PREMOTOR AND PARIETAL CORTEX: Corticocortical Connectivity and Combinatorial Computations[1]

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ABSTRACT

The dorsal premotor cortex is a functionally distinct cortical field or group of fields in the primate frontal cortex. Anatomical studies have confirmed that most parietal input to the dorsal premotor cortex originates from the superior parietal lobule. However, these projections arise not only from the dorsal aspect of area 5, as has long been known, but also from newly defined areas of posterior parietal cortex, which are directly connected with the extrastriate visual cortex. Thus, the dorsal premotor cortex receives much more direct visual input than previously accepted. It appears that this fronto-parietal network functions as a visuomotor controller—one that makes computations based on proprioceptive, visual, gaze, attentional, and other information to produce an output that reflects the selection, preparation, and execution of movements.

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INTRODUCTION

In early studies of the primate frontal lobe, the region between the primary motor representation (M1) and the prefrontal areas (PF) was considered an undifferentiated motor association cortex, also known as Brodmann's area 6 (Wise 1984, 1985; Preuss et al 1996). This region, sometimes termed the premotor cortex (PM) or the nonprimary motor cortex, is now known to contain several functionally distinct cortical fields (Kurata 1994, Preuss et al 1996) (Figure 1). The overview presented here considers the interactions of one of these regions, the dorsal premotor cortex (PMd), with the posterior parietal cortex. Our analysis results from the convergence of several lines of anatomical and physiological evidence pertinent to visually guided reaching, and from their
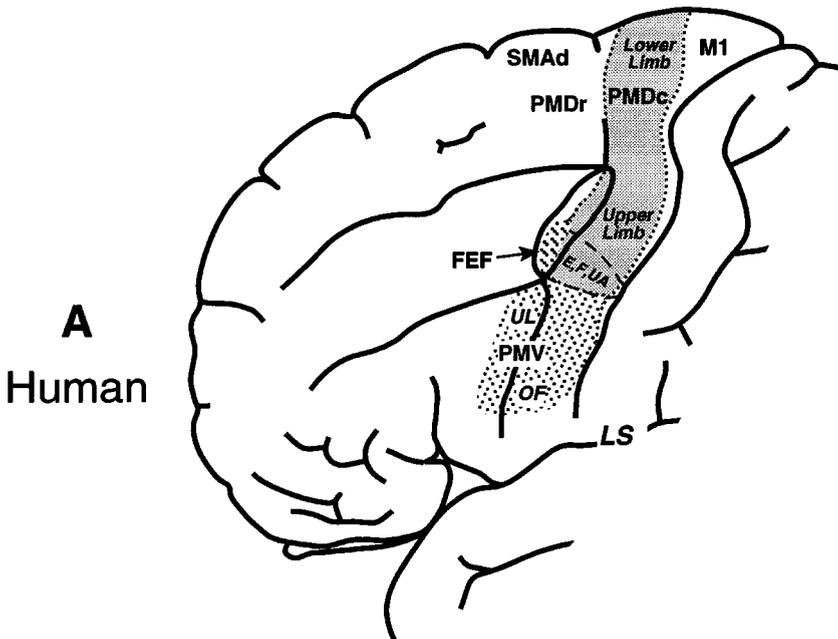

