Early Coding of Visuomanual Coordination During Reaching in Parietal Area PEc

STEFANO FERRAINA,[1] ALEXANDRA BATTAGLIA-MAYER,[1,2] ALDO GENOVESIO,[1] BARBARA MARCONI,[1] PAOLO ONORATI,[1] AND ROBERTO CAMINITI[1,3]
[1]*Dipartimento di Fisiologia umana e Farmacologia, Università di Roma 'la Sapienza', 00185 Rome;* [2]*Istituto di Ricovero e Cura a Carattere Scientifico S. Lucia, 00179 Rome, Italy; and* [3]*Institut National de la Santé et de la Recherche Médicale U. 483, Université Pierre et Marie Curie, 75005 Paris, France*

Received 20 July 2000; accepted in final form 11 September 2000

Ferraina, Stefano, Alexandra Battaglia-Mayer, Aldo Genovesio, Barbara Marconi, Paolo Onorati, and Roberto Caminiti. Early coding of visuomanual coordination during reaching in parietal area PEc. *J Neurophysiol* 85: 462–467, 2001. The parietal mechanisms of eye-hand coordination during reaching were studied by recording neural activity in area PEc while monkeys performed different tasks, aimed at assessing the influence of retinal, hand-, and eye-related signals on neural activity. The tasks used consisted of *1*) reaching to foveated and *2*) to extra-foveal targets, with constant eye position; and *3*) saccadic eye movement toward, and holding of eye position on peripheral targets, the same as those of the reaching tasks. In all tasks, hand and/or eye movements were made from a central position to eight peripheral targets. A conventional visual fixation paradigm was used as a control task, to assess location and extent of visual receptive field of neurons. A large proportion of cells in area PEc displayed significant relationships to hand movement direction and position. Many of them were also related to the eye's position. Relationships to saccadic eye movements were found for a smaller proportion of cells. Most neurons were tuned to different combination of hand- and eye-related signals; some of them were also influenced by visual information. This combination of signals can be an expression of the early stages of the composition of motor commands for different forms of visuomotor coordination that depend on the integration of hand- and eye-related information. These results assign to area PEc, classically considered as a somatosensory association cortex, a new visuomotor role.

INTRODUCTION

Understanding the cerebral cortical coding of reaching requires knowledge of the functional properties of reach-related neurons within different areas. Recent physiological studies have elucidated the potential role of different regions of the superior parietal lobule (SPL) on visuomanual and oculomotor behavior (Batista et al. 1999; Battaglia-Mayer et al. 2000; Ferraina et al. 1997; Johnson et al. 1996; Tanné et al. 1995).

Nothing is known on the physiological properties of neurons of parietal area PEc. As part of area 5, PEc has traditionally been considered as a somatosensory association cortex. However, PEc is linked by association connections (Pandya and Seltzer 1982) with 7m, PEci, in the cingulate sulcus, and with parietal areas PE, PEa, and PG (7a). In addition, PEc is reciprocally connected with dorsal premotor cortex (Johnson et al. 1996; Matelli et al. 1998), where cell activity is tuned to arm position and movement direction (Caminiti et al. 1991), and is also influenced by eye position signals (Jouffrais and Boussaoud 1999).

This pattern of association connections is consistent with a visuomotor, rather than a somatosensory, role of PEc. Therefore single-cell activity was recorded in PEc while monkeys were performing four behavioral tasks, aimed at assessing the influence of eye- and hand-related information on neural activity. These tasks consisted of reaching to foveated targets, reaching to extrafoveal targets with constant eye position, and saccadic eye movement. A visual fixation task was used as control.

METHODS

Animals, apparatus, and tasks

Two rhesus monkeys (*Macaca mulatta;* body weights 3.7 and 3.5 kg) were used in this study. They sat in a primate chair, 17 cm in front of a touch-sensitive computer monitor used to display the tasks and control the animals' hand position. Monkeys performed four different tasks (Fig. 1).

REACHING TO FOVEATED TARGETS (REACH, R). A red center light was presented. The animals fixated and touched it with the hand for a variable control time (Fig. 1*A;* CT, 1–1.5 s). Then, one of the eight red targets was lit, in a randomized block design. The animals moved the eyes and the hand to it within a reaction-time task (RT, 0.5 s, upper limit; movement time MT, 1 s, upper limit; Fig. 1*A*, RMT = RT + MT) and keep them there for a variable target holding time (Fig. 1*A;* THT, 1–1.5 s), before receiving a liquid reward.

