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Posterior Parietal Cortex: An Interface between Attention and Learning?

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Abstract

The posterior parietal cortex (PPC) of rats has most recently been defined based on patterns of thalamic and cortical connectivity. The anatomical characteristics of this area suggest that it may be homologous to the PPC of primates and contribute to similar functions. This review summarizes evidence for and against a role for the rat PPC in attention and working memory and evaluates how the function of the rat PPC compares to that of primates on these dimensions. Theories of how the rat PPC contributes to behavior are presented, including the notion that PPC may serve as an interface between attention and learning. Finally, several avenues for future research are considered.

1. Introduction

Previous studies have identified a caudal region of cortex in the rat that shares several neuroanatomical features with the posterior parietal cortex (PPC) of primates (Chandler, King, Corwin, & Reep, 1992; Kolb & Walkey, 1987; Krieg, 1946; Reep, Chandler, King, & Corwin, 1994). Substantial research has been conducted to examine how this region contributes to behavior and to determine if it is functionally homologous to the primate PPC. Indeed, the rat PPC has been studied in a variety of functions related to the processing of sensory information, including attention, perception, spatial learning, and working and long-term memory. However, mixed results have often been obtained and the particular contribution of the rat PPC to behavior remains unclear. Moreover, the regional boundaries of PPC have varied across studies, making it difficult to compare results and further complicating attempts to draw firm conclusions about the function of PPC in rats.

The purpose of this article is to review the evidence for and against the involvement of the rat PPC in various aspects of attention and in working memory. Studies involving spatial learning and navigation will not be included since they are the topic of several other articles in this issue. Emphasis will be placed on studies that have examined PPC as it has been most recently defined using patterns of thalamic and cortical connectivity in addition to cytoarchitecture. Thus, a brief review of the boundaries and connectivity of the rat PPC will first be presented. The involvement of the rat PPC in various aspects of attention and working memory will then be considered, focusing on the specific demands and requirements of the tasks that have been used to study PPC in an effort to reconcile conflicting results. An overarching goal will be to identify *how* PPC is involved in these aspects of behavior. For example, PPC might support a fundamental computation upon which several functions depend. Alternatively, PPC may have

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unique contributions to aspects of attention and working memory. To that end, recent data from associative learning studies will be considered that may provide new insight into how PPC contributes to information processing. Lastly, possible unifying theories of PPC function will be presented along with avenues for future research.

2. Anatomical Considerations

The neuroanatomy of the rat PPC is comprehensively reviewed in another article in this issue. Discussion here will focus only on the neuroanatomical boundaries of PPC as they impact the interpretation of behavioral studies presented in the following sections. In addition, the connectivity between PPC and medial temporal lobe structures will be emphasized to provide a foundation for subsequent discussion of how PPC may provide an interface between sensory processes and mnemonic function.

2.1 Regional boundaries of PPC in rats

The PPC is located in the caudal part of the cortex in the rat brain and is bordered rostrally by somatosensory regions and caudally by visual areas (Krieg, 1946; Palomero-Gallagher & Zilles, 2004). Identified as a larger area of cortex in earlier studies (Kolb & Walkey, 1987; Krieg, 1946), more recent studies (Chandler et al., 1992; Reep et al., 1994) have defined this area by its thalamic and cortical connectivity. Delimited in this way, the PPC is the area of cortex located approximately 3.5 to 5.0 mm posterior to bregma and 1.5 to 5.0 mm lateral from the midline suture. It is the function of this part of cortex that will be emphasized in this review.

The rat and primate PPC receive similar projections from thalamic and cortical regions. In the rat, PPC receives thalamic input primarily from the lateral posterior, laterodorsal, and posterior nuclei (Chandler et al., 1992; Kolb & Walkey, 1987; Reep et al., 1994). These nuclei appear to be homologous to the pulvinar-lateral posterior complex (Price, 1995; Takahashi, 1985), which innervates the primate PPC (Baleydier & Mauguière, 1987; Kadson & Jacobson, 1978; Schmammann & Pandya, 1990). The rat PPC receives sensory projections from secondary visual, somatosensory, and auditory cortex (Reep et al., 1994) that are similar to primates (Baizer, Ungerleider, & Desimone, 1991; Seltzer & Pandya, 1980; Stanton, Cruce, Goldberg, & Robinson, 1977; Vogt & Pandya, 1978). The PPC in rats and primates also has reciprocal connections with areas of frontal cortex, ventrolateral and medial orbital areas, and retrosplenial cortex (Cavada & Goldman-Rakic, 1989a, 1989b; Mesulam, Van Hoesen, Pandya, & Geschwind, 1977; Pandya, Van Hoesen, & Mesulam, 1981; Reep et al., 1994; Vogt & Pandya, 1987).