Figure 1 Cortical fields of the frontal cortex in a variety of primates. Lateral views of the frontal lobe of humans (*A*), owl monkeys (*B*) and macaque monkeys (*C*). Abbreviations for movement representations: E, eye movement; F and OF, orofacial; UA and U. Axial, upper axial; FL, forelimb; HL, hindlimb; UL, upper limb. Abbreviations of sulci: LS, lateral sulcus; CS, central sulcus; SPcS, superior precentral sulcus; AS, arcuate sulcus. Abbreviations of cortical areas: SMA, supplementary motor area; M1, primary motor cortex; PMd, dorsal premotor cortex; FEF, frontal eye field; PMv, ventral premotor cortex; FV, ventral frontal area; SEF, supplementary eye field; OMD, dorsal oculomotor field; 8b, area 8b. Abbreviations of cortical field subdivisions: r, rostral; c, caudal; m, medial; d, dorsal; Pre-, rostral. [Modified from Preuss et al (1996).]
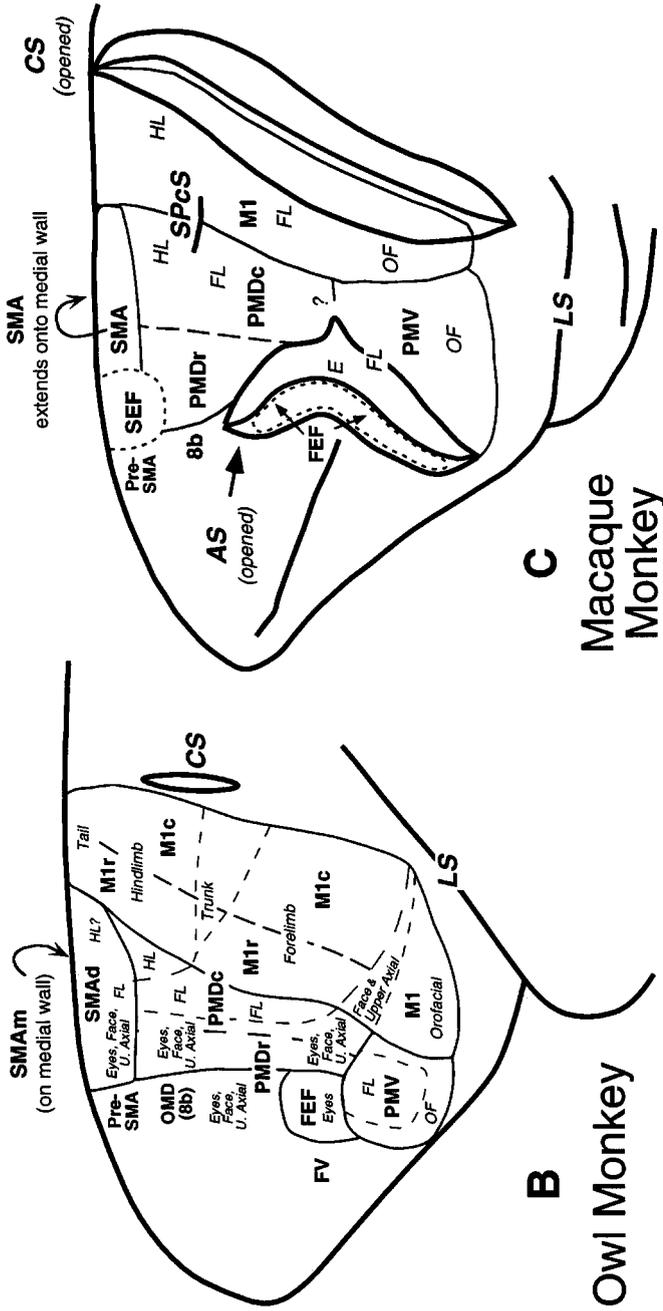
Figure 1   (*Continued*).

reinterpretation in the context of theoretical studies stressing the importance of combining different sources of information for accurate and context-appropriate movements.

A NEW VIEW OF VISUAL INPUTS TO PMd

It has been accepted since the early experimental studies on corticocortical pathways that visual areas of the occipital cortex lack direct access to the primate frontal lobe (Pandya & Kuypers 1969, Jones & Powell 1970). Nevertheless, the idea has persisted that these striate and extrastriate areas relay visual information to the premotor areas, including the region now considered PMd, and that they probably do so via parietal cortex, traditionally considered the bridge between vision and movement (Critchley 1953, Milner & Goodale 1993). In pursuing this attractive idea, the pioneers of experimental neuroanatomy uncovered an apparent paradox. They found that PMd receives rich afferentation from the superior parietal lobule (SPL, area 5). However, that region was considered "blind" in that it appeared to be devoid of visual input. The inferior parietal lobule (IPL, area 7), which receives considerable visual input, was thought to project to PF rather than to PMd (Jones & Powell 1970). Thus, the source and even the existence of visual inputs to PMd remained doubtful (Stein & Glickstein 1992).

This picture changed little, at first, as modern axoplasmic transport methods were used to reinvestigate corticocortical connectivity (see Caminiti et al 1996). However, as anatomical analysis began to take into account the finer functional subdivisions of the parietal and frontal cortex, a new view of visual inputs to PMd emerged (Figure 2). In this review, we recognize the parcellation of posterior parietal cortex into areas 5d, 7a, and 7b on the cortical surface; the medial intraparietal area (MIP), traditionally considered part of area 5 and located within the medial bank of the intraparietal sulcus; the lateral (LIP) and ventral (VIP) intraparietal areas in the lateral bank and fundus of the intraparietal sulcus, respectively; and the medial dorsal parietal area (MDP) and area 7m, on the medial aspect of the parietal lobe. The parieto-occipital area (PO) lies nearby, somewhat ventrally within the parieto-occipital sulcus. Of course, there are many alternative demarcations and nomenclatures. Recently, for example, the anterior portion of PO has been designated area V6A (Matelli et al 1995, Shipp & Zeki 1995), which possibly includes part of MDP. However, the scheme illustrated in Figure 2 suffices for the present purposes.

