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Sensorimotor Integration in Posterior Parietal Cortex

Richard A. Andersen and Christopher A. Buneo

Division of Biology, California Institute of Technology, Pasadena, California

INTRODUCTION

The view of the functioning of the posterior parietal cortex (PPC) has evolved over time. In the 19th century this area of cortex was believed to be an "association area," responsible for associating different sensory modalities. In this conceptual framework the PPC was considered to have a purely sensory role. Further refinement of the sensory role of PPC occurred in the last century based on observations of deficits following lesions in humans and nonhuman primates. This and other research led to the influential proposal of Ungerleider and Mishkin (1) that there are two functional pathways in visual cortex, a dorsal pathway that includes the PPC and is involved in spatial perception, and a ventral pathway involved in object perception.

Parallel neurophysiologic studies of behaving monkeys by Mountcastle and colleagues (2), identified correlations between single cell activity and the behaviors of the animals, including reaching, fixation, saccades, and smooth pursuit eye movements. They proposed that PPC was involved in programming motor behaviors. This view was challenged at the time by Goldberg and colleagues (3,4), who found similar results to Mountcastle and associates, but interpreted the neural activity concomitant with movement as resulting from sensory or attentional processes, rather than motor processes.

Examination of cell activity during control experiments that separated sensory- from behavior-related activity determined that both are found in PPC (5). This finding led to the proposal that PPC is neither strictly sensory nor motor in function, but rather is important for sensorimotor integration. More recent clinical data from humans also support this view. For example, Goodale, Milner, and colleagues (6) have shown that shape is represented in the PPC specifically for action planning. They refined the dichotomy of Ungerleider and Mishkin, proposing that the dorsal pathway is involved in sensorimotor processing, with spatial processing being one aspect of action planning.

Thus, the concept that PPC is important for sensorimotor integration is generally accepted. The main points of contention now relate to where the area sits along this sensorimotor continuum (7,8). The goal of the current chapter is to examine four partially overlapping views of the PPC and its role in sensorimotor integration. One view posits that there exists a high degree of functional specificity within the PPC, and that this specificity is in the form of separate cortical fields or subregions. A second proposes that, in regard to the issue of position along the sensorimotor continuum, PPC occupies a largely intermediate position. The third proposes that the different functional subdivisions within PPC are nodes in specific, dis-

tributed networks, and share features in common with nodes located in the PPC and frontal lobe. The final view holds that PPC exhibits functions that are represented throughout the cerebral cortex, including attention and learning. However, this view also holds that a role in these functions is only evident during processes specific to the particular function of individual cortical areas. Thus, attention and learning in PPC are related to sensorimotor processes, whereas these same functions in the ventral pathway are related to object recognition.

This chapter examines these four views by concentrating largely on two subregions of the PPC that have been the focus of many studies, the lateral intraparietal area (LIP) and the parietal reach region (PRR), although studies from most parts of PPC are considered as well. At the end of the chapter we attempt to synthesize these four views of PPC function using LIP and PRR as examples. All four views are insightful and complementary avenues for understanding how the PPC performs sensorimotor transformations.

SPECIFICITY

The posterior parietal cortex was originally recognized, based on cytoarchitectural criteria, to contain three different cortical areas, Brodmann's areas 5, 7a, and 7b (9), or areas PE, PG, and PF of von Economo and Koskinas (10), and von Bonin and Bailey (11). In recent years these areas have been further parceled based on anatomic, clinical, and physiologic criteria (12–19). An emerging view is that PPC follows the same rules as sensory and motor cortices, containing a large number of specialized regions (Fig. 10-1). We review evidence for functional specialization within PPC in the following.

Functional Subdivisions of the Posterior Parietal Cortex in Macaque Monkeys

A most remarkable observation is the specificity of connections of different parts of the PPC. Small regions of cortex, often adjacent to one another and no bigger than one fourth of the area of one's small fingernail, can have very different patterns of connectivity (12). In recent years it has become apparent that cells within several of the anatomically defined subregions of the PPC also have very different response properties. The combination of these findings has led to the recognition of a number of cortical areas within the PPC, several of which are described herein.

Perhaps the most studied subregion of the PPC is area LIP, which is specialized for saccadic eye movements (20–27). This area was initially identified anatomically as an eye movement area based on its strong connections to other saccade regions, including the frontal eye fields (FEF) and the superior colliculus (SC) (12,28–30). LIP has been divided into ventral and dorsal subdivisions on myeloarchitectural and connectional grounds (15,29). Cells in both subdivisions have saccade related responses that precede eye movements (29). In instructed-delay tasks LIP neurons typically have stronger activity when monkeys are planning saccades rather than reaches, indicating that a large component of this delay activity is related to saccade planning (26). A similar area has been identified in a number of functional magnetic resonance imaging (fMRI) experiments in humans (31,32). Reversible inactivation of this area produces eye movement deficits in memory saccade tasks (23), and biases decisions toward the healthy field in eye movement tasks (33). Finally, electrical stimulation of this area generates saccades (27).

The cells in LIP represent primarily the contralateral visual field in retinal coordinates (21). These response fields are gain modulated by other body position signals, including eye position signals and proprioceptively derived head position signals (34,35). Thus, this area can conceivably represent other coordinate frames in a distributed fashion (see Gain Fields). Neurons in LIP are also sensitive to auditory stimuli, but generally only when the auditory stimuli are targets for saccades (36,37). The activity of LIP neurons also code decision variables related to eye movements (38).