REACHING TO EXTRAFOVEAL TARGETS (REACH-FIXATION, RF). This task was similar to the previous one, but reaches were made with eye position kept constant on a central fixation point.

EYE MOVEMENT AND POSITION TASK (SACCADE, S). Monkeys made saccades of the same amplitude from a central origin toward the same targets used in the two previous tasks, within a RT paradigm. The position of the hand was controlled by using a telegraph key.

Address for reprint requests: R. Caminiti, Dipartimento di Fisiologia umana e Farmacologia, Università di Roma 'La Sapienza', Piazzale Aldo Moro 5, 00185 Rome, Italy (E-mail: roberto.caminiti@uniroma1.it).

0022-3077/01 $5.00 Copyright © 2001 The American Physiological Society

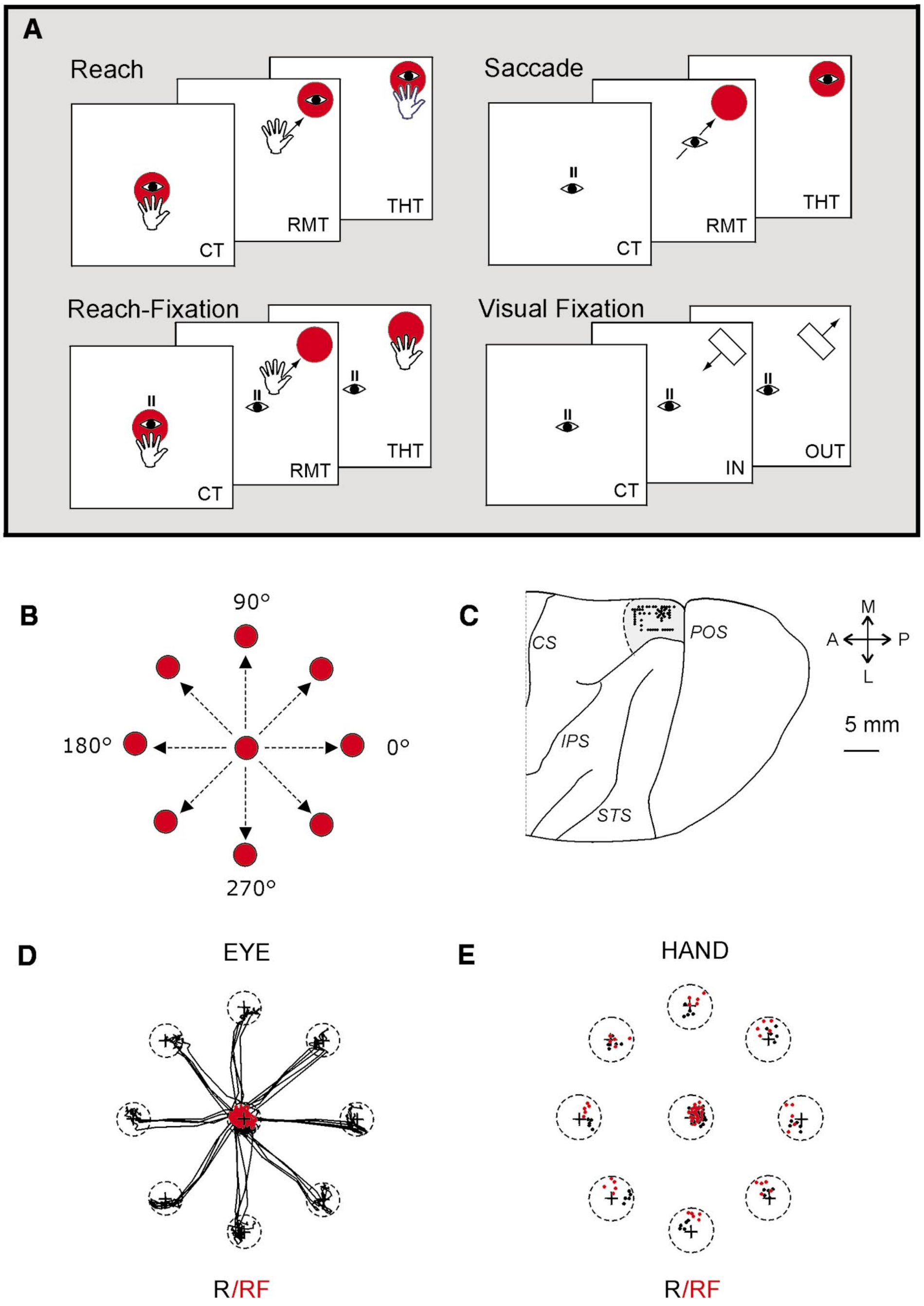

FIG. 1. *A*: behavioral tasks. CT, RMT, and THT indicate control time, reaction and movement time, and target holding time, respectively. IN and OUT indicate, respectively, movement of the visual stimulus (white bar) toward and away from the fovea. *B*: directional array of the Reach, Reach-Fixation, and Saccade tasks: eye and/or hand movements were made in 8 different directions at 45° angular interval. In the Visual Fixation task, the visual stimulus was moved in 16 directions, at 22.5° angular interval. *C*: figurine of the parieto-occipital region of the macaque brain showing the entry points (dots) of microelectrode penetrations in area PEc (gray shading) for one animal. CS, IPS, STS, and POS indicate central, intraparietal, superior temporal, and parieto-occipital sulci, respectively; A, P, M, and L indicate anterior, posterior, medial, and lateral, respectively. *D*: eye position records during Reach (black) and Reach-Fixation (red) tasks. The crosses indicate target positions; the interrupted circles indicate the eye tolerance window. *E*: hand position records with hand tolerance windows (interrupted circles) during CT and THT of Reach (black) and Reach-Fixation (red) tasks. The data shown in *D* and *E* were collected during recording of spike activity from the cell shown in Fig. 2*A*.

VISUAL FIXATION TASK. Visual stimuli were moved along 16 radial directions of the visual field, at 22.5° angular intervals. The orientation of the visual stimulus was always perpendicular to the direction of motion. Location and extent of the visual receptive fields were reconstructed as described in Battaglia-Mayer et al. (2000).