Superior Parietal Inputs

INPUTS FROM SPL TO PREMOTOR AND MOTOR AREAS   Anatomical studies have confirmed that most parietal input to PMd and M1 originates from the SPL. However, these projections arise not only from the dorsal aspect of area 5 (area
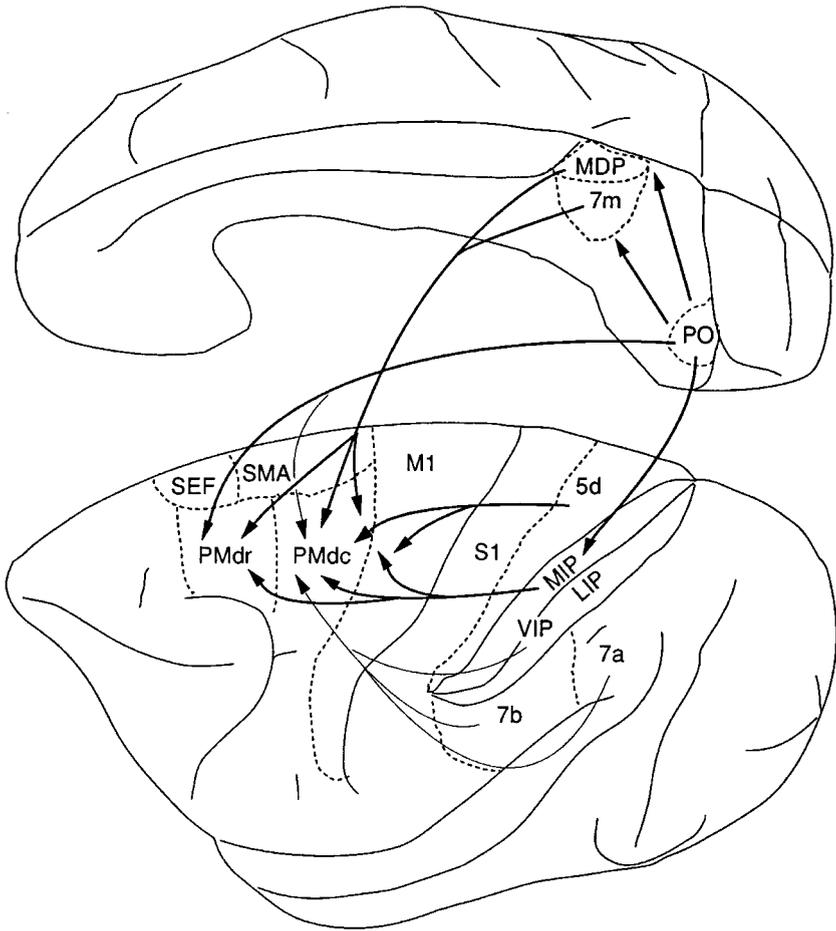
Figure 2 A summary of connectivity from posterior parietal cortex primarily to PMd and M1, adapted from Johnson et al (1993, 1996), Tanné et al (1995), and other sources cited in the text. (*Bottom*) Lateral view of the left hemisphere. (*Top*) medial view of the hemisphere, depicting areas of the same left hemisphere as the bottom figure. Arrows are shown projecting to PMd, but note that most corticocortical projections are reciprocal. Quantitatively more significant projections are marked by the thicker lines. Abbreviations are as in Figure 1, with these additions: MIP, LIP, and VIP, respectively, medial, lateral, and ventral intraparietal areas; PO, parieto-occipital visual area; MDP, medial dorsal parietal area; areas 7a, 7b, and 7m, subdivisions of posterior parietal cortex; area 5d, dorsal area 5; S1, somatosensory cortex.

5d), as has long been known (Pandya & Kuypers 1969, Jones & Powell 1970, Jones et al 1978), but also from newly defined areas of the SPL (Figure 2). These areas include MIP, MDP, and area 7m (Johnson et al 1993, 1996; Tanné et al 1995; Matelli et al 1995; Shipp & Zeki 1995), which receive visual and other sensory information. Visual inputs to these areas are not controversial: MIP, MDP, and area 7m receive inputs from areas that are directly connected to, or are considered part of, the extrastriate visual cortex (Felleman & Van Essen 1991).

