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Gaze effects in the cerebral cortex: reference frames for space coding and action

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Abstract Visual information is mapped with respect to the retina within the early stages of the visual cortex. On the other hand, the brain has to achieve a representation of object location in a coordinate system that matches the reference frame used by the motor cortex to code reaching movement in space. The mechanism of the necessary coordinate transformation between the different frames of reference from the visual to the motor system as well as its localization within the cerebral cortex is still unclear. Coordinate transformation is traditionally described as a series of elementary computations along the visuomotor cortical pathways, and the motor system is thought to receive target information in a body-centered reference frame. However, neurons along these pathways have a number of similar properties and receive common input signals, suggesting that a non-retinocentric representation of object location in space might be available for sensory and motor purposes throughout the visuomotor pathway. This paper reviews recent findings showing that elementary input signals, such as retinal and eye position signals, reach the dorsal premotor cortex. We will also compare eye position effects in the premotor cortex with those described in the posterior parietal cortex. Our main thesis is that appropriate sensory input signals are distributed across the visuomotor continuum, and could potentially allow, in parallel, the emergence of multiple and task-dependent reference frames.

Key words Motor system · Coordinate transformation · Frontal cortex · Visually guided movement · Eye-hand coordination

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Introduction

The brain receives visual inputs in a retinal coordinate system, and the retinotopic maps are propagated throughout the visual system, up to high-order visual areas of the parietal and temporal cortices. Ultimately, visual information reaches the premotor cortical regions, where visually guided reaching movements are planned (for reviews see Boussaoud et al. 1996; Caminiti et al. 1996; Wise et al. 1997). On the other hand, it is widely believed that the motor system codes movements to locations specified relative to shoulder or body axis, not in a retinocentric frame of reference (Soechting and Flanders 1989; Flanders et al. 1992; Bock and Eckmiller 1986; Gordon et al. 1994). The question then is how the brain transforms the coordinates of a visual target from retinocentric coordinates to body-centered coordinates. This issue has been the focus of several studies over the past 20 years in psychophysics (for reviews see, e.g., Abrams 1992; Flanders et al. 1992; Soechting and Flanders 1992), neurophysiology (Andersen et al. 1985, 1990; Duhamel et al. 1992, 1997), and modeling (Bremmer et al. 1998; Pouget and Sejnowski 1995, 1997; Pouget et al. 1993; Zipser and Andersen 1988). From a conceptual point of view, the prevailing idea has been that this “coordinate transformation” is performed in a serial or hierarchical manner with progressive shifts of target location from retinocentric, to head-centered, to body-centered coordinates (Flanders et al. 1992; Jeannerod 1991). In most models of coordinate transformations between reference frames, retinal and eye position signals are conceived to converge at low levels of the visual pathways, where a head-centered representation of visual space is computed. Then, at later stages, head position signals are used to create a body-centered representation which is used by the motor output stage, in conjunction with limb position signals, to produce movements in space.

One of the brain regions thought to play a major role in coordinate transformation and space coding is the posterior parietal cortex. Within the inferior parietal lobule, neurons have been shown to receive retinal signals, or-

bital eye position signals, and head-position signals (Andersen et al. 1985, 1990; Andersen and Mountcastle 1983; Bremmer et al. 1997a, 1997b; Brotchie et al. 1995). Yet, neurons whose activity reflects a convergence of retinal and eye position signals have also been reported in many different areas of the visuomotor networks: areas V1 (Guo and Li 1997; Trotter et al. 1992, 1996), V3A (Galletti and Battaglini 1989), MT, and MST (Bremmer et al. 1997a), the parieto-occipital region (Galletti et al. 1991, 1995), the supplementary eye field (Schlag et al. 1992), the prefrontal cortex (Boussaoud et al. 1993) and premotor cortex (Boussaoud et al. 1993, 1998; Boussaoud 1995; Jouffrais and Boussaoud 1996; Mushiaké et al. 1997). The frontal regions, in particular, are involved in processing levels beyond just target localization, including movement planning, and thus modulation of activity by eye position calls for a reevaluation of the functional implication of gaze signals in visuomotor processing and coordinate transformation. We will first review gaze effects in the dorsal premotor cortex (PMd) examined under a visuomotor task (Boussaoud et al. 1998). Then, we will present data showing that the activity of neuronal populations of both parietal and premotor cortices allows for accurate coding of gaze direction in space. Finally, we will discuss these data within the framework of reaching movements at a behavioral level.

Effects of eye position in the premotor cortex

In the dorsal premotor cortex, Boussaoud and his coworkers (Boussaoud 1995; Boussaoud et al. 1998; Jouffrais and Boussaoud 1996, 1999) have used two experimental designs to study the effects of eye position on the neuronal activity. In one task, the conditional visuomotor task, monkeys made limb movements in one of two directions (left or right) depending on the color of a visual cue, while fixating at five different locations on a video screen. In the other, a reaching task, monkeys were required to reach and point to visual targets presented on a touch screen. Due to space limitations, this review will focus on the findings of the first set of experiments (but see Jouffrais and Boussaoud 1999, this issue, for the reaching task).