Arm and eye movements originated from a central position and were directed to eight peripheral targets (1.5° visual angle) on a circle of 7.5 cm radius (23.8° visual angle; Fig. 1*B*).

Eye accuracy was controlled through 7.5° diam circular windows centered on the targets. Hand position was monitored using the touch screen. Hand accuracy was controlled through 3-cm-diam (~10° visual angle) circular windows centered on the targets. Eye position signals were recorded by using implanted scleral search coils, with 1° resolution and sampled at 100 Hz. The instantaneous tangential velocity of the eye was calculated off-line and used to determine the onset and end times of the saccade.

The activity of single neurons was recorded through glass-coated tungsten-platinum electrodes.

Behavioral control and collection of neural and behavioral data were performed using personal computers. The eye-coil, recording chamber, and head-holder were implanted aseptically under general anesthesia (pentobarbital sodium, 25 mg/kg iv).

The mean firing rates during the different epochs of the task were calculated for each trial. Data analysis was performed through a repeated measure design (5V, BMDP, Statistical Software, Los Angeles, CA) to assess *1*) modulation of cell activity during a given epoch relative to the CT of the same task; *2*) variations of cell activity across movement directions and/or positions for both arm and eyes;

and 3) differences in the cell activity across similar or different epochs of different tasks. For all statistical tests (Wald, χ^2 test) $P < 0.05$ was set as significance level.

RESULTS

Sixty-six microelectrode penetrations were performed in PEc (Fig. 1*C*). Ninety-five cells were studied in the *Reach task,* 91 in the *Reach-Fixation task,* 93 in the *Saccade task,* and 78 in the *Visual Fixation task*. In the flat exposed part of the superior parietal lobule, recording of cell activity was confined to the first 2–3 mm of cortical tissue. The assignment of cell to area PEc, rather than to the adjacent V6A or 7m, was made not only on architectonic criteria (Pandya and Seltzer 1982), but also on the basis of the pattern of association connection with frontal cortex. Injections of different fluorescent tracers in dorso-rostral (F7) (Matelli et al. 1985) and dorso-caudal (F2) (Matelli et al. 1985) premotor cortex of one of the two experimental animals (Caminiti et al. 1999) showed that V6A and 7m are cortico-cortically connected with F7, while PEc is mainly linked to F2 (see also Matelli et al. 1998).