These projections are arranged in a parallel, although partly overlapping, fashion: Area 5d projects predominantly to M1; MIP projects to both PMd and M1 near their border, as well as to PMd further rostrally; and both area 7m and MDP project primarily to PMd. Physiological studies have shown that parietal and frontal regions displaying similar activity patterns tend to be preferentially linked through parallel sets of corticocortical connections (Johnson et al 1996). Such studies have frequently used instructed-delay tasks, in which a visual stimulus provides a motor instruction, which is followed by a delay period, after which another stimulus triggers movement execution. Under those conditions, neurons with directional postinstructional discharge predominate in the ventral aspect of MIP and in the more rostral part of PMd. By contrast, movement- and posture-related activity is more common in the dorsal part of MIP (as well as in area 5d) and in M1. Directional delay-period activity seems most prominent at intermediate locations (Johnson et al 1996).

Tanné et al (1995) have found additional direct inputs to PMd from PO, as defined architectonically. PO receives direct projections from the striate visual cortex as well as from several peristriate visual areas (Colby et al 1988). Not only does PO project directly to PMd (Tanné et al 1995, Johnson et al 1996), but it also has less direct access to PMd via area 7m (Cavada & Goldman-Rakic 1989a) and MIP (Blatt et al 1990).

PHYSIOLOGY OF AREAS PROJECTING TO PMd   The functional properties of neurons in the parietal areas projecting to PMd are crucially important for understanding the fronto-parietal network. Unfortunately, most physiological analyses of the SPL have failed to distinguish area 5d from MIP, which complicates any consideration of their respective contributions to PMd's neuronal properties. Further, the SPL has not been completely explored. To our knowledge, no relevant physiological data are available on area 7m. However, some information is available on PO, MIP, and area 5d.

PO is of particular interest because it appears to be the only visual area devoid of a strong foveal magnification. Neurons in PO have large, and usually peripheral, receptive fields characterized by orientation and direction selectivity. Saccade-related activity has also been described. These data suggest that PO is important for ambient vision (Trevarthen 1968), both in target localization and

detection. The visual responses of most neurons depend on the eye's orbital position, but a minority of cellular responses are independent of gaze angle (Gattass et al 1985; Colby et al 1988; Galletti et al 1991, 1993). Therefore, PO's neural signals seem suitable for both the computation of target location in retinal and extraretinal coordinates.

Neuronal activity in MIP seems to depend on several factors. Cell activity reflects limb movement and position (Johnson et al 1996). MIP cells are sensitive to both visual and somatosensory stimuli, and some are more strongly modulated by visual stimuli when the contralateral (vs the ipsilateral) hand performs an action (Colby & Duhamel 1991). We expect that other extraretinal signals, such as gaze angle, influence MIP because they do so in both PO (Galletti et al 1991) and PMd (Boussaoud 1995), to which MIP is connected. Thus, it appears that a synthesis of somatosensory, retinal, and (probably) extraretinal information occurs in MIP and that it does so within some hybrid coordinate scheme.

Area 5d, which primarily projects to M1 and the caudal parts of PMd, appears to encode arm position in a shoulder-centered coordinate system (Lacquaniti et al 1995). Area 5d neurons reflect the positional, or kinematic, aspects of limb movement, rather than the forces required to move the limb (Kalaska et al 1990), and they lag behind M1 premovement discharge by about 50 ms, on average (Kalaska & Crammond 1992). Recent evidence suggests that information on azimuth, elevation, and distance of the hand relative to the shoulder is largely segregated into different neuronal populations—a striking example of parallel organization (Lacquaniti et al 1995). The reference system of M1 and PMd neurons has not been definitively established. When expressed in a hand-centered frame, directional preferences in M1 and PMd neurons change substantially with the position of the arm in space (Caminiti et al 1990b, 1991; Burnod et al 1992) but vary less when expressed in shoulder- or head-centered coordinates (E Guigon, F Lacquaniti, S Ferraina & R Caminiti, unpublished results). Thus, within the distributed fronto-parietal network, a combination of visually derived and proprioceptive signals necessary for reaching could occur in a unique, shoulder-centered frame of reference that reflects both retinal and extraretinal information.