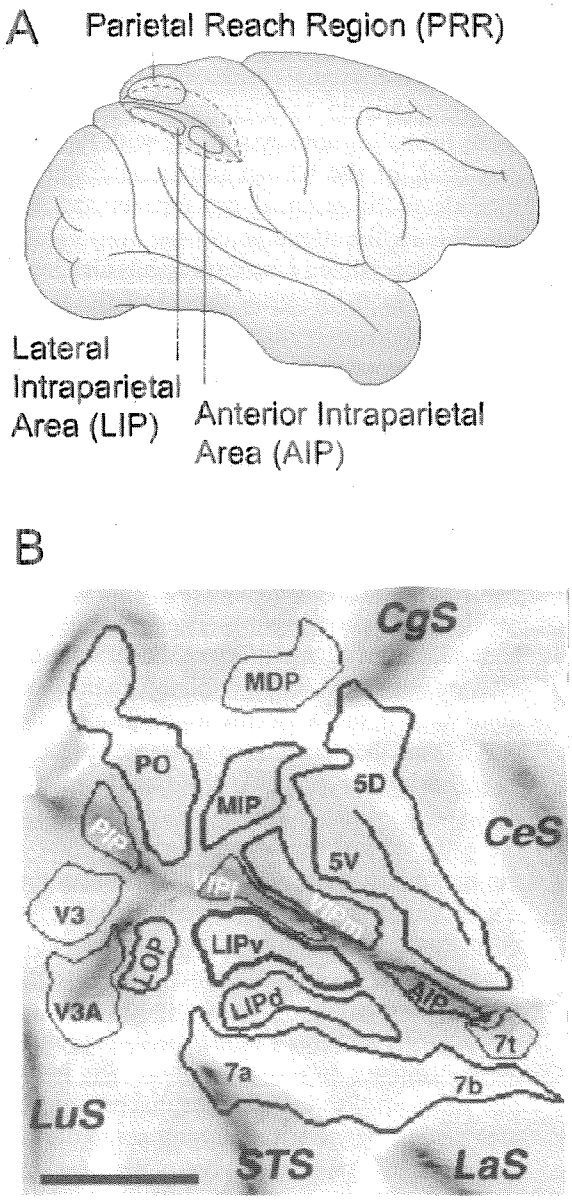


FIG. 10-1. A: Diagram of the cerebral cortex of a macaque monkey, with the intraparietal sulcus (IPS) opened up to reveal the approximate locations of the lateral intraparietal area (LIP), the parietal reach region (PRR), and the anterior intraparietal area (AIP). (Adapted from: Cohen YE, Andersen RA. A common reference frame for movement plans in the posterior parietal cortex. *Nat Rev Neurosci* 2002;3:553–562, with permission.) **B:** Flat map representation of the cortex in and near the IPS of a single macaque monkey. Seventeen architectonically defined subregions are shown, including the dorsal and ventral subdivisions of LIP (LIPd and LIPv, respectively), the medial and lateral subdivisions of the ventral intraparietal area (VIPm and VIPl, respectively), and AIP. The PRR consists of the subdivision labeled MIP (medial intraparietal area) and also possibly parts of those labeled PO (parieto-occipital area) and 5v (ventral subdivision of area 5). (Adapted from Lewis JW, Van Essen DC. Mapping of architectonic subdivisions in the macaque monkey, with emphasis on parieto-occipital cortex. *J Comp Neurol* 2000; 428:79–111, with permission.)

A second eye field, the medial parietal area (MP) has also been identified in PPC (39). This region is located on the medial surface of the hemisphere, above the cingulate sulcus, and has been much less studied than LIP. It appears to be coextensive with anatomically defined area 7ip (40) (also called PGm) (16). The cells in this region show delay and saccade-related responses similar to LIP neurons, and electrical stimulation of this region also provokes eye movements (39).

Several subregions of the PPC have been shown to be active during arm movements including dorsal area 5 (PE), PEc, V6A, 7a, and 7m (41–45). The PRR is a newly described arm movement area of the PPC that includes area MIP and parts of V6A and area 5 residing within the anterior bank of the intrapari-

etal sulcus. Area MIP receives input from areas V6A and 7m, which have direct connections to cortical visual areas, and projects to areas of the prefrontal and frontal cortex that process limb movements (46). Cells in this region have delay activity related to plans for limb movements, but not eye movements (26). A striking feature of this area is that the coding of these limb movements is in eye, not limb, coordinates (47,48).

Area VIP lies in the floor of the intraparietal sulcus. This region appears to be highly multimodal, even for sensory stimuli that are not task relevant (49,50). In particular, many neurons have somatosensory fields on the head, and respond when visual stimuli approach those head locations (50). The visual responses of cells in VIP are found in head and retinal coordinates, with a substantial population being intermediate between the two (51).

Studies by Sakata and colleagues (52,53) point to the anterior intraparietal area (AIP) being specialized for grasping. Cells in this area respond to the shapes of objects and the configuration of the hand for grasping the objects. Reversible inactivations of AIP produce deficits in shaping the hand prior to grasping in monkeys. This deficit is reminiscent of problems in shaping the hands found in humans with parietal lobe damage (54).

The medial superior temporal area (MST) appears to play a specialized role in smooth pursuit eye movements. Cells in this area are active for pursuit, even during brief periods when the pursuit target is extinguished (55). Inactivations of this area produce pursuit errors that are not a result of sensory deficits (56). The cells in this cortical area are sensitive to optic flow stimuli (57), and compensate for visual motion during smooth pursuit eye movements and head movements to maintain invariant representations of heading direction (58,59). These studies suggest that MST plays not only a role in pursuit eye movements, but also a role in navigation using visual motion cues.

Human fMRI experiments suggest the functional anatomy of the human and monkey PPC is similar. Rushworth and colleagues (32) reported that peripheral attention tasks activate the lateral bank of the intraparietal sulcus, whereas planning manual movements activates the medial bank. They concluded that their results have strong similarities to those found in monkey studies, with the medial bank of the human intraparietal sulcus specialized for manual movements and the lateral bank for attention and eye movements. An area specialized for grasping has also been identified in the anterior aspect of the intraparietal sulcus in humans (31,60), which may be homologous to monkey AIP.

INTERMEDIATE PROPERTIES

A second, and very natural view of the PPC is that, given its intermediate anatomic position between sensory and motor cortices, it occupies an intermediate stage in the sensorimotor transformation process. It also appears to be the location where different sensory modalities are combined, again implying an intermediate stage in the sensorimotor pathway.

An issue that has proven tractable for study in sensorimotor cortex is the transformation between coordinate frames. Sensory stimuli are gathered and represented in early parts of the nervous system in coordinate frames that are different from the eventual motor reference frames required to execute movements. For instance, visual stimuli are initially represented in retinal coordinates, but to reach to a visual target requires a transformation to muscle coordinates to move the limb. Studies of this issue in PPC suggest that this area occupies an intermediate processing stage during sensorimotor transformations. We use the topic of coordinate transformations to illustrate the intermediate nature of PPC in the next section. However, other sensorimotor processes also appear intermediate in nature in PPC. For instance, movement plans appear more cognitive and abstract in PPC than at subsequent stages in motor cortex.