Figure 2*A* shows a typical parietal cell. Neural activity was directional during hand movement (RMT) and holding of combined eye-hand position on the target (THT), both in the Reach and Reach-Fixation tasks. In this last task, the hand moved toward and then remained motionless on the target, in absence of eye movement. No significant difference was observed in the activity of this cell across these two task conditions during RMT, suggesting that neural activity during this epoch carries information about hand movement, independently of eye-related signals. On the contrary, a significant difference was observed during THT, indicating that eye position signals influence hand position–related activity. The eye and hand position records obtained during collection of neural data from this cell (Fig. 1, *D* and *E*) indicate that this difference cannot be attributed to differences in hand position across tasks during static holding.

In the Saccade task, cell activity was rather low and directional during RMT and THT.

This cell had an extrafoveal visual receptive field (VRF, Fig. 2*A*) straddling the vertical meridian, and extending over parts of both the ipsi- and contralateral visual fields. The location and extent of the VRF indicate that cell activity, during hand movement and holding of static position on the targets, was not dependent on the cell's VRF.

A different type of processing is illustrated by the cell shown in Fig. 2*B*. Neuronal activity was modulated when the eyes and the hand moved to the target (Reach, RMT) and during hand reaches with the eyes fixating at the center of the workspace (Reach-Fixation, RMT). A significant difference of cell modulation was observed across these conditions during both RMT and THT, in spite of the absence of cell modulation in the Saccade task. Therefore an eye position signal influenced neural activity during all epochs of the reaching task. This cell had no visual properties.

At the population level (Fig. 3*A*), in the Reach task, significant modulation of activity, relative to the control time, was observed in 76/95 (80%) cells during RMT, and in 47/95 (50%) during THT. In the Reach-Fixation task, 67/91 (78%) cells were modulated during RMT, and 54/91 (57%) during THT. The cells modulated in both tasks were 56/84 (67%) during RMT and 33/84 (39%) during THT. Therefore the activity of these cells was influenced by both arm movement and position signals. Similar results were obtained when the analysis was performed on the directional properties of cell activity during different epochs (Fig. 3*A*).

The comparison of neural activity during the Reach and Reach-Fixation tasks, for those cells modulated in both tasks, showed no differences in 24/56 (43%) cells during RMT, and in 13/33 (39%) cells during THT (Fig. 3*B*). Therefore the activity of these cells was related to hand movement and position, respectively, and was not influenced by eye-related information. On the contrary, the differences observed for the remaining cells (32 during RMT, 20 during THT), in addition to eye-related signals, could be attributed to the influence of a variety of inputs, including visual ones. In fact, a VRF was found in 43% of the cells with significant Reach/Reach-Fixation differences during RMT, and in 33% of those with such differences during THT. In conclusion, it cannot be excluded that, for the cells with visual properties, the modulation of activity, during hand movement and holding of hand position on the target, could be attributed to stimulation of the VRF.

In the Reach-Fixation task, the arm moved from the fovea toward the periphery of the visual field. Therefore this task offered the opportunity to assess whether or not cell activity during arm movement and static holding was dependent on the stimulation of a potential visual receptive field. Figure 3*C* shows that only a minority of cells out of those modulated or directional in different epochs of the Reach-Fixation task had a VRF. Thus for the majority of cells, neural activity during reaches was arm-related.

It is worth stressing that when the data analysis concerning RMT was repeated for RT in isolation, the cells modulated were 67/95 (71%) in the Reach task, 64/91 (70%) in the Reach-Fixation task, and 49/84 (58%) in both tasks. When the activities of these last cells were compared, significant differences were found in 33% of the cells studied. Therefore these changes in activity across Reach and Reach-Fixation tasks cannot be attributed to potential difference in arm kinematics across task conditions, since they were observed before onset of arm movement.

In the Saccade task (Fig. 3*A*), only 16/93 (17%) cells were modulated during eye movement (RMT). A higher percentage of cells was influenced by eye-position signals, as shown by the directional activity during THT (38/93; 41%).

DISCUSSION

Neural activity in area PEc relates to directional signals concerning arm movement and position in space, and, to a lesser extent, to information about eye position and movement direction. Many cells are also sensitive to retinal inputs. These signals influence different cells to different degrees. They are common to all the areas of the distributed system underlying reaching (Battaglia-Mayer et al. 2000; Johnson et al. 1996).