Inferior Parietal Inputs

In addition to the projections outlined above from the SPL, Tanné et al (1995) reported that injections of retrogradely transported tracers into PMd identified inputs from VIP, LIP, and area 7a (Figure 2). These results confirm that although most of the direct visual information to PMd arises from the SPL, additional projections come from visual areas of the IPL. This direct and probably reciprocal connection could account for reach-related neurons in area 7a (Mountcastle et al 1975; see also Caminiti et al 1996).

Frontal Inputs

Less-direct routes for access of visual information to PMd are also possible, and some of these involve PF. Broadly stated, the IPL sends its prefrontal projections predominantly to the dorsolateral PF cortex (Cavada & Goldman-Rakic 1989b), whereas the SPL projects more dorsomedially in PF (Petrides & Pandya 1984). In turn, these prefrontal areas project mostly to the dorsal and medial premotor areas (Barbas 1988). PF inputs to PMd appear to be concentrated in its more rostral aspect (Barbas & Pandya 1987, Stepniewska et al 1993, Lu et al 1994), the region designated as PMdr in Figures 1 and 2. Thus, a prefrontally mediated route could indirectly provide part of PMd with visual information from both SPL and IPL.

Anatomical Summary

Figure 2 summarizes some of the corticocortical projections surveyed here. Among the many cortical connections not illustrated are those with somatosensory areas and with medial premotor areas such as the supplementary and cingulate motor cortex (Kurata 1991, Luppino et al 1993). PMd does not appear to be very densely interconnected with PMv, the ventral premotor areas (Kurata 1991), but its caudal part reciprocally connects with M1.

It may be worthwhile to consider Figure 2 in the context of the corticospinal system. It had been thought that the region of precentral gyrus projecting directly to the spinal cord was limited to M1 (Sessle & Wiesendanger 1982), but recent studies show that corticospinal cells extend well beyond the limits of M1 into PMdc (He et al 1993). Thus, it seems that PMdc, which projects directly to the spinal cord, receives its parietal information mainly from areas 5d, MIP, MDP and 7m. Its frontal connections arise from the primary, supplementary, and cingulate motor areas, but not to any large extent from PF. PMdr, which probably does not project directly to the spinal cord, receives its parietal information mainly from MIP, MDP, and area 7m (like PMdc), as well as from PO (unlike PMdc). PMdr's frontal connections also contrast with those of PMdc; they arise from PF but not to any great extent from primary motor cortex.

SIGNAL PROCESSING IN PMd

Evidence for Proprioceptive Signals

Neurophysiological studies of PMd have revealed a signal reflecting the actively held position of the arm in space (Caminiti et al 1991, Crammond & Kalaska 1996). Arm posture also influences the activity of PMd neurons less directly, both during movement execution (Caminiti et al 1991) and during the delay period of an instructed-delay task (Bauswein & Fromm 1992). In experiments where the initial arm position was varied systematically across the workspace,

the directional tuning properties during movement of PMd neurons, as measured in an external reference frame, change significantly (Caminiti et al 1991). At the population level, these changes parallel the initial arm position.

The dependency of cellular tuning properties on initial position, however, does not indicate a "pure" sensory proprioceptive signal in PMd: Visual and motor efference information also influences PMd activity. There appears instead to be a mechanism that uses proprioceptive information in the generation of an output that reflects, in addition to the information on arm position, target location and other factors.

Evidence for Gaze Signals

When all other variables are held constant, gaze angle strongly influences PMd activity. Boussaoud (1995) studied PMd activity during a task in which the fixation point differed from the location of an instruction stimulus as well as from the target of a limb movement. He found that delay-period activity is, in 80% of the sample tested, dramatically affected by the direction of gaze. Further, this gaze effect is approximately linear in both horizontal and vertical dimensions and could either enhance or diminish the directional selectivity of a particular neuron.

The functional significance of gaze dependency is not as obvious as for proprioceptive inputs. As one possible role, gaze signals could be used for reaching to eccentric targets, i.e. those away from the point of visual fixation. Boussaoud & Jouffrais (D Boussaoud & C Jouffrais, unpublished data) trained monkeys to make limb movements toward a foveal target during some trials and toward a more a eccentric target (approximately $5°$ from the fixation point) during other trials. Preliminary results show that the PMd activity differs in these two conditions, although the movements appear to be virtually identical. Gaze signals could play a role in reaching to extrafoveal targets by providing information about the angular deviation of gaze from the target.