Recent studies have begun to parcel the rat PPC into subregions based primarily on cytoarchitectural and histochemical differences (Swanson, 1998; Palomero-Gallagher & Zilles, 2004; Pérez-Clausell, 1996). To date, few (if any) studies have attempted to describe the functional differences between these putative subregions. Thus, for the purpose of this review, the area defined above as PPC will be considered as a whole.

2.2 Connectivity between PPC and the medial temporal lobe

The rat and primate PPC both have specific connections with medial temporal lobe cortical structures, a point that will be emphasized later in this review. Together with the retrosplenial cortex, PPC provides the major source of cortical polymodal sensory input to one of two relatively separate corticohippocampal pathways in the rat brain (Burwell & Amaral, 1998a; Burwell, Witter, & Amaral, 1995; Kosel, Van Hoesen, & Rosene, 1983; Naber, Caballero-Bleda, Jorritsma-Byham, & Witter, 1997; Shi & Cassell, 1997). Specifically, input from PPC and the retrosplenial cortex converge on the postrhinal cortex. The postrhinal cortex, in turn, is primarily connected with medial regions of entorhinal cortex and discrete areas of the

hippocampal formation (Burwell, 2000; Burwell & Amaral, 1998b). A second corticohippocampal pathway involves the perirhinal cortex, which receives input from all sensory modalities, although most visuospatial information to the perirhinal cortex arrives via a sparsely-reciprocated projection from the postrhinal cortex (Burwell & Amaral, 1998a, 1998b). Thus, information being processed in PPC likely contributes significantly to functions that depend on the medial temporal lobe. The relevance of this connectivity will be addressed after considering the involvement of PPC in different aspects of attention and addressing the question of functional homology between the PPC of rats and primates.

3. Contralateral neglect and inattention

A hallmark of PPC damage in humans and non-human primates is contralateral sensory neglect. Patients with unilateral PPC lesions appear to be unaware or unresponsive to stimuli or events occurring in extrapersonal space contralateral to the site of damage (Heilman, Watson, & Valenstein, 1993). Since neglect occurs in the absence of sensory or motor deficits and involves multiple sensory modalities, it has been characterized as a deficit in attention rather than sensory or perceptual processing per se (Brain, 1941; Critchley, 1949; Heilman et al., 1993). A number of studies have examined whether PPC damage also produces contralateral neglect and inattention in rats. Crowne, Richardson, and Dawson (1986) found that large, unilateral aspiration lesions of the caudal extent of the rat cortex produced symptoms of contralateral neglect. When presented with visual, auditory, or tactile stimuli to one side of the body, normal rats responded by turning their heads toward the stimulus. Lesioned rats were slow to respond to each type of stimulus when it was presented to the side of the body opposite the lesion but showed normal responses to ipsilateral stimulation. Unfortunately, these lesions included damage to frontal, and fore- and hindlimb somatosensory cortex, as well as PPC and only bordered on the very rostral extent of the PPC as defined by Reep et al. (1994). Similar results were produced by an aspiration lesion that included more of the PPC, but also encroached upon adjacent visual and somatosensory cortex (King & Corwin, 1993; Kirvel, Greenfield, & Meyer, 1974).

Using lesion coordinates that did restrict damage to PPC, Ward and Brown (1997) found no evidence of somatosensory neglect. Visual and auditory stimuli were not included in that experiment. Yet, multimodal contralateral neglect was observed following unilateral disconnection of the rat PPC from medial agranular cortex (Burcham, Corwin, Stoll & Reep, 1997). In that study, the corticocortical axons connecting the two regions were severed without damaging either the PPC or medial agranular cortex. Based on these findings and the extent to which lesions were or were not restricted to PPC, it is difficult to conclude that PPC damage in rats necessarily produces neglect like that observed in primates. It remains possible that damage restricted to PPC was responsible for the neglect for visual and auditory stimuli observed by Crowne et al. (1986) and King and Corwin (1993), but that has yet to be tested using lesions restricted to PPC. Moreover, the aspiration and electrolytic techniques used in these studies prevent a functional role from being ascribed to a specific cortical area distinct from destruction of fibers of passage. The question of whether damage to PPC results in multimodal neglect in rats as observed in primates should be addressed in future studies that restrict damage to PPC and employ fiber-sparing neurotoxic lesions to more accurately examine the effects of damage restricted to neurons in this region.