In these experiments, visual cues were presented on a video monitor, and the monkeys made limb movements on a panel of three metal touch pads located at the bottom of the monitor. One touch pad served to initiate the trials and was aligned on the monkey's body axis, one was 12 cm to the right of that axis, and one 12 cm to the left. Each trial began when the monkey put its hand on the central pad, and fixated a target (Fig. 1). After a delay of steady fixation, a 2×2 degrees white square appeared at one of nine locations forming a grid centered on the fixation point. This stimulus served as a precue (PC) which directed the monkey's attention to that screen location. Next, following a variable delay (0.5–1 ms), a colored square of the same size appeared at the precued location. This stimulus (the motor instructional conditional cue,

MIC) guided the monkey's motor response according to a conditional rule: if red, the appropriate response was to contact the left touch pad, if green a movement to the right pad was the correct response. The MIC cue was presented for a 1- to 3-s instructed delay period and the monkey had to wait for its offset, the go signal, to perform the appropriate response and receive a liquid reward.

This experimental design allowed a constant eye position to be maintained during the presentation of visual cues as well as during movement preparation and execution (Fig. 1A). In order to examine the effects of eye position on the neuronal activity during these task epochs, the location of the fixation point was varied from a block of trials to the next, with visual cues presented at constant retinal coordinates (Fig. 1B; see Boussaoud et al. 1998 for details). Since the head was restrained, under these experimental conditions, peripheral fixations caused deviations of the eyes within the orbits, while all other task parameters remained the same (cf. Fig. 1Ba,b), namely the cue's visuospatial parameters, limb initial position, intended movement direction and movement end point. In addition to gaze effects, the experimental design allowed the deter-

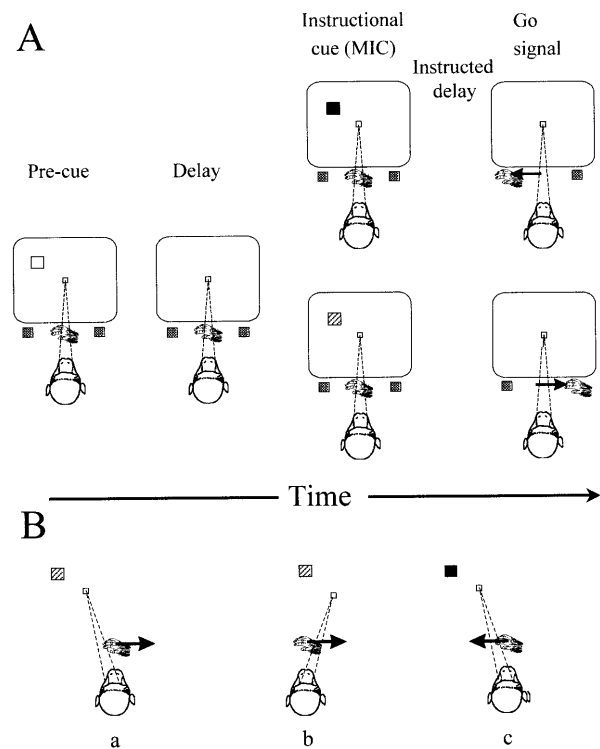


Fig. 1A, B Schematic representation of the behavioral task used by Boussaoud et al. (1998). **A** depicts the major steps in the performance of two trials which both begin when the monkey puts its hand on a central pad and fixates the fixation point (*small square*). A precue appears at a given location, and after a delay a motor instructional cue (*MIC*) appears at the precue's location (see text for details). After a variable instructed delay, *MIC* goes off (the go signal), and the monkey moves its hand to contact the appropriate touch pad. **B** Examples of trials with different gaze angles, but the same movement direction (cf. **a** and **b**), or with same gaze angle, but limb movement in opposite directions (cf. **a** and **c**). See text for more details

mination of the effects of changing the retinal location of the MIC cue, or movement direction on the cells' activity. This was achieved by varying the location of the cue or limb movement direction independently of one another, while orbital eye position remained the same. For example, a red cue could appear at different locations for a single fixation point, but its instructional meaning was always the same (move to the left). Any change in the cell's activity in this situation is attributable to the change in retinal coordinates (termed "retinal effect" in Boussaoud et al. 1998). On the other hand, in some trials, red and green cues were presented at the same screen location, in which case movement direction changed, but neither fixation nor cue location varied. Variations in cell activity in such trials cannot be attributed to the change in the cue's color per se, as previous more controlled experiments (Boussaoud and Wise 1993a, 1993b; Boussaoud and Kermadi 1997) have shown that none of the sampled PMd cells differentiated between stimuli based on their color. Rather, any difference in the activity between these trials can be attributed to the coding of limb movement direction. Finally, the presentation of a precue allowed us to determine whether neuronal activity is visuospatial or visuomotor in nature. During the delay that follows the precue, the monkey has no indication as to the direction of movement, only where the MIC cue will appear later. Thus, any activity associated with the precue's presentation may reflect spatial attention and/or memory, or the spatial location of the visual stimulus.

Under these experimental conditions, it appears that neuronal activity in PMd is largely modulated by at least three experimental parameters: target location in retinal coordinates (i.e., cells have coarse retinal receptive fields), orbital eye position, and limb movement direction. We will review these findings and suggest that neuronal discharges in PMd might allow for at least two distinct sensory-to-motor transformations: one combines retinal and eye position signals for target localization as has been proposed, e.g., for the parietal cortex (Andersen et al. 1985, 1990; Bremmer et al. 1997a, 1997b, 1998; Zipser and Andersen 1988); the other combines movement preparatory signals with eye position for movement representation in a higher order coordinate system.

Premotor cortex and target localization

Computational experiments have shown that target location in head-centered coordinates can be derived from two basic inputs: retinal location of the target, and orbital eye position (e.g., Zipser and Andersen 1988; Bremmer et al. 1998). It was thus proposed that the posterior parietal cortex, which contains neurons with retinal receptive fields and whose response properties are modulated by orbital eye position (Andersen et al. 1985, 1990), is capable of creating a head-centered representation of targets from a distributed neuronal network.

