: 528–541, 1992.
- SCHWARTZ, A. B. Motor cortical activity during drawing movements: population representation during sinusoid tracing. *J. Neurophysiol.* 70: 28–36, 1993.
- SCHWARTZ, A. B. Direct cortical representation of drawing. *Science Wash. DC* 265: 540–542, 1995.
- SCHWARTZ, A. B., KETTNER, R. E., AND GEORGOPOULOS, G. E. Primate motor cortex and free arm movements to visual targets in three-dimensional space. I. Relation between single cell discharge and direction of movement. *J. Neurosci.* 8: 2913–2927, 1988.
- SCOTT, S. H. Comparison of onset time and magnitude of activity for proximal arm muscles and motor cortical cells prior to reaching movements. *J. Neurophysiol.* 77: 1016–1022, 1997.
- SCOTT, S. H. AND KALASKA, J. F. Motor cortical activity is altered by changes in arm posture for identical hand trajectories. *J. Neurophysiol.* 73: 2563–2567, 1995.
- SCOTT, S. H. AND KALASKA, J. F. Temporal changes in the effect of arm orientation on directional tuning of cells in monkey primary motor (MI) and dorsal premotor (PMd) cortex during reaching. *Soc. Neurosci. Abstr.* 22: 1829, 1996.
- SHADMEHR, R. AND MUSSA-IVALDI, F. A. Adaptive representation of dynamics during learning of a motor task. *J. Neurosci.* 14: 3208–3224, 1994.
- SMITH, A. M., HEPP-REYMOND, M.-C., AND WYSS, U. R. Relation of activity in precentral cortical neurons to force and rate of force change during isometric contractions of finger muscles. *Exp. Brain Res.* 23: 315–332, 1975.
- SNEDECOR, G. W. AND COCHRAN, W. G. *Statistical Methods*. Ames, IA: Iowa State University Press, 1980.
- SOECHTING, J. F. AND FLANDERS, M. Sensorimotor representations for pointing to targets in three-dimensional space. *J. Neurophysiol.* 62: 582–594, 1989.
- SOECHTING, J. F. AND FLANDERS, M. Moving in three-dimensional space: frames of reference, vectors, and coordinate systems. *Annu. Rev. Neurosci.* 15: 167–191, 1992.
- SOECHTING, J. F. AND LACQUANITI, F. An assessment of the existence of muscle synergies during load perturbations and intentional movements of the human arm. *Exp. Brain Res.* 74: 535–548, 1989.
- TANAKA, S. Hypothetical joint-related coordinate systems in which populations of motor cortical neurons code direction of voluntary arm movements. *Neurosci. Lett.* 180: 83–86, 1994.
- THACH, W. T. Correlation of neuronal discharge with pattern and force of muscular activity, joint position, and direction of intended next movement in motor cortex and cerebellum. *J. Neurophysiol.* 41: 654–676, 1978.
- TURNER, R. S., OWENS, J. W. M., AND ANDERSON, M. E. Directional variation of spatial and temporal characteristics of limb movements made by monkeys in a two-dimensional work space. *J. Neurophysiol.* 74: 684–697, 1995.
- WADMAN, W. J., DENIER VAN DER GON, J. J., GEUZE, R. H., AND MOL, C. R. Control of fast goal-directed arm movements. *J. Hum. Mov. Stud.* 5: 3–17, 1980.
- ZAJAC, F. E. AND GORDON, M. E. Determining muscle's force and action in multi-articular movement. *Exer. Sports Sci. Rev.* 17: 187–230, 1989.