Gain Fields

Gain fields represent a form of intermediate representation used to compute transfor-

mations between reference frames. For instance, in many of the areas within the PPC cells have eye-centered response fields, but are also gain modulated by body position signals (Fig. 10-2B). These "gain field" effects are found throughout the PPC and include modulation of retinotopic fields by eye, head, body, and limb position signals (34,35, 61–63). Although referred to as gain fields, the modulation effects can be additive as well as multiplicative (64). Theoretical studies suggest that gain fields are a computational mechanism for transforming information between coordinate frames (65,66). In fact, small populations of neurons with retinal response fields, modulated by various body part position signals, can be read out in multiple frames of reference (67,68) as would be needed to direct movements of the eyes, head, or hands. These results suggest that the PPC represents space in a distributed fashion, with groups of cells potentially representing multiple reference frames.

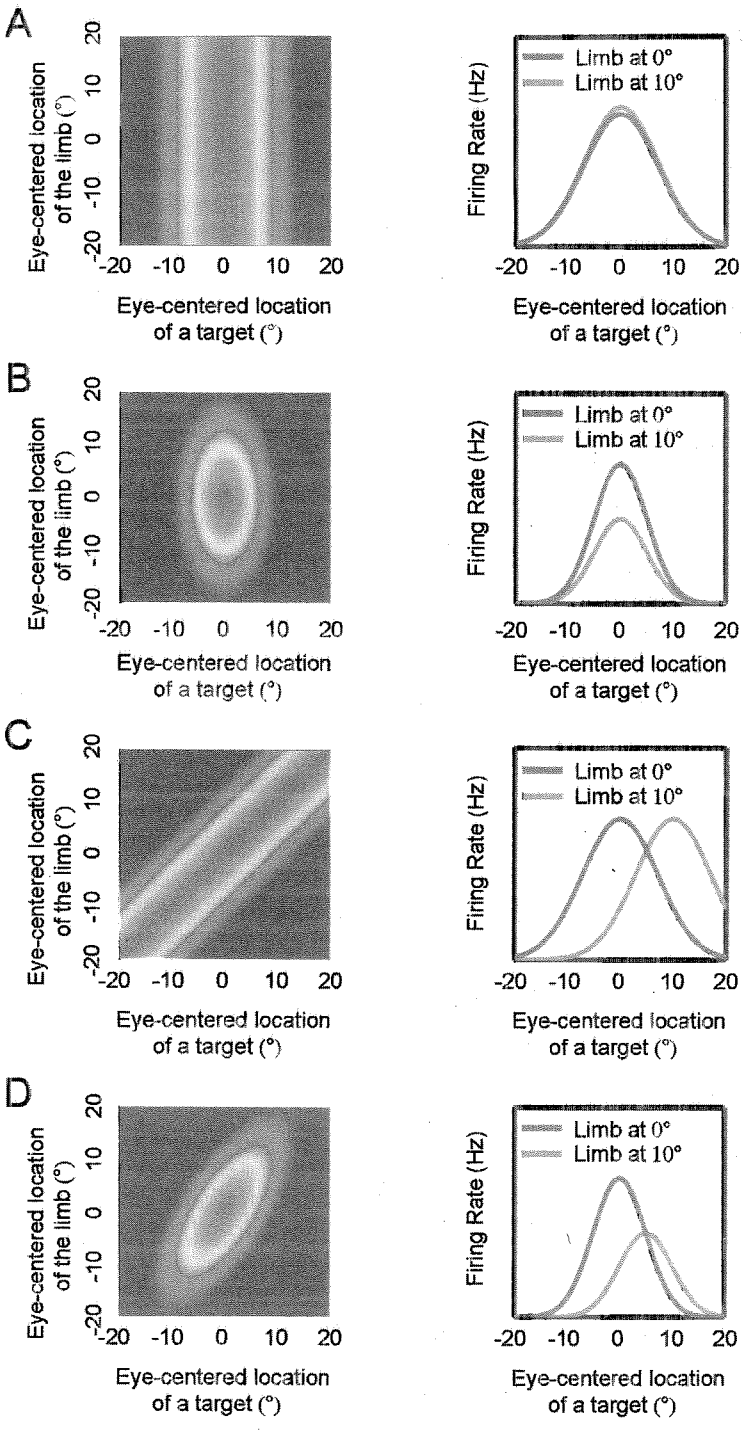
Although originally identified in areas of the PPC, gain effects have been subsequently identified throughout the brain, including the dorsal premotor cortex, V1, V4, and the SC (69–72). These findings suggest that multiplicative and additive interactions between different inputs to neurons may reflect a general method of neural computation. Although the role of gain fields in coordinate transformations has been highlighted in this chapter, gain fields appear to play a role in many other functions, including attention, navigation, decision making, and object recognition. These other functions have been reviewed by Salinas and Thier (73).

Multisensory Integration

Several areas of PPC are considered to be primarily visual in terms of sensory inputs (e.g., areas MST, 7a, PO, and LIP), whereas others are considered primarily somatosensory (e.g., dorsal area 5), or somatosensory and visual (e.g., 7b and VIP). Interestingly, area PRR has been shown recently to code locations in eye-centered coordinates, which is surprising given the area's major role in limb movements (47). However, recent experiments have demonstrated that many neurons in area 5 and VIP have response fields that are partially shifted between eye and limb-centered representations (for area 5) (74) or eye- and head-centered representations (for VIP) (51). These types of responses can be interpreted as reflecting an encoding of spatial location in both reference frames (74,75), or as reflecting the existence of a single but ambiguously defined "intermediate" reference frame (Fig. 10-2D). Regardless, these results suggest that vision exerts a strong influence over spatial behaviors, which is perhaps not surprising given its superior spatial acuity.