Neuronal properties like those of the parietal cortex have been reported in a variety of extrastriate visual areas (see "Introduction"), suggesting that these cortical regions participate in the process of coordinate transfor-

mation. In addition, retinal receptive fields and eye position modulation have been described even in the prefrontal cortex and the ventral premotor area (Boussaoud et al. 1993; Mushiaké et al. 1997). Therefore, our assumption here is that any brain area which contains neurons with properties resembling those described in the parietal cortex is capable of a coordinate transformation of the type performed by the posterior parietal cortex.

Retinal effects

When all other parameters of the task are held constant, change in the cue's retinal location alone affects the dis-

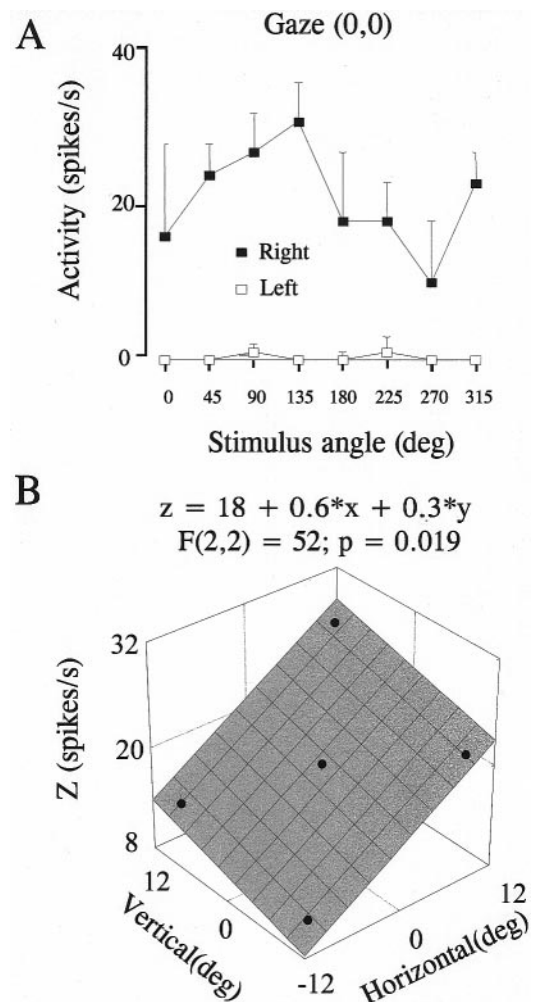


Fig. 2 Retinal effects in PMd. **A** Mean discharge rate (+SD) of a PMd cell as a function of the location of MIC cues in retinal coordinates (represented as polar coordinates). **B** Two-dimensional regression function fit to the signal-related activity of another PMd cell following onset of a red MIC cue (leftward limb movement) presented at nine different retinal locations. Mean activity for five fixation angles (black circles) is plotted against eye position along the horizontal and vertical axes. The shaded area represents the regression plane, whose regression equation is given above the graph. The size of the bar between the black circles and the plane represents the deviation of activity from the plane. The *P* value indicates the significance level of the fit

charge rate of a substantial proportion of PMd cells (Boussaoud et al. 1998), although we stress that the receptive fields were not studied in detail. Figure 2A shows an example of PMd cells whose discharge rate is tuned to the location of the visual cue (presented in polar coordinates) which instructs a limb movement to the right (green). This tuning to target location in a conditional task (i.e., movements are not made to the visual targets) taken alone, would suggest that the neuronal activity of this cell is visual in nature. However, the presence of a visual stimulus in the receptive field, whether attended to or not, is not sufficient to trigger the cell's response. This is well illustrated in Fig. 2A, which shows that the cell's discharge in relation to cues with identical retinal coordinates differs dramatically depending on whether they instruct a movement to the left or to the right. Cues which instruct movement to the left, although presented at the same retinal coordinates as the cues directing a movement to the right, trigger no activity. As this example illustrates, activation of the majority of PMd neurons requires visual stimuli which guide a given limb movement direction (Boussaoud and Wise 1993b; Boussaoud and Kermadi 1997; Boussaoud et al. 1998).

Retinal effects are observed during all epochs of the task analyzed (Boussaoud et al. 1998), but they are more predominant on signal-related (43% of PMd sample) than on set- (29%) and movement-related (29%) activity. It appears, thus, that target representation in retinal coordinates is more likely in the early neuronal activity, and as time progresses the coding switches to the representation of the intended movement direction. Previous studies have already shown that sensory aspects, as opposed to the direction of movement, are reflected in the early discharge of PMd cells after target onset (Boussaoud and Wise 1993b; di Pellegrino and Wise 1993; Kalaska and Crammond 1994). According to these studies, set- and movement-related activity is less correlated with target parameters, reflecting instead the direction of limb movement. Taken together with the retinal effects reviewed above, it appears that information processing within the premotor cortex is related to the visual information that guides behavior, early after target presentation, and progressively switches to movement representation.

Gaze effects

Boussaoud et al. (1998) found that a large majority of PMd cells show modulation of signal-related activity as a function of eye position in the orbits. Further analysis showed that for most cells such a modulation occurs in a linear manner with variations of eye position in the horizontal and vertical domain. In such cases, activity measured for different experimental eye positions can be approximated by a two-dimensional linear regression function. In the example illustrated in Fig. 2B, the mean signal-related activity was strongest when the monkey fix-

ated the upper right part of the screen, weakest for fixation down and to the left, and intermediate for central fixation. Individual cells have different gradients of activity in relation to gaze angle, as represented by the direction of the steepest slope of the regression plane.

