

Research Note

Shift of preferred directions of premotor cortical cells with arm movements performed across the workspace

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Summary. The activity of 156 neurons was recorded in the premotor cortex (Weinrich and Wise 1982) and in an adjoining rostral region of area 6 (area 6 DR; Barbas and Pandya 1987) while monkeys made visually-guided arm movements of similar direction within different parts of space. The activity of individual neurons varied most for a given preferred direction of movement within each part of space. These neurons (152/156, 97.4%) were labeled as directional. The spatial orientation of their preferred directions shifted in space to "follow" the rotation of the shoulder joint necessary to bring the arm into the different parts of the work-space. These results suggest that the cortical areas studied represent arm movement direction within a coordinate system rotating with the arm and where signals about the movement direction relate to the motor plan through a simple invariant relationship, that between cell preferred direction and arm orientation in space.

Key words: Premotor cortex – Arm movement – Movement direction – Coordinate system – Monkey

Introduction

A central issue of theories of motor control concerns the coordinate system used by the brain to represent movement. The redundancy of degrees of freedom available when making movements in space is compatible with a multiplicity of domains of representation (Saltzman 1979) and suggests the existence of invariances in motor behavior (Bernstein 1967). Arm movements, for instance, can be coded either in intrinsic coordinates, such as the angles of the limb joint or the muscle activity and torque

necessary for the movement, or in extrinsic ones, such as the path followed by the hand in space. On behavioral grounds, experimental data have provided support for both kinds of coding mechanisms (Morasso 1981; Soechting and Lacquaniti 1981; Abend et al. 1982; Lacquaniti and Soechting 1982; Hogan 1984; Atkeson and Hollerbach 1985; Hogan 1988; Soechting and Terzuolo 1988; Lacquaniti 1989; Soechting and Flanders 1989a; 1989b). At the neural level, however, it is essential that information from more than one domain of representation interact, given that most limb movements (which are ultimately performed using limb coordinates) are directed towards targets which are located by vision.

To approach these issues we studied the activity of individual neurons in the premotor cortex (Weinrich and Wise 1982) and in an adjoining rostral region of the frontal lobe (area 6 DR; Barbas and Pandya 1987) while monkeys made arm movements of similar direction within different parts of space. Since these movement directions were similar spatial vectors only in the coordinates of the extrapersonal space, but corresponded to different angular excursion of the shoulder joint if viewed in terms of intrinsic body coordinates, movement direction was dissociated from the angular changes of the shoulder joint and from the patterns of muscle activity necessary to perform the task or, in other words, the information represented in intrinsic coordinates was dissociated from that represented in extrinsic ones.

Methods

Two *Macaca nemestrina* monkeys were trained in a behavioral apparatus which allowed the performance of free arm movements within 3 different parts of space (Fig. 1A,B). The apparatus consisted of 19 push buttons which could be illuminated. Of these, 16 were arranged at the corners of 3 adjacent imaginary cubes, 3 at their centers. The center button of the center cube was located 25 cm