Both areas LIP and PRR respond to auditory stimuli if the animal is planning a saccade (in LIP) (36,37,76) or a reach (in PRR) (77) to the auditory target. Interestingly, in both areas many cells encode sound locations in eye-centered coordinates, whereas others encode them in head-centered coordinates, or in coordinates intermediate between these two reference frames (77). Area LIP appears to respond poorly, if at all, to auditory targets when the targets do not have behavioral significance to the animal (36,76). Similarly, LIP neurons only appear to show color selectivity if the color is relevant to eye movement planning (78). These results suggest the areas are visual by default, but other sensory modalities can be gated into them depending on the requirements of the task.

Neural network models that perform multisensory integration typically have an intermediate step in which units have receptive fields that are gain modulated by eye and other body position signals (68,75,79). Often these receptive fields show intermediate coding, for instance, with the integration of auditory and visual signals some intermediate units demonstrate response fields midway between eye-centered and head-centered coordinates. The finding of gain fields and intermediate coordinate frames in PPC is suggestive that multisensory integration and coordinate transformations are taking place in this cortical area. In particular, this seems to be the


A
B
C
D
Eye-centered location of the limb (°)
Eye-centered location of a target (°)
Firing Rate (Hz)
Limb at 0°
Limb at 10°
-20
-10
0
10
20

case for transformations of auditory receptive fields from head-centered coordinates, which is typical of lower levels of the auditory system, to eye-centered coordinates, which are found in LIP and PRR. This can be surmised from the recent finding that an auditory cortical area that provides major projections into PPC (area Tpt) has auditory fields in head-centered coordinates that are gain modulated by eye position (80). On the other hand, LIP and PRR have auditory response fields in head, intermediate, and eye-centered coordinates, as well as gain field effects, suggesting that the sites of integration and transformation include these two parietal areas.

Direct Transformations

Although the preceding results suggest that there are intermediate steps in coordinate transformations, the number of steps may be limited. An example considered here is that of visually guided reaching movements. In transforming the location of a visual target for a reach from retinal to limb-centered coordinates, must the brain also use intermediate representations in head and body-centered coordinates, or can this transformation be performed more directly?

A scenario that uses explicit head- and body-centered representations, which we call the *sequential* model, is illustrated in Figure 10-3A. First visual signals in retinal coordinates are combined with eye position signals to represent targets in head-centered coordinates. Next, head position is combined with the representation of target location in head-centered coordinates to form a target representation in body-centered coordinates. In the last step, the current location of the limb, in body-centered coordinates, is subtracted from the location of the target, in body-centered coordinates, to generate the motor vector, in limb-centered coordinates. A drawback of this approach is that it requires several stages and separate computations, which would likely require a large number of neurons and cortical areas. Moreover, although there are some reports of cells in the PPC coding visual targets in extraretinal, perhaps head-centered, coordinates (51,81), the vast majority of PPC cells code visual targets in eye-centered coordinates or coordinates intermediate between eye and other reference frames (47,74,77).

One alternative scenario that uses only a single intermediate step is referred to as the *combinatorial* model (41). In this model (Fig. 10-3B), retinal target location, eye, head, limb position, and other body position signals are all combined at once, and the target location in limb-centered coordinates is then read out from this representation. A potential problem with this model is the "curse of dimensionality," which results from a combinatorial explosion when tiling a space for a large number of parameters. For example, if it takes 10 cells to tile each dimension in visual space, and 10 for each dimension of eye position, head position, and so on, the number of cells required to represent all possible combinations of such signals quickly becomes larger than the number of cells in PPC. One method the PPC ap-

FIG. 10-2. A–D: Responses of idealized posterior parietal cortex neurons. In the left column, responses are plotted for a range of target locations (x-axis) and initial limb locations (y-axis) along the horizontal, in eye-centered coordinates. In the right column, two tuning curves are shown, representing slices though each response field at initial hand locations of 0 degrees and 10 degrees. **A:** Responses of a neuron encoding target location in eye-centered coordinates. The tuning curves corresponding to the different starting locations are identical. **B:** Responses of a neuron encoding target location and limb location in eye-centered coordinates. The tuning curves are gain-modulated, but this gain effect is also represented in eye coordinates. **C:** Neuron encoding target location in hand-centered coordinates. The tuning curves are shifted with respect to one another, with the magnitude of the shift corresponding to the difference between the two starting locations. No gain modulation is observed. **D:** Neuron encoding target location in hand-centered and eye-centered coordinates. Tuning curves are partially shifted and gain-modulated.

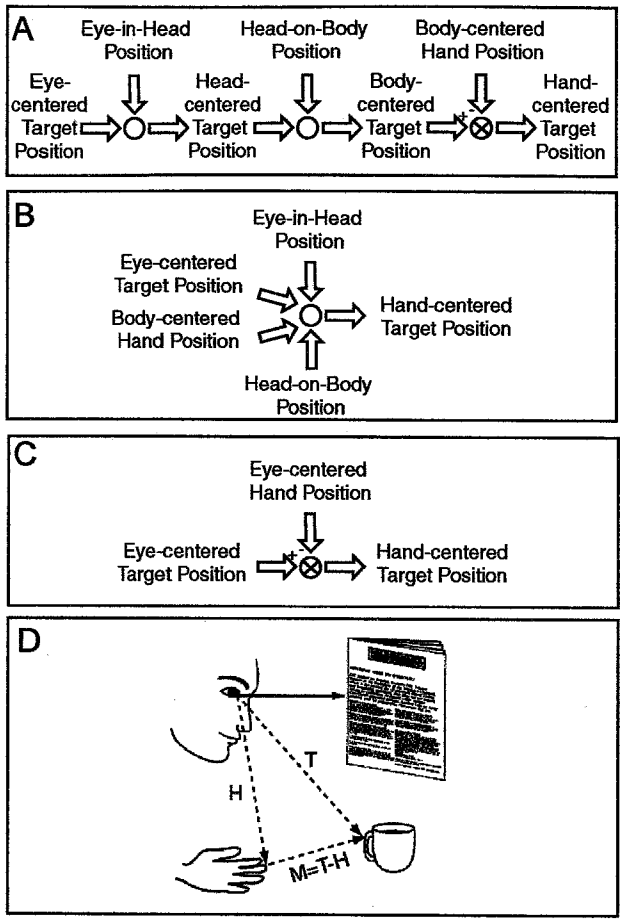


FIG. 10-3. A–C: Schemes for transforming target position from eye-centered to hand-centered coordinates. **A:** Sequential method. **B:** Combinatorial method. **C:** Direct method. **D:** Illustration of reaching for a cup while fixating a newspaper, using the direct method. The position of the cup with respect to the hand (M) is obtained by directly subtracting hand position (H) from target position (T), both in eye coordinates. (Adapted from: Andersen RA, Buneo CA. Intentional maps in posterior parietal cortex. *Annu Rev Neurosci* 2002;25: 189–220; Buneo CA, Jarvis MR, Batista AP, et al. Direct visuomotor transformations for reaching. *Nature* 2002;416:632–636, with permission.)