Premotor cortex and reference frames for movement representation

There is now a large consensus that set-related activity reflects predominantly kinematic aspects of limb movement, as opposed to the target that triggered the movement. Indeed, during the instructed delay period, as well as after the go signal, neuronal activity has appeared to be primarily associated with movement direction, amplitude or trajectory, rather than with spatial attentional or sensory processes (Boussaoud and Wise 1993b; Crammond and Kalaska 1994; Caminiti et al. 1991; di Pellegrino and Wise 1993; Fu et al. 1993, 1995; Hoehnerman and Wise 1991; Kalaska and Crammond 1995; Kurata and Wise 1988; Passingham 1994; Riehle and Requin 1989; Tanji et al. 1988; Weinrich and Wise 1982; Wise 1984). If gaze signals were used only for coordinate transformation from retinocentric to head-centered frames, one might predict that gaze modulation would decrease as the informational content of neuronal activity progressively shifts from target to movement representation (i.e., from signal-related to set- and movement-related activity). Such is not the case, as gaze effects remain strong across the activity that follows MIC cues, up to movement execution (Boussaoud et al. 1998). Furthermore, the proportion of cells with gaze effects is strikingly high (74–79%) independent of the activity examined, and the modulation takes the form of linear functions in all trial epochs. Figures 3 and 4 illustrate the

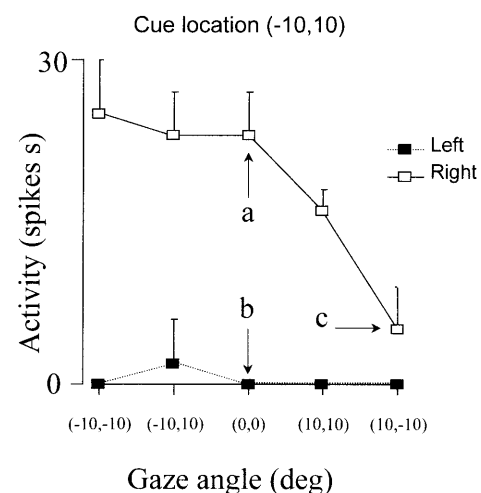


Fig. 3 Gaze effect on set-related activity of a PMd cell. Mean activity plotted against eye position while the monkey prepared to make a limb movement to the left, or to the right. Note the conjunction of the effects of two factors: limb movement direction (cf., e.g., *a* and *b*) and gaze angle (cf. *a* and *c*)

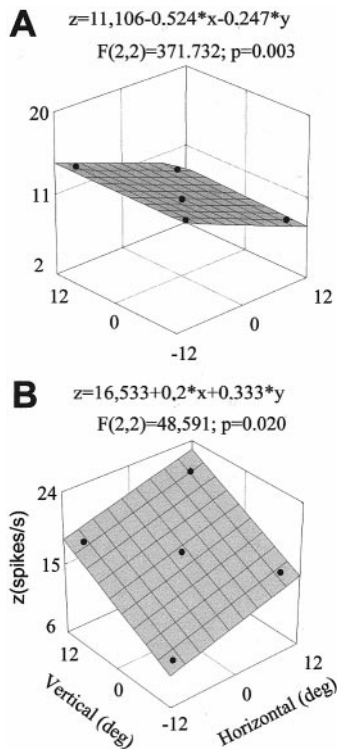


Fig. 4 Regression plane fit to the set-related activity (**A**) and movement-related activity (**B**) of two PMd neurons. Same conventions as in Fig. 2B

modulation of set-related activity of two PMd neurons by gaze angle. Figure 3 illustrates a striking phenomenon in PMd: set-related activity is tuned for limb movement direction, and yet it strongly varies with gaze angle. Figure 4 illustrates the linear regression planes fitted to set- and movement-related activity of two different neurons.

Thus, gaze effects are a general phenomenon that is present throughout the temporal evolution of the monkey's reaching behavior, i.e., gaze modulates activity across the sensory-to-motor continuum within PMd. The functional significance of gaze dependency of preparatory and movement-related activity is not, at first glance, apparent, especially given that behavioral studies have suggested that limb movements rely on shoulder- or hand-centered coordinate systems (Soechting and Flanders 1989; Flanders et al. 1992; Bock and Eckmiller 1986; Gordon et al. 1994). These behavioral studies would predict that neurons in the premotor and motor cortical areas build motor commands in a limb-centered coordinate system. Such neurons have been reported by Caminiti et al. (1991), but because gaze shifts and limb movements were not dissociated from one another in that study, the reference frame used by these neurons remains unclear. In theory, just as explicit target representation in head-centered coordinates can be derived from a distributed coding in retinal coordinates, a limb-centered reference frame may emerge from neuronal processes which represent movement at more basic coordinate systems (Pouget and Sejnowski 1997). The presence of gaze-

dependent neuronal properties in PMd, and in fact in M1 (Jouffrais and Boussaoud, unpublished data; Sanes et al. 1996), together with retinal and motor intentional signals, suggests that an ensemble of neurons represents movement information in a higher order, e.g., head- or limb-centered frame of reference. One advantage of such a distributed representation of movement might be to allow a flexibility for building in parallel appropriate task-dependent reference frames (see below).