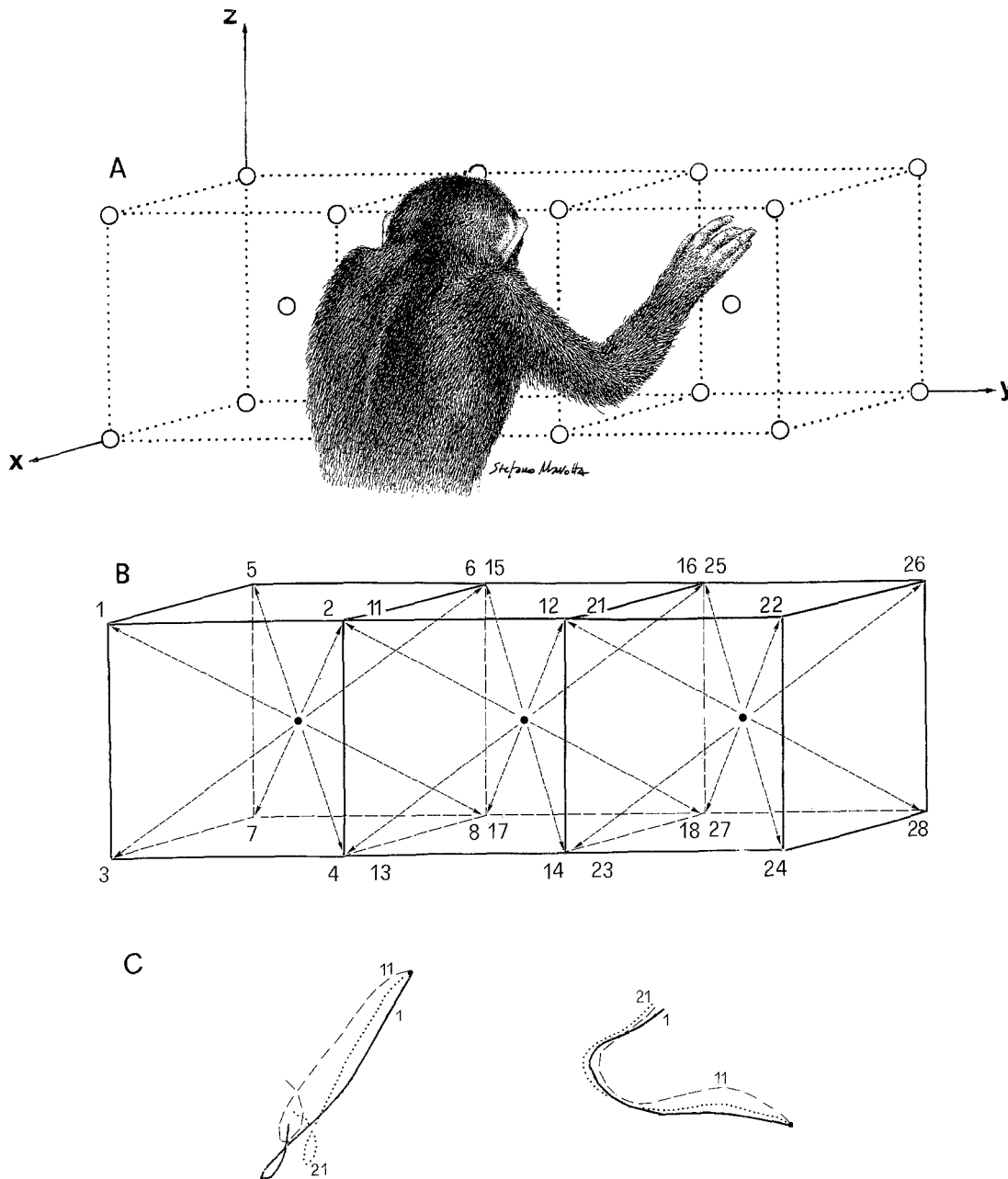


Fig. 1. **A** The animals sat on a primate chair 25 cm away from the apparatus. **B** Within any one part of the 3-D work-space (left, center, right), the animals made arm movements of the same amplitude (8.7 cm) in 8 different directions (arrows), starting from a common central position (black dots), toward targets located at the vertices of an imaginary cube. Across the work-space, animals made

8 triplets of movements of similar "parallel" direction (1-11-21; 2-12-22; 3-13-23; etc). Numbers indicate directions of movement. **C** Top (left) and side (right) views of movement trajectories in directions 1, 11, 21. Paths followed within different parts of space are aligned on a common movement origin to show their degree of similarity

away from the animal and was situated on the body midline at shoulder height. In a typical trial, the center light of one of the 3 cubes came on, and the animal was required to push it for at least 1.5 s. This light was then extinguished and one of the 8 target lights was turned on. The animal was required, within specified reaction (350 ms) and movement (1 s) times, to move his hand and press the target light for at least 1 s, to receive a liquid reward. Subsequently, the animal placed again his hand on the central light and different peripheral targets were presented in a random sequence. Five replications of movements, always starting from the center light, were performed in each of the 8 directions tested. This sequence was then repeated in the remaining two cubes. The order of cube presentation was continuously changed. Because of the side-by-side arrangement