Our study suggests that area PEc is an early node of parietal system underlying eye-hand coordination during reaching. It assigns to PEc a visuomotor role, rather than the classical somatosensory one. This role in combined eye-hand actions was predicted by the pattern of association connections of PEc.

When studied only in one task, the activity of most cells appeared as related either to visuo-manual or oculomotor be-

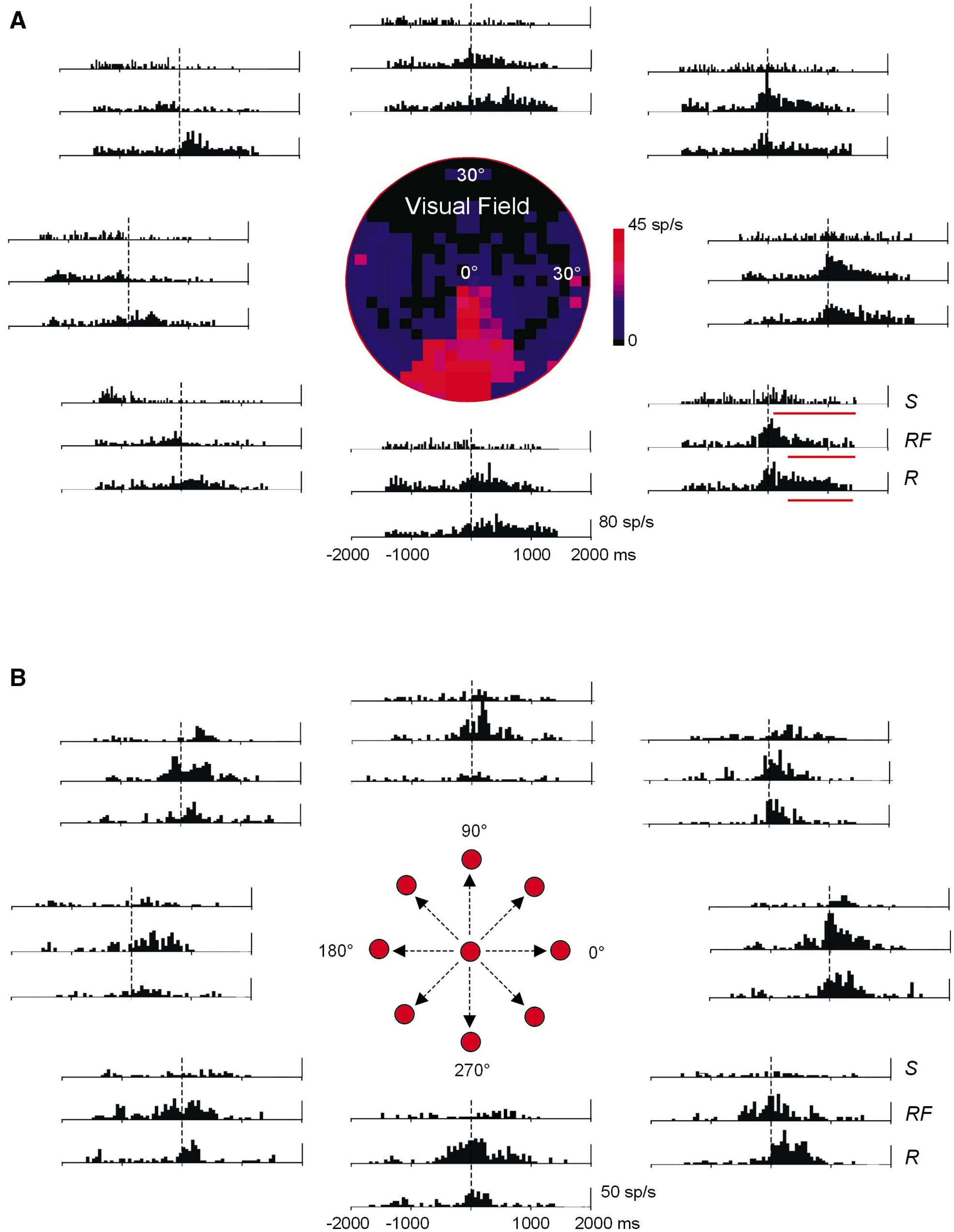

FIG. 2. *A*: peri-events time histograms of the activity of a parietal neuron in the 8 different directions of the Reach (*R*), Reach-Fixation (*RF*), and Saccade (*S*) tasks are aligned to the onset (vertical interrupted line) of hand (*R* and *RF*) and eye (*S*) movement. Red bars under the time axis indicate average range of THT. Bin size is 25 ms. In the center, the color-coded map of cell activity in the Visual Fixation (*VF*) task shows the location and extent of the visual receptive field. Sp/s and ms indicate, respectively, spikes per second and milliseconds. *B*: peri-events time histograms of the activity of another parietal neuron. Bin size is 50 ms. Conventions and symbols as in *A*. In the center, the directional array of the workspace is shown.