Summary

The data reviewed above indicate that various signals are combined at the level of single neurons in PMd: a given cell may combine sensory processing (e.g., retinal effects), motor processes (e.g., activity reflects movement direction), and gaze signals. In addition to this combinatorial processing, there is a transition from sensory processing to movement representation: retinal effects decrease in time between the onset of an instruction to the execution of movement execution, whereas movement representation increases. Parallel to this temporal evolution of information processing, gaze direction remains a highly important factor across time. One possible interpretation of these observations is that, at the premotor cortex level, neuronal representation evolves as a function of time, from target localization in a head-centered reference frame to movement representation in a higher order frame. Theoretical models have been used to test how neuronal populations may code target location in head-centered coordinates (Zipser and Andersen 1988), but no such models have been developed as yet where gaze and retinal signals, together with limb position and other proprioceptive signals, are combined to code for movement kinematics.

We will now briefly review data collected from the posterior parietal cortex by Bremmer et al. (1997b) under a fixation paradigm. Most importantly, we will compare how the cell populations in areas LIP/7A and PMd represent eye position. The main point is to highlight the similarities between neuronal properties in the parietal and premotor levels.

Comparison with the posterior parietal cortex

As reviewed in the "Introduction," several areas within the posterior parietal cortex contain cells whose visual responses and oculomotor properties are modulated by orbital eye position. In a recent work, Bremmer et al. (1997b) studied modulation of cell properties by eye position in areas LIP and 7A in a task where monkeys maintained gaze on a fixation point in darkness. They found that, in both LIP and 7A, the activity during fixation (epoch of 1 s) changed with eye position in a majority of cells. In addition, Bremmer et al. found that eye position modulation is linear, and that two-dimensional regression planes can be fitted to the neuronal activity. In

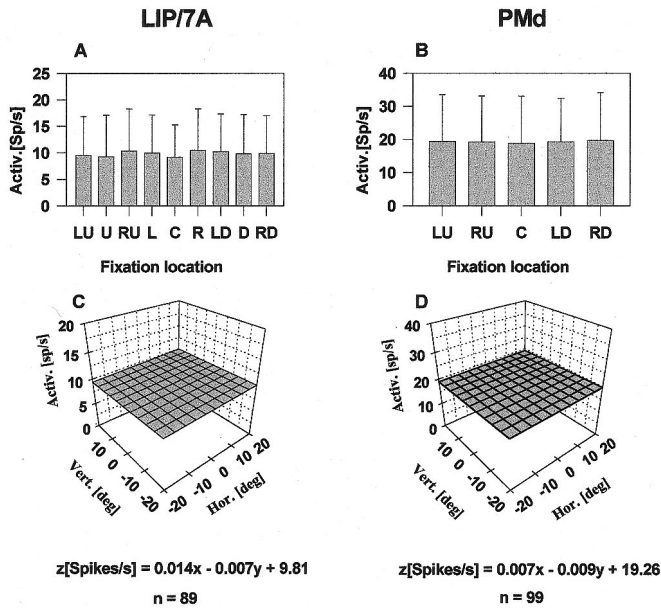


Fig. 5A–D Population response for parietal areas LIP/7A and PMd. **A,B** Mean and standard deviation of the discharge rate averaged across the neuronal samples for each fixation location (*C* center, *D* down, *L* left, *LD* left and down, *LU* left and up, *R* right, *RD* right and down, *RU* right and up). **C,D** Mean regression plane for the total cell sample for LIP/7A and PMd, respectively (see text). Note that for both areas the resulting regression planes are almost flat

a follow-up study, Bremmer et al. (1998) have shown that the population of parietal neurons sampled was capable of encoding the position of the eyes in the orbits.

These findings on parietal cortex neurons together with recent results from PMd (Boussaoud et al. 1998) led us to hypothesize that the same neuronal mechanisms might take place in both cortical regions in order to gen-

erate non-retinocentric representations of visual spatial information. To test this hypothesis, we compared the properties of cells recorded from areas LIP/7A with those recorded from PMd. It appears that, in both parietal and premotor areas, the neuronal samples recorded are capable of creating an accurate representation of eye position.

Eye position modulation at the population level

In order to test for a resulting net effect of orbital eye position at the population level in both cortical regions, we computed the mean discharge rate for the entire sample of neurons in each area ($N=99$ for PMd; $N=89$ for LIP/7A). In a first approach, we compared the original spike data at the different fixation locations (Fig. 5A,B). Statistical analysis revealed that the mean discharge values at the different fixation locations did not differ significantly from each other (ANOVA: $P>0.9$ for areas LIP/7A and PMd). In a second approach, we averaged all linear regression planes fitted to the individual cells of LIP/7A and PMd. It appears that for both LIP/7A and PMd the mean regression plane is essentially flat, indicating that the modulatory effect of eye position observed at the neuronal level is balanced out at the population level (Fig. 5C,D). These two analyses show that the distribution of cell activity across eye positions is not biased.

Distribution of the gradients of the regression planes

The analysis of the distribution of the regression planes confirms the absence of bias due to eye positions. A primary observation is that the activity of most cells chang-

Fig. 6 Distribution of the gradients of the regression planes for parietal areas LIP and 7A (combined) as well as for PMd. In both central figures the gradient of an individual linear regression plane, treated as a two-dimensional vector, is represented by a single data point. Statistical analysis shows that the directions of the gradients for both LIP/7A and PMd are uniformly distributed. *The histograms to the top and the side represent the distributions of the slopes along the horizontal and vertical axes, respectively. A normal distribution (represented by a dotted line within each histogram plot) is the best approximation for the values of the slopes, when tested against a Poisson or uniform distribution*