of the cubes, the animals made movements of similar directions which traveled along similar "parallel" paths within different parts of the work-space. A 3-dimensional sonic tracking system (SAC, model GP-8-3D), using a spark gap mounted on the radial side of the wrist, was used to monitor movement trajectories. The activity of several muscles acting at the shoulder joint was recorded using stainless steel electrodes implanted intramuscularly. The control of the behavioral task and the collection of all data were performed by a minicomputer.

The preparation of the animals for neural recording was performed under aseptic conditions and general barbiturate anesthesia (Nembutal, 40 mg/kg; i.p.). A recording chamber was implanted over the frontal lobe to permit extracellular recordings of individual

neurons in the premotor cortex. A metal head-holder was also cemented on the skull to immobilize the head during the recording session.

Microelectrode penetrations were made in a region coextensive with the premotor cortex (Weinrich and Wise 1982) and with an adjoining rostrally located frontal field, corresponding to the posterior part of areas 6 DR, according to Barbas and Pandya 1987. The area of recording, always located medially to the medial limb of the arcuate sulcus, extended from the arcuate spur to the posterior half of the medial limb of the arcuate sulcus. Cells were selected for study in the task if their activity was related to natural arm movements involving the shoulder joint, or shoulder girdle or to passive manipulation of these structures.

Results and discussion

The analysis of movement trajectories recorded during the task showed that movements of similar direction performed within different parts of space traveled along pathways having very similar spatial orientation, as shown in Fig. 1C. To perform these "parallel" movements across the work-space, the monkey's (right) shoulder joint rotated about 20° from the left to the center and of 18° from the center to the right parts of the work-space.

The activity of 156 neurons related to motion at the shoulder joint was recorded extracellularly during microelectrode penetrations into the hemisphere contralateral to the performing arm. The frequency of discharge from the target presentation to the end of movement was chosen as a measure of cell activity.

One hundred fifty two cells (97.4%) varied their firing frequency in a significant way (ANOVA, F-test, $P < 0.05$; Snedecor and Cochran 1980) with movement direction. These cells were labeled as directional (Georgopoulos et al. 1982; 1986; Schwartz et al. 1988). Only those cells which were directional in more than one part of space were further analyzed (121, 77.6%). To assess whether cell activity varied in an orderly fashion with movement direction, the firing frequency of each cell was linearly regressed on the direction of movement using a least squares method (Draper and Smith 1981) in each of the 3 parts of the work-space. The regression model predicts that there exists a given direction of movement for which a cell's activity will be maximal, the cell's preferred direction (Georgopoulos et al. 1982; 1986; Schwartz et al. 1988). The results showed the existence of a good fit (multiple regression, F-test, $p < 0.05$) in 71.1% of the cell-cube combinations. Figure 2A shows the activity of a premotor cortical neuron recorded during the task. The firing frequency of this cell changed in a significant way (ANOVA, F-test, $P < 0.05$) with movement direction in the three parts of the work-space where the animal performed. In addition the frequency of discharge of this cell varied when movements of similar direction were made across the work-space. This can be seen in movement directions 1, 11, 21 and 4, 14, 24. These changes were reflected in a change of the spatial orientation of the cell preferred direction across the work-space. This is shown in Fig. 2B where the preferred direction vectors in the left, center and right parts of space are shown by using