Evidence for Spatial Visual or Attentional Signals

Gaze angle and initial limb position are not the only factors influencing cell activity in PMd. As noted above, visual stimuli can influence PMd activity as well. PMd (and PMv) neurons more strongly modulate their activity during the performance of a visuospatially instructed sequence than during a memorized one (Mushiake et al 1991). This finding suggests an interaction between visual and motor signals in PMd, as well as a preference for visuomotor vs purely motor signals.

PMd cells also show a preference for visuomotor signal processing vs the processing of visual information, per se. For example, most PMd cells show greater discharge modulation when a stimulus provides information about limb

movement than when an identical stimulus guides the reorientation of attention. However, the distinction is not absolute. Many PMd cells show significant activity modulation following both motor and attention-orienting instructions, further suggesting an interaction between or a combination of these signals (Boussaoud & Wise 1993a,b, Kermadi & Boussaoud 1995). In a different experimental design, a limb-movement target either varied from trial to trial or was fixed in a block of trials (di Pellegrino & Wise 1993). When it was fixed, it could be triggered by visuospatial stimuli at several locations. Under such conditions, the activity of PMd neurons is systematically influenced by the location of the visual stimuli (which corresponds, in this experiment, to the locus of spatial attention). At the population level, the direction of the PMd population vector clearly shows the influence of a signal reflecting the location of the visuospatial stimuli (Wise et al 1996). This visuospatial-attentional factor has a larger influence on the PMd population vector than does the direction of intended limb movement (Shen & Alexander 1995). Although the balance between motor and visuospatial-attentional effects differs to an extent among the studies cited here, most indicate that such signals coexist in individual neurons and in the population as a whole.

Evidence for Nonspatial Visual Signals

A substantial body of data shows that the most serious deficits after ablation (Passingham 1993) or inactivation (Kurata & Hoffman 1994) of PMd involve the use of nonspatial visual information to guide action. By nonspatial visual information we do not mean to imply that the pertinent visual stimulus does not exist at some location in space, but rather that its location is irrelevant to the motor instruction. In accord with the neuropsychological studies, when a given movement is instructed by several different stimuli, the activity of PMd neurons differs depending on the location of the instruction stimulus and its nonspatial features. This phenomenon has been termed a stimulus effect (Boussaoud & Wise 1993b), and it is observed in the majority of PMd neurons (Boussaoud & Wise 1993b, Kermadi & Boussaoud 1995).

As noted above for spatial visual stimuli, when nonspatial visual information guides action, PMd activity reflects neither a pure movement signal nor an unmitigated visual signal. Rather, its neurons appear to reflect, in part, the motor significance of nonspatial visual stimuli. PMd activity significantly differs during trials that occur early during the learning of a novel stimulus-response association, when those responses are largely chosen on a trial-and-error basis, compared to trials with the same response (to the same stimulus) selected later, after a new stimulus-response association is mastered (Mitz et al 1991). Furthermore, the change in modulation with successive correctly performed trials correlates very closely with the animals' learning curve. These data provide

strong support for the hypothesis (Passingham 1993) that PMd plays a central role in the selection of action that is based on arbitrary, nonspatial cues.

Evidence for Motor Command and Preparatory Signals

ARE THEY MOTOR SIGNALS?   In an experiment mentioned above, di Pellegrino & Wise (1993) developed a rigorous test for the presence of motor command, preparation, or selection signals in PMd. Their behavioral experimental design established that a given stimulus—which guided two different limb movements—was identical in spatial and nonspatial properties, that it was identical in all spatial coordinate frames, and that it was attended to equivalently when it guided the two actions. The instructional significance of a stimulus affects neuronal activity in the vast majority of PMd cells (di Pellegrino & Wise 1993) as well as the PMd population vector (Wise et al 1996). This conclusion applies to all task periods, including an average taken during the 500-ms duration of the visual stimulus.

The effect of cue location on PMd cells has also been investigated by Crammond & Kalaska (1994). In their experiment, visuospatial stimuli could instruct movements toward the stimuli or directly (180°) away from them. Within the first 200 ms or so of stimulus onset, PMd activity reflects primarily visuospatial information. However, in other respects, activity can depend to a lesser extent on cue location (when two diametrically opposed stimuli instruct the same movement) or, more commonly, on movement direction (when two diametrically opposed movements are instructed by the same stimulus). These findings correspond to the stimulus and movement effects of Boussaoud & Wise (1993b).