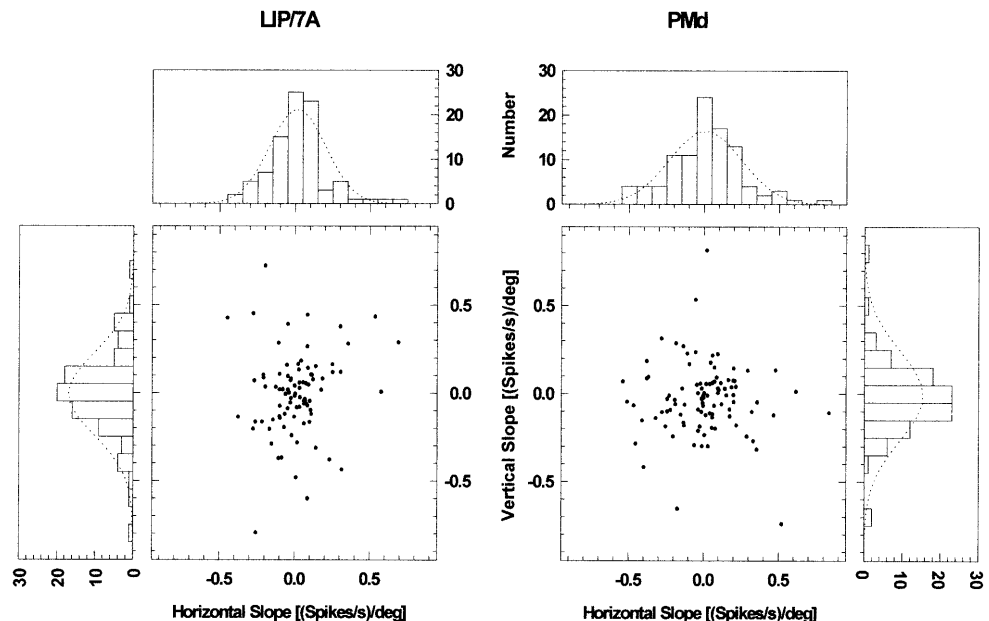


Fig. 7A–D Principle of the isofrequency encoding of eye position. **A** For an experimental fixation at (20, -20), the isofrequency lines (green and red lines) of two hypothetical neurons (see text) will cross each other at a single point (the point of intersection, *PI*). **B** Actual fixation location. **C, D** Color-coded representation of the computed eye position in 2D and 3D, respectively. Red is the maximum number of PIs (*I*), dark blue is the lowest (zero). In **C**, the actual eye position is represented by a cross

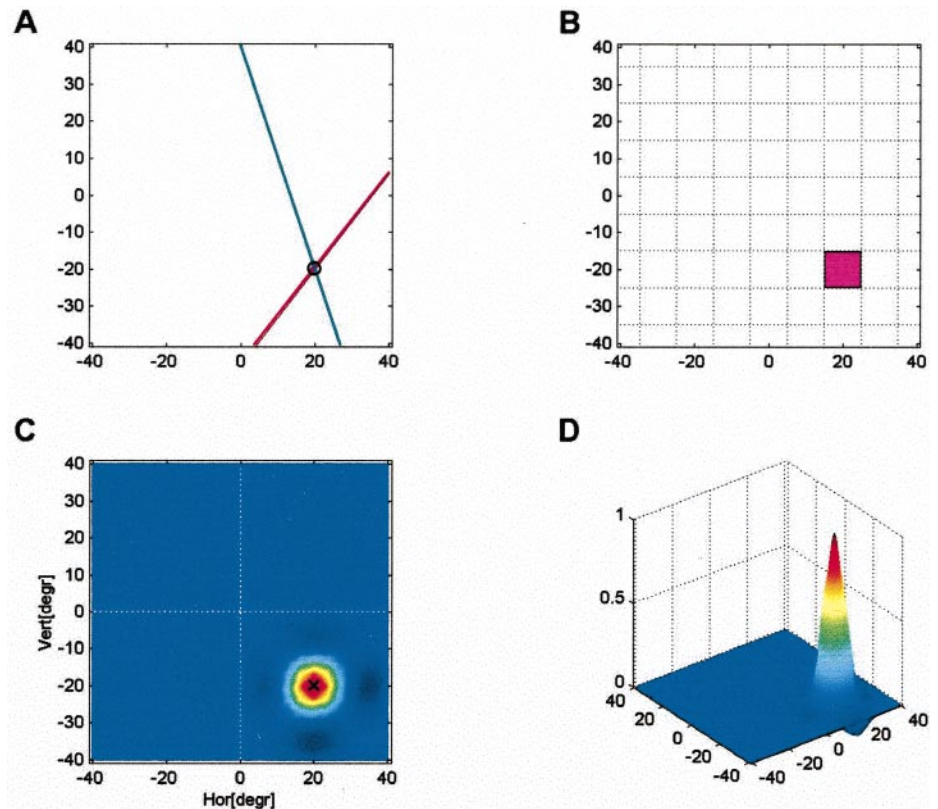


Fig. 8A–D Isofrequency encoding of eye position. Color-coded distribution of the number of intersections between the isofrequency lines for the neuronal sample (red maximum, dark blue minimum). The distribution is represented in 2D (**A, C**) and in 3D (**B, D**). **A, B** Distribution for PMd (99 cells). **C, D** Distribution for LIP/7A (89 cells). Same conventions as in Fig. 7. Experimental fixation coordinates (10°, -10°) are represented by the cross hair