parently used to avoid this curse of dimensionality is to code only a limited number of variables in each of its subdivisions (35). In fact, knowledge of the set of variables encoded by an area may provide clues to its specific functions.

Another scenario that also uses one intermediate step is the *direct* model. Figure 10-3C,D shows how this model can produce a transformation in one step by vector subtraction: The current position of the hand, in eye coordinates is subtracted from the position of the target, also in eye coordinates, to directly generate the movement vector in limb coordinates. This computation is accomplished with neural circuits by representing a limited number of parameters in the same coordinate frame, and by multiplying them together (i.e., gain fields). An advantage of this approach over the sequential method is that it requires fewer computational stages. In addition, the computation is restricted to only dimensions in eye coordinates, and does not suffer the "curse of dimensionality" of the combinatorial approach.

A recent study provides evidence for the direct transformation mechanism. Single cells in area 5 of PPC, classically considered a somatomotor region, were found to code target locations simultaneously in eye- and limb-centered coordinates (74). This result is consistent with the PPC transforming target locations directly between these two frames of reference. Moreover, cells in the adjacent PRR code target location in eye-centered coordinates, and there is gain modulation by ini-

tial hand position, also coded in eye-centered coordinates (62). These two findings suggest a simple gain field mechanism underlies the transformation from eye- to limb-centered coordinates. A convergence of input from gain-modulated cells in PRR onto area 5 neurons can perform such a transformation directly without having to resort to additional stages or to a large combination of retinal, eye, head, and limb position signals (65). Note that, although explicit head- and body-centered representations are not needed in this scheme, eye and head position information would still be needed at later stages to convert the movement vector into muscle coordinates. It remains to be seen whether these signals are carried by cells in PRR and/or area 5, or by different populations of neurons.

Psychophysical evidence supporting a sequential-type model has been provided by Flanders et al. (82) and McIntyre et al. (83, 84). These results, as well as the physiologic study of Buneo et al. (74) supporting an alternative direct scheme, may reflect an underlying context dependence in the coordinate transformations that subserve visually guided reaching (85). For instance, direct transformations may be the preferred scheme when both target location and the current hand position are simultaneously visible, even for a brief instant. On the other hand, a sequential scheme may be used when visual information about the current position of the hand is not available.

Lesions

The deficits observed following lesions of the PPC are consistent with the area playing an intermediate role in sensorimotor integration. Patients with PPC lesions do not suffer from primary sensory or motor deficits. However, numerous defects become apparent when they attempt to connect perception with action, for instance, during sensory-guided movements. Such patients often suffer from optic ataxia, a difficulty in estimating the location of stimuli in three-dimensional space. This deficit results in pronounced errors in reaching movements (86,87). Patients with PPC lesions often show one or more of the apraxias, a class of deficits characterized by the inability to plan movements (88). These defects can range from a complete inability to follow verbal commands for simple movements, to difficulty in performing sequences of movements. Patients with PPC damage also have difficulty correctly shaping their hands in preparation to grasp objects. This grasp deficit again points to a disconnection between the visual sensory apparatus that registers the shape of objects, and the motor systems that shape the configuration of the hand (6,54). A most thorough review detailing the neurologic deficits following parietal lobe damage can be found in Macdonald Critchley's classic book on the subject, *The Parietal Lobes* (89).

Lesions do produce different deficits depending on the location of the damage. These results provide evidence for specificity within the PPC, as outlined in the preceding. For instance, extinction (the lack of awareness of objects in the unhealthy side of the visual field when there are competing stimuli toward the healthy side) is more common with lesions of the superior parietal lobule, whereas profound neglect is more common with lesions of the inferior parietal lobule (90). However, lesions are often large and, of course, the product of accident and not experiment; as a result, it is difficult to precisely differentiate different parts of PPC based on patient data. In fact, there is even now some debate regarding whether neglect is the result of inferior parietal lobule or superior temporal gyrus damage (91).

NETWORK PROPERTIES

Parietal and frontal cortical areas are strongly interconnected via cortical–cortical connections, and via loops through subcortical structures (92). Laboratories that have directly compared the response selectivity of areas LIP and FEF in saccadic eye movement tasks have noted a surprising similarity between these two areas. This similarity has led

to the proposal that they are best understood as being parts of a network, rather than separate stages in neural processing (92,93). Moreover, the parieto-frontal circuits involved in eye movements, reaching, and grasping appear to be parallel and at least partially separated, leading to the proposal of separate networks for different movement behaviors (94).

As an example of network behaviors we examine the similarities between areas LIP and PRR. These two areas are anatomically interconnected by reciprocal corticocortical connections (29), and as such form a part of a network. LIP and PRR seem to use a number of the same operational rules, even though they are involved in very different behaviors (i.e., eye and arm movements). This similarity in operations may facilitate cooperation between these areas during behaviors requiring coordinated movements of the eyes and hands.

Coordinates

Eye and limb movements require very different coordinate frames near the output stage of a sensorimotor transformation, because of the unique mechanical and geometric properties of the different end effectors. However, neurons in both LIP and PRR encode visual targets using the same, eye-centered coordinate frame (47,48,77,95). Interestingly, the response fields of LIP and PRR neurons remain eye-centered during the sensory, delay and movement epochs of memory-saccade and memory-reach tasks, indicating that the coordinate frame remains fixed over the course of the sensorimotor transformation for these neurons.