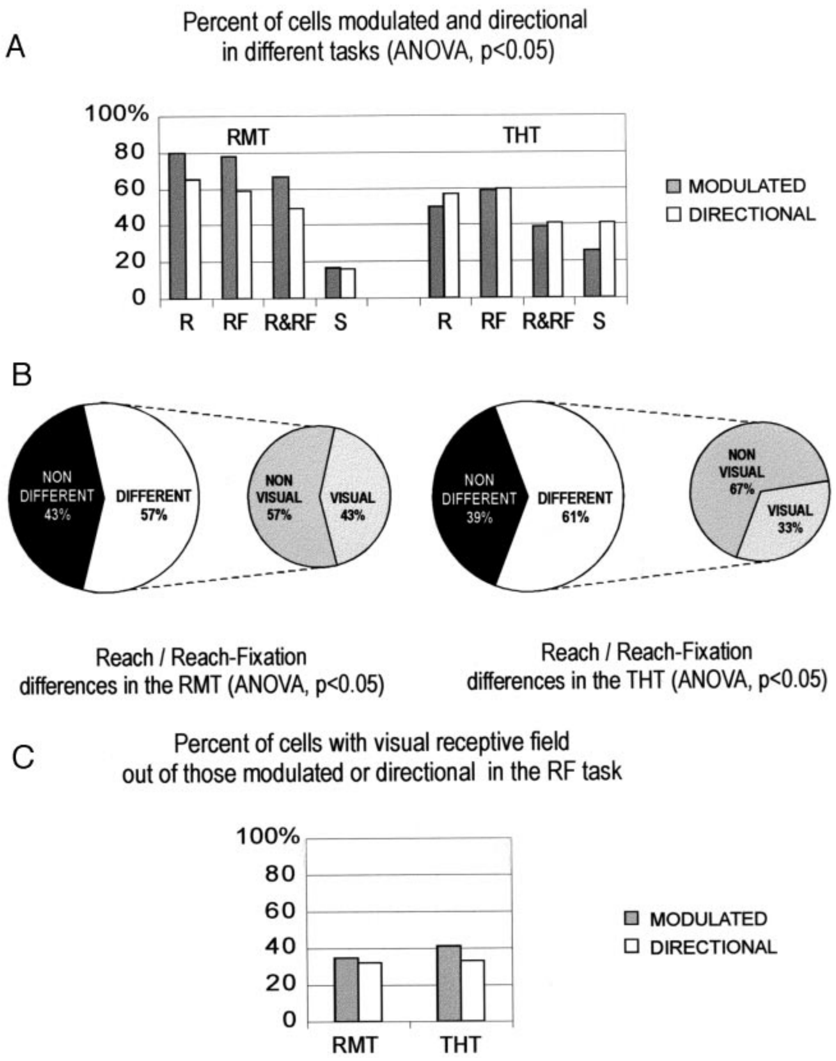

FIG. 3. *A*: bar graphs showing percentages of neurons modulated, relative to the control time, and directionally modulated, during RMT and THT of different tasks. R&RF refers to modulation and directionality occurring in both reaching tasks. *B*: pie diagrams showing fractions of cells with and without significant differences of modulation between R and RF. Smaller pie diagrams represent the fraction of cells modulated in the VF task among those displaying significant differences of activity between R and RF. *C*: percentages of neurons modulated in the VF task out of those modulated and directional during different epochs (RMT, THT) of the RF task.

havior. When studied under different task conditions, designed to dissociate the hand- and eye-related signals, the activity of most neurons was influenced by a combination of these signals. Although different response properties were observed, the relationships with arm movement and position were prevalent.