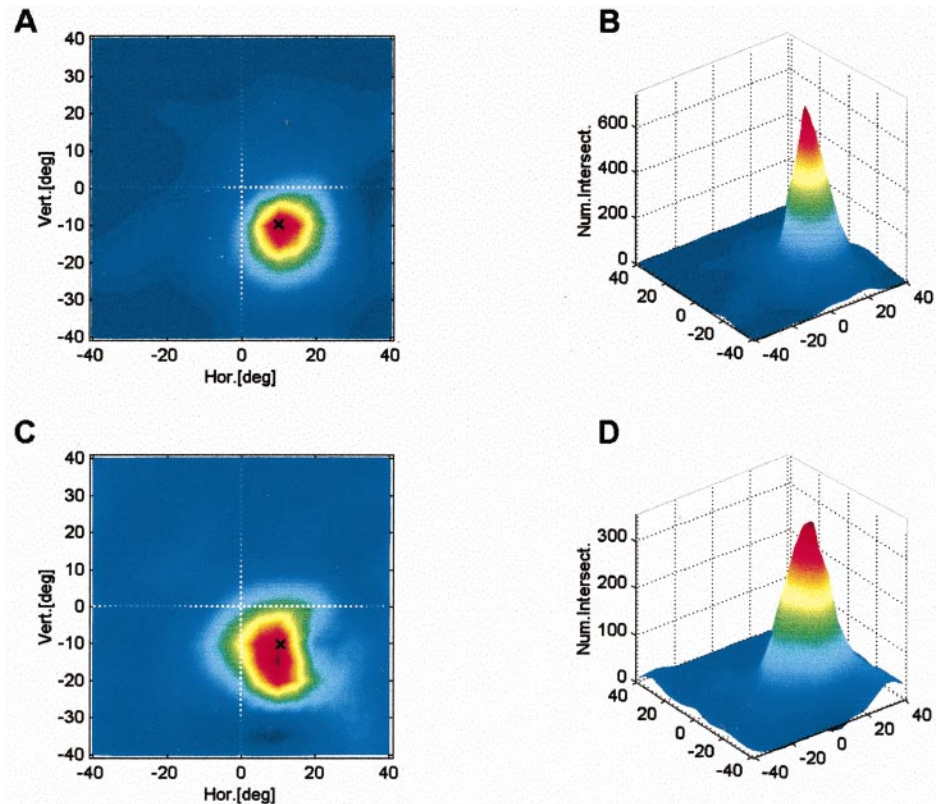


Table 1 Experimental and computed eye positions: posterior parietal cortex. From left to right: first column fixation locations, columns 2, 3 values for horizontal eye position defined experimentally (*HORexp*) or computed from the neuronal discharge (*HOR*

theo), columns 4, 5 values for vertical eye position defined experimentally (*VERTexp*) or computed from the neuronal discharge (*VERTtheo*), column 6 difference between experimental and computed eye position (*Error*). The mean error is 3.48°

Position	HORexp	HORtheo	VERTexp	VERTtheo	Error
Up left	-10.6	-11.76	10.6	10.67	1.16
Up right	10.6	8.96	10.6	7.56	3.45
Down left	-10.6	-8.17	-10.6	-9.19	2.81
Down right	10.6	8.03	-10.6	-10.53	2.52
Center	0.0	-0.46	0.0	3.89	3.91
Right	15.0	13.45	0.0	2.46	2.89
Down	0.0	-3.10	-15.0	-13.88	3.29
Left	-15.0	-9.51	0.0	-1.14	5.61
Up	0.0	0.50	15.0	9.32	5.70

Table 2 Experimental and computed eye positions: dorsal premotor cortex. Abbreviations as in Table 1, except that only five eye positions were tested. Mean error is 2.03°

Position	HORexp	HORtheo	VERTexp	VERTtheo	Error
Up left	-10.0	-8.18	10.0	7.96	2.73
Up right	10.0	6.38	10.0	7.51	4.39
Down left	-10.0	-11.13	-10.0	-9.36	1.3
Down right	10.0	10.44	-10.0	-10.40	0.59
Center	0.0	0.28	0.0	-1.1	1.14

es in a linear manner with variations of eye position, and the modulation of the activity can be approximated (with statistical significance) by a two-dimensional linear regression function. In order to assess the uniformity of the distribution of gaze effects in the parietal and premotor areas, the gradients of the regression planes of individual neurons were analyzed (Boussaoud et al. 1998; Bremmer et al. 1998). Figure 6 shows the distribution of these gradients for both populations. It appears that the distribution of the directions of the gradients did not deviate significantly from a normal distribution ($P > 0.9$ for the parietal neurons and $P > 0.5$ for the premotor neurons).

Isofrequency encoding of actual eye position

In order to test whether experimentally defined eye positions can be predicted from the neuronal properties of parietal and premotor cells, we developed a simple algorithm for computing eye position from the discharge rates of cell populations. Briefly, each cell's discharge measured while monkeys fixated at the predefined locations is fitted with a two-dimensional regression plane. A given neuron (N1) will display a specific discharge rate when the monkey fixated at a given location [(20°, -20°) in Fig. 7]. However, the same discharge rate occurs for a whole range of eye positions, which, due to the planar tuning, are given by a straight line, termed "*the isofrequency line*." Along the isofrequency line the discharge frequency remains constant for varying eye positions (Fig. 7A). Relying on a single neuron will thus provide ambiguous information on the actual eye position. However, such an ambiguity should theoretically be reduced

by taking into account the activity of a second neuron (N2). As for the first neuron, a given discharge rate of neuron N2 occurs for a range of eye positions given by that neuron's isofrequency line. However, taken together, the specific discharge patterns (defined by the isofrequency lines) for neurons N1 and N2 coincide for a unique eye position, which corresponds to the point of intersection (PI) of the two isofrequency lines. The tunings of cells sampled from the parietal and premotor areas are not all ideally planar, and, therefore, relying on only two neurons to predict the actual eye position is an ideal situation. The population of parietal cells and that of PMd cells each provide a variety of isofrequency lines, and the actual eye position can then be computed as the center of mass of the distribution of the intersection points. Figure 8 shows that, although the distributions of PIs proved to be fairly broad, the representation of gaze direction is relatively precise. Quantitative analysis revealed that the mean error (difference between actual and predicted eye positions) of this isofrequency coding is 3.48° for nine experimental eye positions used in the posterior parietal study, and 2.03° for the five eye positions tested in the PMd study. Tables 1 and 2 present the experimentally given numerical values and the theoretically retrieved eye positions.