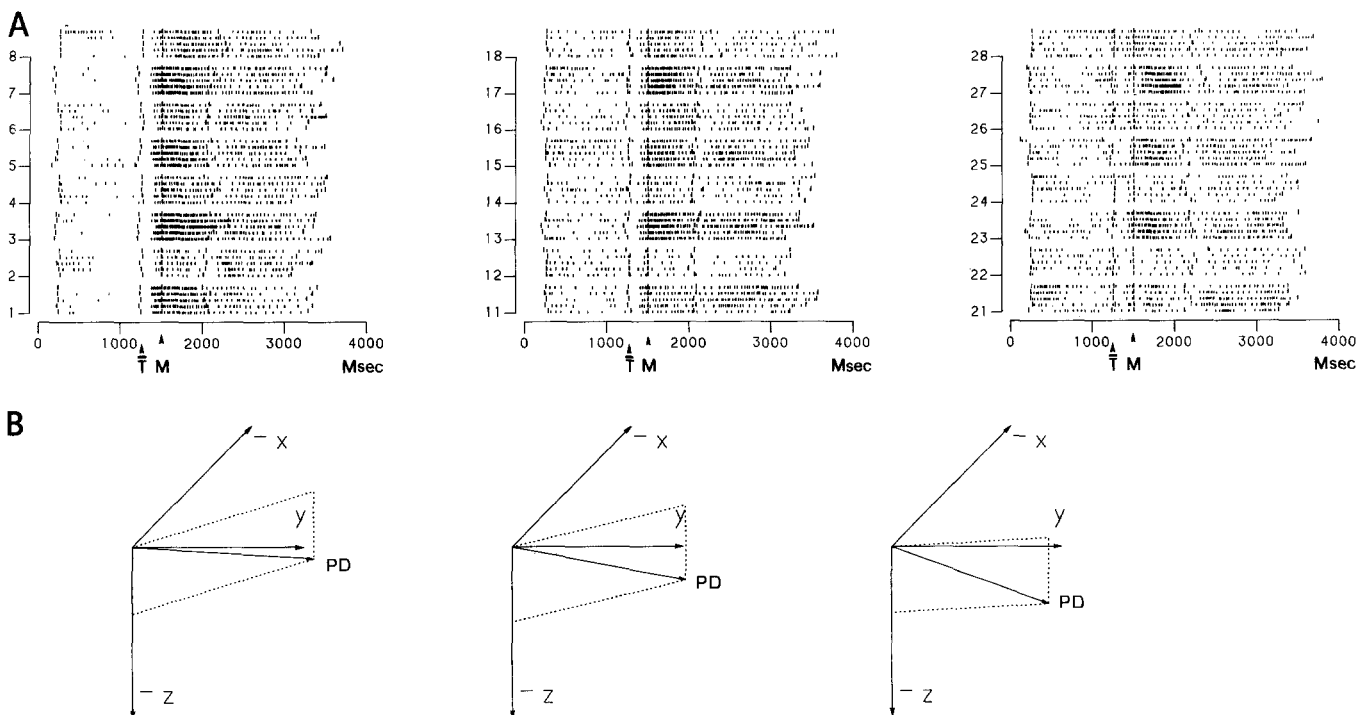


Fig. 2. A Rasters of impulse activity of a premotor cortical cell recorded during the task. Five replications for every movement direction were aligned to the movement onset (M). T indicates target presentation. Longer vertical bars indicate, from left to right, beginning of the trial, target onset, movement onset, beginning and end of target holding time. Numbers on the vertical axes indicate

directions of movement, as labeled in Fig. 1B. In each part of the work-space, movement in different directions had the same central origin. B Spatial orientation of a premotor cortical cell's preferred direction computed from cell activity collected while the animal was working on the left, center and right parts of the work-space. Notice the rotation in space of the preferred direction vector