Reach-related activity was sometime influenced by the position of the eye in the orbit. This was observed by comparing reaches with and without previous eye movement. The eye influence was detected already during the hand reaction time in the Reach-Fixation task, when the eye was fixating at the center of the workspace. This suggests that the eye signals are of central origin and that the change of activity under these circumstances was independent of the kinematics of the arm, since it occurred well before onset of arm movement. An influence of eye position signals on reach-related activity in the superior parietal lobule has recently been described also by Batista et al. (1999). The activity of fewer cells was instead dominated by eye position information alone.

This combinatorial mechanism that operates at a very early stage in the information processing flow leading from vision to movement emerges as a prominent functional feature of area PEc. A similar combination of eye- and arm-related information has also been observed in areas 7m (Ferraina et al. 1997) and V6A (Battaglia-Mayer et al. 2000), where, however, eye movement–related neurons are more numerous than in PEc. In spite of this, the functional properties of the two adjacent areas PEc and V6A are remarkably similar, at least when analyzed under the experimental conditions of the tasks adopted in this study. Thus different parietal areas share common functional properties, although different signals are represented with different strength. Similar results were obtained in a previous study (Johnson et al. 1996) of parietal areas 5 (PE) and MIP.

Recently, it has been reported (Jouffrais and Boussaoud 1999) that reach-related activity in the dorso-caudal premotor (PMdc, F2) cortex is influenced by eye position signals, probably carried through the reciprocal association connections linking PEc and premotor cortex (Johnson et al. 1996; Matelli et al. 1998; Tanné et al. 1995).

This similarity of dynamic properties of cells in parietal and premotor cortex suggests that the coordinate transformation underlying hand movement to spatial targets is based on a parallel and recursive mechanism. Reentrant signaling (Edelman 1993) through reciprocal association connections can be a way to link the functional operations of those areas underlying the coordinated eye-hand action necessary for different motor tasks.

This study was supported by funds from the Human Frontiers Science Program Organization and the Ministry of Scientific and Technological Research of Italy.

REFERENCES

Batista AP, Buneo CA, Snyder LH, and Andersen RA. Reach planes in eye-centered coordinates. *Science* 285: 257–260, 1999.

Battaglia-Mayer A, Ferraina S, Mitsuda T, Marconi B, Genovesio A, Onorati P, Lacquaniti F, and Caminiti R. Early coding of reaching in the parieto-occipital cortex. *J Neurophysiol* 83: 2374–2391, 2000.

Caminiti R, Genovesio A, Marconi B, Battaglia-Mayer A, Onorati P, Ferraina S, Mitsuda T, Giannetti S, Squatrito S, Maioli MG, and Molinari M. Early coding of reaching: frontal and parietal association connections of parieto-occipital cortex. *Eur J Neurosci* 11: 3339–3345, 1999.

Caminiti R, Johnson PB, Galli C, Ferraina S, and Burnod Y. Making arm movements within 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.

Edelman GM. Neural Darwinism: selection and reentrant signaling in higher brain functions. *Neuron* 10: 115–125, 1993.

Ferraina S, Johnson PB, Garasto MR, Battaglia-Mayer A, Ercolani L, Bianchi L, Lacquaniti F, and Caminiti R. Combination of hand and gaze signals during reaching: activity in parietal area 7m of the monkey. *J Neurophysiol* 77: 1034–1038, 1997.

Johnson PB, Ferraina S, Bianchi L, and Caminiti R. Cortical networks for visual reaching: physiological and anatomical organization of frontal and parietal lobe arm regions. *Cereb Cortex* 6: 102–119, 1996.

Jouffrais C and Boussaoud D. Neural activity related to eye-hand coordination in the primate premotor cortex. *Exp Brain Res* 128: 205–209, 1999.

Matelli M, Govoni P, Galletti C, Kutz D, and Luppino G. Superior area 6 afferents from the superior parietal lobule in the macaque monkey. *J Comp Neurol* 402: 327–352, 1998.

Matelli M, Luppino G, and Rizzolatti G. Patterns of cytochrome oxidase activity in the frontal agranular cortex of the macaque monkey. *Behav Brain Res* 18: 125–136, 1985.

Pandya DN and Seltzer B. Intrinsic connections and architectonics of posterior parietal cortex in the rhesus monkey. *J Comp Neurol* 204: 196–210, 1982.

Tanné J, Boussaoud D, Boyer-Zeller N, and Rouiller EM. Direct visual pathways for reaching movements in the macaque monkey. *Neuroreport* 7: 267–272, 1995.