An important question concerns the relationship between accuracy of the isofrequency coding and the size of the neuronal sample. To answer this question, and compare with previous studies in visual cortex (e.g., Vogels 1990), we plotted the mean error of the predicted eye position as a function of the number of neurons. To do so, we created subsets of neurons by selecting, in a random process, neurons from the data sets for parietal

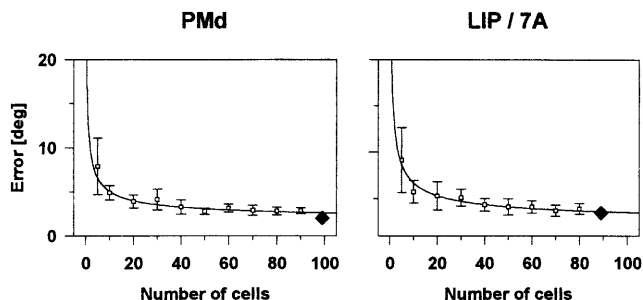


Fig. 9 Error as a function of the number of cells. Mean error and standard deviation were computed for small sets of PMd and LIP/7A cells and plotted as a function of the size sample. Subsets of cells were created by drawing randomly an increasing number of cells (5, 10, 15...80 for parietal; 90 for premotor). The largest sample is below the total cells in the database as to be able to fit the mean error for the total sample (*black diamonds*)

and premotor areas, respectively. The size of the subsets ranged from 5 to 80 neurons for parietal areas ($n=5, 10, 20, 30, 40, 50, 60, 70, \text{ and } 80$) and from 5 to 90 neurons for the premotor area ($n=5, 10, 20, 30, 40, 50, 60, 70, 80, \text{ and } 90$). We then calculated the mean error for the predicted eye position on the basis of each subset. Figure 9 illustrates the mean values (\pm SD) of computed eye positions as a function of the number of neurons. It appears that the error is inversely proportional to the square root of the number of neurons. These findings are very similar to those obtained for population coding in the visual cortex (e.g., Vogels 1990).

Summary

Eye position effects found in the dorsal premotor cortex have many similarities with those described in areas LIP/7A of the posterior parietal cortex, at both the single cell and the population levels. We have shown that actual eye position can be predicted from the discharge rates of each cell population (i.e., LIP/7A and PMd) with reasonable accuracy. The mean error, i.e., the distance of the computed eye position from actual eye position decreases as the size of the neuronal sample increases. At the parietal as well as the premotor levels, the computed eye position can be used in conjunction with retinal information to derive an implicit head-centered representation of the target, or the reaching movement required to capture the target.

Distributed processing and coordinate systems

From a conceptual point of view, coordinate transformation was originally thought of as a series of simple computations which gradually transform visual spatial information from a retinocentric into a body-centered frame of reference (Andersen et al. 1993; Jeannerod 1991). However, the distributed nature of eye position signals within and across areas suggests that these processing

stages do not map onto serially connected levels of the pathways linking visual and motor cortical areas. Rather, as reviewed above, various stages of the visuomotor pathways, such as the posterior parietal cortex and the dorsal premotor cortex, contain the necessary signals for an implicit representation of targets using eye position and retinal information. This suggests that the same neuronal mechanisms might be used in different cortical regions to construct in parallel different, task-dependent reference systems. As shown by Pouget and Sejnowski (1997), individual neurons could be part of multiple different neuronal circuits generating these different spatial representations. This, obviously, does not exclude the existence of neurons that code explicitly target information in a head-centered reference frame, as has been shown in the ventral intraparietal area (VIP; Duhamel et al. 1997). Nor does our proposal preclude the existence of premotor cortex and motor cortex cells whose activity represents movement direction in body-centered coordinates (Caminiti et al. 1991). Just that neuronal populations at all levels of the visual-to-motor chain of transformations are potentially capable of creating a distributed, implicit coding of both target location and movement direction in space. One advantage of distributed coding of reference frames for spatial localization and movement planning is to allow for flexible, task-dependent frames of reference. Heuer and Sangals (1998) have recently suggested that, even at the behavioral level, visuomotor transformations are best described in terms of "mixtures" of coordinate systems, the weight of which is task dependent. They argued that these "mixtures" emerge from distributed neuronal representations using multiple reference frames.

In conclusion, multiple reference frames may exist not only within each brain area of the visuomotor network, but also in distinct areas. A comprehensive theory of visuomotor transformations must take into account the distributed nature of gaze modulation of the discharge rates of individual neurons across the cerebral cortex. One possible implication of the reviewed findings is that the interactions between the parietal areas and PMd, through their anatomical connections (e.g., Johnson et al. 1996; Tanné et al. 1995, 1996), might play an important role in building flexible and task-dependent reference frames for coding target location as well as for coordinated gaze and arm movements.

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