WHAT MOTOR SIGNALS?   The direction of limb movement is a highly salient aspect of the information reflected in neuronal discharge in PMd, as it is in M1, when neural activity is expressed in hand-centered reference frames (Caminiti et al 1990a, 1991; Fu et al 1993, 1995; Crammond & Kalaska 1994, 1996; Johnson et al 1996). In a three-dimensional limb-movement task, in excess of 90% of PMd neurons show directional selectivity, and the direction of a population vector corresponds very closely with the direction of limb movement (Caminiti et al 1991). Even in one-dimensional movements, more than half of PMd cells typically show directional preferences (Riehle & Requin 1989, Weinrich et al 1984).

In addition to directional signals, several investigators have searched PMd for a movement or force amplitude signal (Riehle & Requin 1995). Kurata (1993) reported that movement amplitude affects the majority of PMd cells. In the most comprehensive study to date, Fu et al (1993, 1995) have mapped the preferred directions and amplitudes of PMd cells and found that individual

cells not only reflect both amplitude and direction, but also the interactive term between the two, i.e. the location of the target independent of either direction or amplitude. Further, the time course of the development of these signals differs, although they are typically combined in an individual neuron. Fu et al (1995) found that directional signals develop earliest, followed, in turn, by signals reflecting target position and movement amplitude. The temporal dispersion of direction, targeting, and amplitude information may help resolve conflicts that might occur when single neurons participate in several partially independent networks.

Despite the evidence for directional and amplitude signals, the information processed in PMd should not be construed as a straightforward output signal. The parametric coding that they reflect is often found to be context specific. Tanji et al (1988) reported that PM cell discharge shows dramatic, context-dependent dissociations from muscle activity. In contrast to cells in M1, where activity is tightly linked to movements in the contralateral limb (regardless of the activity of the ipsilateral limb), some PM cells require bilateral movements, whereas others require that the action be unilateral. Similarly, Kurata & Tanji (1986) reported that PMv cell activity depends on the sensory modality of a stimulus triggering a movement. There would appear to be no direct data on that subject regarding PMd, but it is reasonable to suppose that the modality specificity observed in PMv applies to PMd as well. Taken together with the stimulus and movement effects described above (see also Mushiake et al 1991), the results indicate that PMd neurons reflect certain movement parameters, but do so only conditionally: Their activity is contingent on the context in which movement with those parameters is performed.

PMd IN MODELS OF VISUALLY GUIDED MOVEMENT

A prominent feature of several network models has been their emphasis on the combination of external information concerning target location with internal information regarding body configuration. Distributed networks are capable of learning to use retinal target position information, angle of gaze, vergence angles, and head angles to derive a representation of target position in three-dimensional space (Grossberg et al 1993, Guenther et al 1994). Further, network computations can combine such an internal spatial representation with visual and proprioceptive information regarding the position of the arm in order to compute a movement-direction vector and then a motor command (Bullock et al 1993). A different modeling strategy (Burnod et al 1992) assumes the existence of a visually-derived movement-direction vector, which is encoded relative to the fixation point. Although these models differ, they have several common features, including a single combinatorial layer of units where visual

information concerning target location combines with proprioceptive information reflecting arm configuration, and an output layer where further transformations are computed. In what follows, we discuss these layers in terms of particular anatomical structures. The models do not, of course, depend on any such correspondence, but a discussion of their features in the context of brain organization may have some heuristic value.

The models impose certain restrictions on the properties of the units in each layer. The output units command movement in a direction that, to a first approximation, is constant in a muscle- (Miller & Houk 1995) or joint-based (Caminiti et al 1990a) coordinate system and, thus, rotates when described in an external reference frame. As a result, output units are not tuned to specific arm configurations or target locations and should be active throughout large parts of the workspace. In general, these conditions are met by M1 neurons (Caminiti et al 1990a) and probably also by neurons in the motor components of the brain stem and spinal cord.