Both areas also have response fields for auditory targets that are similar. A large proportion of cells encode auditory responses in eye-centered coordinates, whereas others encode locations in some other coordinate frame (77,95). Because head positions were not varied in these experiments, it cannot be established whether the "other" coordinate frame was a head-centered one, the most likely result for these auditory targets, or some additional reference frame (e.g., body- or world-centered). Although visual response fields, and many auditory response fields, are eye-centered in both LIP and PRR, they are also gain modulated by eye and body position signals in both areas. LIP neurons are gain modulated by eye position and neck proprioceptive signals but generally not by vestibularly derived head position signals (unlike 7a cells, which do have vestibular gain fields) (34,35). PRR neurons are gain modulated by eye and limb position signals (62,63,74). LIP has not yet been tested for limb position gain fields, nor has PRR been tested for head position gain fields.

Delay Activity

A striking feature of both LIP and PRR is strong, persistent activity when animals have planned movements but are withholding their responses. This phenomenon was first observed in LIP using a "memory" saccade paradigm (22) designed to separate sensory from movement-related activity (96). Snyder et al. (26) subsequently demonstrated that the presence of delay period activity in both LIP and PRR depends on the type of movement being planned. Delay period activity is strong in LIP when eye movements are being planned and weak or nonexistent for planned limb movements and vice versa for PRR.

Next Planned Movement

The activity of LIP and PRR neurons in the delay period reflects the next movement the animal plans, and not the memory of a sensory location. This next-movement feature has been demonstrated with sequential movement tasks, in which the animal is required to remember two target locations, and then make sequential movements to the two targets after a GO instruction. In both LIP and PRR, cells are not active when the animal is planning a movement outside the response field of the cell, even though the subsequent movement

target location is within the cell's response field (97,98).

Compensation for Eye Movements

Encoding saccade and reach plans in eye-centered coordinates could be problematic in instances where a movement plan is formed and an intervening saccade is made before the movement is executed. In such cases, particularly when movements are planned to remembered locations in the dark, movements could be inaccurate if no compensation for the intervening saccade occurs, with the size of the error being directly related to the size of the eye movement. Mays and Sparks (99) were the first to probe the effects of intervening saccades on eye movements and perceptual stability while recording in the superior colliculus (SC), which contains an eye movement map in retinal coordinates (100). They found that, under these circumstances, activity shifts within the eye movement map of the SC to compensate for the intervening saccade and still codes the correct motor vector. Gnadt and Andersen (22) reported a similar result for saccade planning in area LIP. Duhamel et al. (101) extended the LIP results by showing that it is not necessary to make an eye movement for this updating to take place.

The same compensation for intervening saccades has been observed during reach planning in PRR also (47). When monkeys plan a reach to a remembered location in the dark, and the animals are required in the task to make an intervening saccade prior to the reach, all PRR cells recorded showed a shift in activity within the eye-centered map to compensate for the eye movement. A remapping of reach plans in eye coordinates has been demonstrated psychophysically in humans as well (102), consistent with this physiologic finding.

Intention

A number of studies have demonstrated that a significant component of both LIP and PRR activity is related to the intention to make a movement, an eye movement in the case of LIP, and a reach movement in the case of PRR. Evidence for an intentional role for LIP and PRR activity (as opposed to purely sensory or attentional roles) comes from studies employing "antireach" tasks, in which animals are trained to make a reach in the opposite direction to the location of a visual stimulus. Such tasks have revealed that activity within area MIP (a part of PRR) is related mostly the direction of the movement, and not the location of the stimulus (44,103). Gottlieb et al. (104) reported that the reverse is true in the lateral intraparietal area (LIP) for "antisaccade" tasks; that is, LIP neurons responded to the stimulus and not the direction of planned movement. However, a subsequent report by Zhang and Barash (105) indicated that, after a brief transient linked to the stimulus, most LIP neurons code the direction of the planned eye movement.

Experiments have been specifically designed to separate the effects of spatial attention from those of intention also (26,106, 107). In one experiment, recordings were made from areas LIP and PRR while animals attended to a flashed target and planned a movement to it during a delay period; however, in one case they were instructed to plan a saccade and in the other a reach. If neurons are selective for attention, then they should be active in both conditions; but if they are selective for intention, then they should be active in only one of the two conditions. Snyder et al. (26) found that the latter was true; the large majority of PRR neurons were active in the delay only when the monkeys were planning reaches, and conversely LIP neurons were active only when planning saccades. A subsequent experiment showed that activity in the PPC is also related to the shifting of movement plans, when spatial attention is held constant (107). Cells with a preference for a particular type of movement (reach or saccade) showed increased activity if a plan was changed from the nonpreferred to the preferred movement type (for the same target location) but not when the nonpreferred (or preferred) plan was simply reaffirmed. This

result is reminiscent of proposals that the PPC plays a role in shifting attention (108), but in this case it is the intended movement that shifts, and not the spatial locus of attention. Finally, when a monkey is cued as to whether an upcoming trial will be a reach or a saccade, activity in LIP and PRR increases selectively for saccades (LIP) and reaches (PRR) (106). Thus, these two areas show differential responses depending on the type of movement that is planned, even before the location of the target has been specified.

Default Planning

Both areas LIP and PRR show default or covert planning; that is, stimuli that are often behaviorally relevant can result in planning activity, even though this plan may not be executed or may change. This issue was directly addressed in the study of Snyder et al. (26), which, found a high degree of movement specificity for LIP and PRR, as mentioned. However, this specificity was not complete—68% of recorded neurons were significantly modulated in the delay period by one movement plan (reach or saccade) but not the other. (Interestingly, even during the cue period 44% showed this specificity.) We reasoned that the remaining cells showing significant activity for both movement plans might reflect covert plans for movement, because it is very natural to look to where you reach. To control for this possibility the animals also performed a "dissociation" task, in which they simultaneously planned an eye and an arm movement in different directions, with one movement into the response field and the other outside. Sixty-two percent of the cells that were not specific for single movements were specific in the dissociation task, bringing to 84% the number of cells that showed movement planning specificity in the delay period. Interestingly, more cells also revealed specificity for the cue response as well in the dissociation task, with a total of 45% being specific for reaches and 62% for saccades. These results suggest that, when given a single target for a reach (or saccade), a proportion of activity in LIP (and PRR) reflects a default plan to also make a saccade (or reach) to the target.