3 cartesian coordinate systems centered at the origin of the movements in the left, center and right parts of the work-space. It can be seen that a shift of the spatial orientation of this cell's preferred direction occurred as movements of similar direction were made in the three parts of the work-space. Such changes in preferred directions were observed for all cells studied, but with varying magnitudes. An analysis of the entire population of cell preferred directions was therefore performed to determine if, at the population level, an orderly change in their orientation was detectable as movements of similar direction were performed within different parts of space. First, the spatial distribution of preferred directions was studied within each of the 3 parts of space. The preferred directions of those cells which fit the regression model described above (111, 71.1%) covered the entire 3-D continuum. A spherical correlation coefficient (Fisher and Lee 1986) was then computed to assess the degree of correlation between the spatial orientation of cell preferred directions obtained from neuronal activity in the left, center and right parts of the work-space. The data indicate a significant correlation ($p < 0.002$) between the orientations of cells preferred directions across the work-space ($r = 0.285$ for left-center, $r = 0.519$, for center-right $r = 0.136$, for left-right correlation). Probability levels for spherical correlations were determined using statistical bootstrapping methods (Efron 1979). A significant correlation permits the computation of a spherical regression (Jupp and Mardia 1980) to detect changes in the spatial orientation of cell preferred directions across space and to determine around which spatial axes they rotated. The spherical regression uses a least squares method to determine the elements of the rotation matrix R in the regression equation

$$\hat{a}_i = R b_i$$

where b_i is the preferred direction vector of the i^{th} cell in one part of space and \hat{a}_i is the predicted preferred direction vector of the same cell in another part of space. Given any 2 sets of preferred direction vectors, the spherical regression analysis determined the rotation necessary to bring into maximal coincidence one set of vectors with the other. Angles of rotation about the X, Y, and Z axes of the cartesian coordinate system were then computed directly from the elements of matrix R .

The results showed that a rotation of the spatial orientation of the whole population of cell preferred directions occurred and that this rotation was much higher in the horizontal plane (around the Z axis) than in the other planes of space. To bring into coincidence preferred directions from adjacent left-center and center-right parts of the work-space, rotations of 17.2° and 17.6° , respectively, were necessary, while a rotation of 42° was required for obtaining the spatial coincidence of preferred directions of the left part of the work-space with those of the right part. Ninety-five percent confidence intervals for rotations in the horizontal plane were $[10.6^\circ-21.8^\circ]$ and $[14.0^\circ-21.7^\circ]$ for regressions between adjacent parts of space, and $[34.2^\circ-47.9^\circ]$ for regression between left-right non adjacent parts of space.

These results indicate that in the frontal cortical fields studied a significant rotation of the population of cell preferred directions occurred as the animals made arm movements of similar directions within different parts of space. The main rotation of cell preferred directions occurred in the horizontal plane. Given the spatial arrangement of the apparatus where the animal performed the task, the rotation in the orientation of cell preferred directions predicted the rotation of the shoulder joint necessary to perform the movement requested by the task. Measurements of shoulder joint angles showed that horizontal rotations of the shoulder of approximately 20° from left to center and 18° from center to right were necessary to move the hand from the center of one cube to the center of the other. The coincidence in the amount of shift of cell preferred directions and shoulder joint excursion suggests the existence of an invariant relationship, that between cell preferred direction and arm orientation in space. It is interesting that qualitatively and quantitatively similar results were obtained in the primary motor cortex (Caminiti et al. 1990). As a consequence, these frontal cortical fields would develop an internal representation of space where coding of arm movement direction occurs within a coordinate system centered on the shoulder joint. This process could relate the signals concerning the movement trajectory to the same frame of reference used to represent the arm orientation in space. Within this frame of reference, signals relative to both movement direction and arm orientation may interact dynamically to provide a neural basis for the visuo-motor transformation necessary to bring the hand to the desired visual target in space. Where, in the brain, this combination of inputs occurs is still to be determined. However, the result of this interaction, a shift of cell preferred directions, can be observed at premotor and motor (Caminiti et al. 1990) cortical level. In this respect it is striking that recent behavioral studies on human subjects (Soechting and Flanders 1989a; 1989b) suggest that reaching at visual targets is planned within a shoulder-centered coordinate system and depends on information concerning both target location and arm orientation in space.

The similarity of the phenomena just described in two cortical areas which, using other criteria, show significant differences, (see Wise 1984, Wise and Godschalk 1987 for a review) may facilitate the transformation of movement related information between these frontal fields and suggests that they are segments of a distributed system (Mountcastle 1978) involved in the control of arm movement in space.