The implications of these models for units in the combinatorial layer are more complex. These units must have access to visual, proprioceptive, and other information, as well as connections with the output layer. Physiological studies have found neurons that appear to satisfy these requirements. As noted above, MIP neurons respond to both visual and somatosensory stimuli (Colby & Duhamel 1991), and they appear to express a combination of target location and arm posture information (Johnson et al 1996). MIP, therefore, is one candidate for part of the combinatorial layer. In addition to receiving inputs from visual and somatosensory modalities, the current models predict that combinatorial layer units should be "tuned" to movements in parts of the workspace. Quantitative evidence of such tuning in bimodal MIP neurons has not yet been obtained, but the predicted tuning for the individual sensory modalities has been seen in both the proprioceptive neurons of area 5d (Lacquaniti et al 1995) and the visual neurons of PO (Colby et al 1988, Galletti et al 1991). Since area 5d and PO are the likely sources, respectively, of somatosensory and visual input to MIP (as well as to MDP and area 7m), these findings support the view that these posterior parietal regions may form parts of the combinatorial layer. Another prediction of the current models is that the activity in posterior parietal cortex does not represent movement, per se. Consistent with that view, Kalaska & Crammond (1995) have concluded that area 5d neurons reflect movement directions that might be executed, even when, during "no-go" trials, movements will not be generated. Thus, although the parietal cortex may look like part of the output layer from the point of view of the retina, its properties differ importantly from those expected of an output layer in the present models. The identification of parts of the posterior parietal cortex with a combinatorial layer is at least consistent with the available experimental data.

Having discussed M1 and posterior parietal cortex in the context of these models, we now address what, if any, implications they may have for PMd. In raising this question, we do not imply that a parietofrontal route is the only significant route in visually guided movement. Cerebellar cortex might convert the distributed representation of spatial information provided by the posterior parietal cortex directly into dynamic, muscle-based commands (Stein & Glickstein 1992, Miller & Houk 1995) with minimal involvement of PMd. We emphasize PMd because we feel that its role, in cooperation with other motor control structures, should be reconsidered in light of recently recognized inputs from visual parietal areas.

One possibility is that PMd may be part of the output layer. In that case, its properties should closely resemble those of M1. Caminiti et al (1991) found that PMd neurons are just as active across the workspace as are M1 cells and that when expressed in a hand-centered coordinate system, their directional properties are very similar to M1 neurons (Caminiti et al 1990b). However, when the same data are analyzed in a shoulder-centered, spherical coordinate system (E Guigan, F Lacquaniti, S Farraina & R Caminiti, unpublished observations) differences between PMd and M1 are revealed: Target position signals predominate in PMd, while directional signals prevail in M1 (see also Fu et al 1995, Shen & Alexander 1995). A large body of literature that concentrates on more complex behavioral tasks (Kurata & Tanji 1986, Tanji et al 1988, Mushiake et al 1991) indicates yet more dramatic differences between PMd and M1. It seems likely that in well-learned tasks, especially relatively simple ones, PMd's activity cannot be distinguished from that of M1. However, during more sophisticated behaviors, especially those involving novel spatial transformations or the conversion of nonspatial information into spatial motor commands, functional differences become sufficiently pronounced to be observed in single-cell activity. These functional differences, together with the evidence for visual, gaze angle, and other signals in PMd argue for its placement hierarchically above that of the output layer.

A second computationally equivalent form of the Burnod et al (1992) model supposes that the combinatorial and output units are not divided into two physically separate layers but, instead, are mixed in a single functional layer spread over multiple cortical regions. Within this single layer, the computation from sensory input to motor output could be calculated progressively, so that as information "percolates" through the units, the motor command gradually emerges and is refined. In such a scheme, the combinatorial process would proceed from parietal to premotor and motor areas. Johnson et al (1993, 1996) have suggested that gradients of functional properties and anatomical connections within PMd and M1 support this progressive combination hypothesis.

A third view, and the final one that we discuss here, postulates that PMd represents a middle (or preoutput) layer, which lies between combinatorial and output layers. MIP, MDP, and area 7m project to PMd, which, in turn, projects to M1. A straightforward analogy might suggest that those parietal areas correspond to parts of the combinatorial layer, M1 to the output layer, and PMd to a preoutput layer. One must be cautious in postulating such a hierarchy, however. For example, PO projects to both the putative combinatorial and middle levels, and these levels are mutually affected by common signals such as stimulus location and gaze angle. However, the results of Kalaska & Crammond (1995), noted above, support the placement of PMd at a level beneath posterior parietal cortex and nearer that of M1. They found that in PMd, trials without movement (no-go trials) are not associated with the high levels of activity observed in area 5d. According to this scheme, the middle layer would perform computations similar to those of the output layer, but with less obligatory connections to the motor periphery. Doing so could result in decreased reaction times: The appropriate activity would only need to be shifted to the output layer. Activity during an instructed-delay period appears consistent with the existence of such precomputations, and a network architecture of this kind also agrees with the context dependency of PMd activity, mentioned above. Finally, the preoutput layer represents an ideal node at which nonspatial visual information could enter the network to allow the computations necessary for conditional motor learning and other forms of symbolically guided action.

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