Default planning may explain activity that is seen in GO/NO-GO tasks. In these tasks a stimulus appears in the response field and the animal is later cued whether to make a movement to it or not. Reach activity in area 5 (109), and saccade activity in LIP (110) continues when the animal is cued not to move. This result is not consistent with attention or intention activity, because the target is no longer important to the animal's behavior (110). However, it is consistent with a covert or default plan, which remains if no new movement plans are being formed. Evidence for this alternative explanation comes from experiments where the plan is canceled, but a new movement plan is put in place (111). When an eye movement plan is canceled by instructing that the target location has changed, LIP neurons that coded the canceled plan fall silent, unlike the NO-GO results, and cells coding the new plan become active. A similar result is found even when the location of the planned movement is held constant, but the type of movement (from reach to saccade or saccade to reach) is changed (107). The data from these various studies indicate that default plans are formed in both PRR and LIP to stimuli of behavioral significance when no alternative plan is provided, but are erased if alternative plans are formed.

Movement Decisions

Both LIP and PRR show activity related to the decisions of an animal. Experiments in LIP by Platt and Glimcher (112) and by Shadlen and colleagues (113,114) have found activity related to the decision of a monkey to make eye movements. Both the prior probability and the amount of reward influence the effectiveness of visual stimuli in LIP, consistent with a role for this area in decision making. As monkeys accumulate sensory information to make a movement plan, activity increases for neurons in LIP and the pre-

frontal cortex (113–115). Similar results have been found in PRR recently, where the activity of cells reflects which of two targets monkeys select for a reach (38). The fact that decision-related activity is found in LIP for saccades, and in PRR for reaches, suggests that decisions are not made by a single brain area, but rather that decision making is a more distributed phenomenon with different networks and areas responsible for different decisions.

Dynamic Evolution of Intention Activity

LIP and PRR activity evolves dynamically, reflecting sensory, cognitive, and motor variables as the demands of a task change. For instance, the temporal dynamics of PRR activity differ depending on whether monkeys plan reaches to auditory targets or visual targets in a memory-reach task (116). At cue onset, activity for visually cued trials carried more information about spatial location than activity for auditory cued trials. However, as the trials progressed and the animal was preparing a movement, the amount of information regarding spatial location increased for the auditory cued trials, so that by the time of the reach movement it was not significantly different from information carried during visually cued trials. This result suggests that the spatial location of the target is represented in the early phases in the task, and is more poorly specified for auditory compared to visual targets (which is consistent with poorer sound localization compared to visual localization in primates). Later in the task, activity reflects the plan of the animal, which is the same for both sensory types, and thus explains the similarity in spatial information at this later period.

In another study, animals were trained to make saccades to a specific location cued on an object. After the presentation of the cue, and before the onset of the saccade, the orientation of the object was changed. Early in the task area LIP cells carried information about the location of the cue and the orientation of the object, both pieces of information being important for solving the task. However, near the time of the eye movement the same neurons coded primarily the direction of the intended movement (117).

Platt and Glimcher (112) showed in a delayed eye movement task that the early activity of LIP neurons varied as a function of the expected probability that a stimulus was a target for a saccade, as well as the amount of reward previously associated with the target. However, during later periods of the trial the cells coded only the direction of the planned eye movement. A similar evolution of activity has been shown in LIP and dorsal prefrontal cortex in eye movement tasks instructed by motion signals. The strength of the motion signal is an important determinant of activity at the beginning of the trial, but at the end of the trial the activity codes the decision or movement plan of the animal (114,115). The preceding studies show that activity in LIP and PRR evolves in time to reflect sensory, cognitive, and movement components of behavior.

GENERAL FUNCTIONS: LEARNING AND ATTENTION

Learning

Few neuroscientists would argue for the existence of a single center in the brain that directs all learning. Rather, learning is a function that is distributed throughout the nervous system. What appears to distinguish different types of learning, at least at the cognitive level, is where it occurs in the nervous system. Consistent with this viewpoint, recent prism adaptation studies have shown that visuomotor learning occurs in the PPC. As demonstrated initially by Held and Hein (118), when human subjects reach to visual targets while wearing displacing prisms, they initially miss-reach in the direction of target displacement but gradually recover and reach correctly if provided with appropriate feedback about their errors. Using positron emission tomography (PET) to monitor changes in

cerebral blood flow, Clower and colleagues (119) showed that this prism adaptation process results in selective activation of the PPC contralateral to the reaching arm, when confounding sensory, motor, and cognitive effects are ruled out.

Similarly, it has been found that hemispatial neglect resulting from damage to the right hemisphere can be at least partially ameliorated by first having affected patients make reaching movements in the presence of a prismatic shift, then removing the prisms. These effects are as resulting from the stimulation of neural structures responsible for sensorimotor transformations, including the PPC as well as the cerebellum. A recent electrophysiologic study employing a prism adaptation paradigm suggests that the ventral premotor cortex plays a role in this process as well (120).

Another example of the effects of learning in the PPC was revealed in a recent electrophysiologic study of LIP (36). The responses of LIP neurons to auditory stimuli in a passive fixation task were examined before and after animals were trained to make saccades to auditory targets. Before such training, the number of cells responding to auditory stimuli in LIP was statistically insignificant. After training, however, 12% showed significant responses to auditory stimuli. This indicates that at least some LIP neurons become active for auditory stimuli only after an animal has learned that these stimuli are important for oculomotor behavior. As with the learning effects discussed in the preceding, effects of this nature have been reported in other areas of cortex (e.g., area 3a for tactile discrimination, and the FEF for visual search training) (121,122), highlighting the distributed nature of learning in cortex.