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References

- Abend W, Bizzi E, Morasso P (1982) Human arm trajectory formation. *Brain* 105:331-348
- Atkeson CG, Hollerbach JM (1985) Kinematic features of unrestrained vertical arm movements. *J Neurosci* 5:2318-2330

- Barbas H, Pandya DN (1987) Architecture and frontal cortical connections of the premotor cortex (area 6) in the rhesus monkey. *J Comp Neurol* 256:211–228
- Bernstein N (1967) *The coordination and regulation of movement*. Pergamon Press, Oxford
- Caminiti R, Johnson PB, Urbano A (1990) Making arm movements within different parts of space: dynamic aspects in the primate motor cortex. *J Neurosci* 10:2039–2058
- Draper NR, Smith H (1981) *Applied regression analysis*, 2nd edn. Wiley, New York
- Efron B (1979) Bootstrap methods: another look at the jackknife. *Ann Statistics* 7:1–26
- Fisher NI, Lee AJ (1986) Correlation coefficients for random variables on a unit sphere or hypersphere. *Biometrika* 73:159–164
- Georgopoulos AP, Kalaska JE, Caminiti R, Massey JT (1982) On the relations between the direction of two-dimensional arm movements and cell discharge in the motor cortex. *J Neurosci* 2:1527–1537
- Georgopoulos AP, Schwartz AB, Kettner RE (1986) Neuronal population coding of movement direction. *Science* 233:1416–1419
- Hogan N (1984) An organizing principle for a class of voluntary movements. *J Neurosci* 4:2745–2754
- Hogan N (1988) Planning and execution of multijoint movements. *Can J Physiol Pharmacol* 66:508–517
- Jupp PE, Mardia KV (1980) A general correlation coefficient for directional data and related regression problems. *Biometrika* 67:163–173
- Lacquaniti F, Soechting JF (1982) Coordination of arm and wrist motion during a reaching task. *J Neurosci* 2:399–408
- Lacquaniti F (1989) Central representations of human limb movement as revealed by studies of drawing and handwriting. *Trends Neurosci* 12:287–291
- Morasso P (1981) Spatial control of arm movements. *Exp Brain Res* 42:223–227
- Mountcastle VB (1978) The unit module and the distributed system. In: Edelman GM, Mountcastle VB (eds) *The mindful brain: cortical organization and the group selective theory of higher brain function*. MIT Press, Cambridge, pp 7–50
- Saltzman E (1979) Levels of sensorimotor representation. *J Math Psychol* 20:91–163
- Schwartz AB, Kettner RE, Georgopoulos AP (1988) Primate motor cortex and free arm movements to visual targets in three-dimensional space. I. Relations between single cell discharge and direction of movement. *J Neurosci* 8:2913–2927
- Snedecor GW, Cochran WG (1980) *Statistical methods*, 7th edn. Iowa State Univ Press, Ames
- Soechting JF, Lacquaniti F (1981) Invariant characteristics of a pointing movement in man. *J Neurosci* 1:710–720
- Soechting JF, Terzuolo CA (1988) Sensorimotor transformations underlying the organization of arm movements in three-dimensional space. *Can J Physiol Pharmacol* 66:502–507
- Soechting JF, Flanders M (1989a) Sensorimotor representations for pointing to targets in three-dimensional space. *J Neurophysiol* 62:582–594
- Soechting JF, Flanders M (1989b) Errors in pointing are due to approximations in sensorimotor transformations. *J Neurophysiol* 62:595–608
- Weinrich M, Wise SP (1982) The premotor cortex of the monkey. *J Neurosci* 2:1329–1345
- Wise SP (1984) The nonprimary motor cortex and its role in the cerebral control of movement. In: Edelman GM, Gall WE, Cowan MW (eds) *Dynamic aspects of neocortical function*. John Wiley & Sons, New York Chichester Brisbane Toronto Singapore, pp 525–555
- Wise SP, Godschalk M (1987) Functional fractionation of frontal fields. *Trends Neurosci* 11:449–450