Recently, rapid learning effects have been observed in PRR in experiments where the activity of a single cell is used to position a cursor on a computer screen, in the absence of

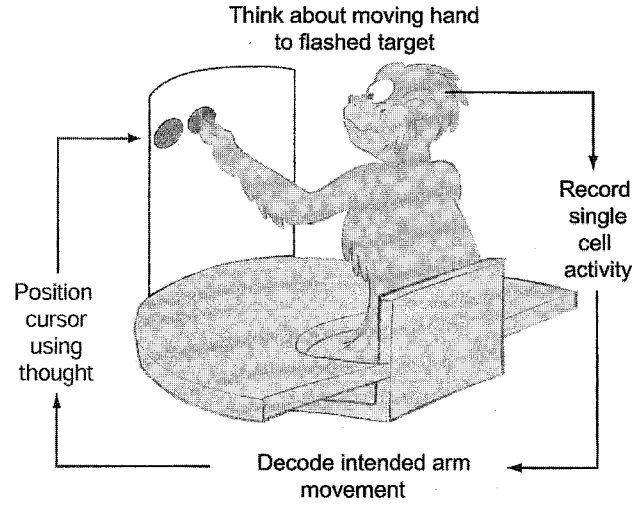


FIG. 10-4. Schematic of an experiment in "closing the loop." In the "baseline" phase, the activity of a single parietal reach region neuron is isolated and a database is constructed of the neuron's responses for reaches in the preferred and nonpreferred direction. In the "cursor-control" phase, the animal fixates and touches a central cursor on a display screen and a target is then presented either in the preferred or nonpreferred direction of the cell. Based on the response of the neuron for this one trial, and the statistics of the previously constructed database, we then predict whether the animal is intending to reach in either the preferred or nonpreferred direction. Importantly, the animal never actually makes the intended movement on these trials. A cursor moves to the location predicted from the cell activity and the animal is rewarded if the prediction corresponds to the cued location. (Adapted from: Andersen RA, Buneo CA. Intentional maps in posterior parietal cortex. *Annu Rev Neurosci* 2002;25:189–220, with permission.)

any arm movement (123). In this experiment, a database of the tuning properties of a neuron is first established while the animal performs reaching movements in the cell's preferred and nonpreferred directions ("baseline" phase). This database is then used in a subsequent "cursor control" phase to predict, on single trials, where the monkey is intending to reach, even though no reach actually occurs (Fig. 10-4). Once the cursor was put under control of the monkey's neural activity, it was found that about one half of the PRR neurons improved their selectivity within 10 to 50 trials, presumably to optimize performance in the task. This rapid learning did not occur in the baseline phase, because the animal was always being rewarded for the correct reach. It was only during the cursor control phase of the task that learning was observed, and this learning was of a similar, rapid time scale as that seen in prismatic adaptation experiments. These experiments suggest that the PPC operates to align and calibrate sensory and motor inputs as part of the sensorimotor transformation process, and that rapid learning occurs in this area in order to maintain these alignments.

Attention

Although learning is largely recognized to be a general property of cortex, the idea of attention as a general property, at least for sensory cortex, is a concept that remains unresolved. The alternative possibility is that a single center for attention exists that resides in the posterior parietal or parietal-prefrontal cortex. The idea that a central attention mechanism resides in PPC may result from the rather dramatic results of lesions to this region, which produce neglect in humans. Patients with neglect appear as if they have a primary deficit in attention, and are completely unaware of the space contralateral to the lesion (89). In addition, experiments manipulating attention produce strong activation of PPC in human fMRI studies (124) and tasks that require attention in monkeys lead to an increase in the discharge of PPC neurons (reviewed in detail in Chapter 7). All of these observations lend support to the idea of PPC being a center for attention, and in directing activity in other cortical areas. On the other hand, attention tasks tailored to the presumed functional role of areas outside the PPC have revealed attentional effects that cannot be easily attributed to PPC. For instance, attention tasks that involve fine spatial scales and contour analysis activate area V1, and tasks that examine feature and object perception show attentional modulation in areas V4 and the inferotemporal cortex (125–128).

Thus, it is possible that attention is similar to learning in that it is a general phenomenon that obtains its specificity only through the underlying functional specificity of the particular brain areas in which it is observed. In this view, attention in PPC would operate in the context of sensorimotor processes, for example, during target selection for movements. More research is required to determine if attention in PPC is restricted to the functions of this region, or if it has a more paramount role for all of sensory cortex.

SYNTHESIS

The two cortical areas focused on in this chapter, areas LIP and PRR, appear to embody the traits of task specificity and intermediate coding while also exhibiting properties consistent with being nodes of a distributed network. It is likely that these properties will generalize to other cortical regions within the PPC. Perhaps the most apparent attribute in the literature is specificity, in part because neuroscientists tend to adapt an approach of "dividing and conquering" different cortical areas in their investigations. Thus, numerous studies reviewed in this chapter point to LIP as specialized for saccades, and PRR for reaches. Within each of these areas is a map of visual space that can be considered a map of potential movements to those locations (i.e., intentional maps).

However, considerable research also points to the intermediate nature of these two cortical fields in sensorimotor transformation. Response fields are gain modulated by body po-

sition signals, and can even represent spatial locations in two distinct reference frames, suggesting that these areas occupy an intermediate stage in coordinate transformations and multisensory integration (34,35,62,63, 74). Moreover, Barash and colleagues found a small class of neurons in LIP that code both the location of a stimulus and the location of a planned movement in antisaccade tasks where the cue and the movement are opposite to one another. They proposed that these cells play an intermediate role in the transformation process in this informative task (105). Finally, even plans appear to be intermediate in PPC, being cognitive and high level at this stage and requiring further elaboration in motor areas prior to execution. One seminal indication of the cognitive nature of the PPC plans is the finding that reaches are coded in visual coordinates (47).

The similarity of coding strategies in PRR and LIP are very dramatic, considering these two areas process very different types of movements. These similarities suggest that they are parts of a single network, with the two areas speaking a common language for the purpose of coordinating movements of the hands and eyes.

Finally, attention and learning play a major role in sensorimotor processing in PPC. Perhaps because most behaviors have a spatial component and require orienting by the subject (e.g., eye movements) the PPC may be engaged in most behaviors, accounting for its apparent universal activation in fMRI experiments (124). In fact, sensorimotor transformations can be considered one of the major and essential functions of all nervous systems. With hand-eye coordination, along with language, being one of the main specializations to contribute to the success of humans as a species, it is no wonder that we have such elaborate neural structures for this exquisite ability.

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