4. Covert orienting of attention

Other studies have examined the effects of PPC damage in humans and non-human primates on the covert orienting of attention using a cue detection paradigm developed by Posner (Petersen, Robinson, & Currie, 1989; Posner, 1980; Posner, Walker, Friedrich, & Rafal, 1984). In this task, subjects fixate on a central point in space and receive a series of trials in

which a peripheral cue is briefly presented (e.g., 300 msec) to the left or right of the fixation point. After a delay of up to a few hundred milliseconds, a target stimulus is presented on either the same side as the cue (valid trials) or on the opposite side (invalid trials). On each trial, subjects respond by pressing a button when the target appears. The time between target onset and the behavioral response (i.e., reaction time) serves as the dependent variable and is typically longer when the target appears on the side opposite the cue. Importantly, subjects must maintain central fixation throughout the trial and not make an eye or head movement directed to the cue or the target. Thus, the increased reaction time to the target stimulus on invalid trials compared to valid trials is thought to result from a covert orienting of attention to the side that is opposite the location of the target (Posner, 1980). In humans and monkeys, unilateral damage to the PPC potentiates the validity effect for trials in which the cue was presented ipsilaterally to the lesioned side and the target was presented contralaterally (Farah, Wong, Monheit, & Morrow, 1989; Petersen et al., 1989; Posner et al., 1984). This effect has been interpreted as reflecting a deficit in shifting attention in that subjects with PPC damage are impaired in disengaging attention from a stimulus presented contralateral to the intact hemisphere to subsequently engage a stimulus presented contralateral to the damaged PPC.

Using a version of this task modified for rats, two studies failed to find evidence for a deficit in covert attentional orienting following damage to the PPC (Rosner & Mittleman, 1996; Ward & Brown, 1997). In one study, damage was largely restricted to the PPC as currently defined (Ward & Brown, 1997) while the study by Rosner and Mittleman (1996) included the larger area defined as PPC by Kolb and Walkey (1987). Thus it is unlikely that the null results were merely due to insufficient damage to the PPC. However, the procedural parameters of the tasks used in primates and rodents are necessarily different. For example, the location of the eyes on the rat's head prevents it from fixating a central point like primates. Instead, in the rat version of this task, subjects must maintain a nosepoke into a central port for set period of time and await presentation of the cues and targets in adjacent ports. The dependent variable is also different in that rats must initiate a movement to withdraw the head out of the center port and then reposition the snout in the target port. Eye movement is also unrestricted during the procedure and raises the issue of whether or not the same 'covert' attentional mechanisms are being measured. Thus, although the current data may indicate that the rat and primate PPC do not have similar roles in covert attentional orienting, it seems highly likely that the procedures used with humans and monkey were not comparably reproduced in rats.

5. Conditioned and unconditioned orienting behavior

Other studies have investigated the role of the rat PPC in another form of attentional orienting. Bucci and Chess (2005) presented rats with a 10-second visual stimulus that was not reinforced. In this procedure, rats typically rear up on their hind legs towards the stimulus ("rearing behavior," Holland, 1977; 1984), an orienting response that is often used as a measure of attentional processing (Gallagher, Graham, & Holland, 1990; Kaye & Pearce, 1984; Lang, Simons, & Balaban, 1997). Rearing behavior rapidly decreases (habituates) when the cue is not followed by reinforcement (unconditioned orienting), reflecting a decrease in attention to a behaviorally-irrelevant stimulus (Kaye & Pearce, 1984; Gallagher et al., 1990; Holland, 1997). The response re-emerges when the light is subsequently paired with food during conditioning sessions (conditioned orienting) and then as the rat learns the new meaning of the stimulus, rearing again decreases. In this paradigm, lesions of PPC affected neither unconditioned nor conditioned orienting behavior, suggesting a limited role for PPC in these aspects of attention. Similarly, Tees (1999) reported intact habituation to repeated presentations of visual or auditory stimuli in rats with large lesions that included PPC based on the Kolb and Walkey (1987) definition of the region. Tees also observed normal dishabituation when the visual or auditory properties of the stimuli were subsequently changed.

6. Perceptual-attentional set-shifting

A version of the set-shifting task for use in rodents has provided a valuable paradigm for examining neural substrates of non-spatial attention. In this procedure, based on the Wisconsin Card Sorting task (Roberts, De Salvia, Wilkinson, Collins, Muir, Everitt, & Robbins, 1994), rats learn to discriminate between pairs of stimuli based on one of several sensory dimensions (e.g., tactile, olfactory, visual). Subsequently, new pairs of stimuli are introduced but the rats must use the same perceptual dimension to learn the new discrimination (intradimensional shift). In the final phase of the task, rats must attend to a new set of stimulus attributes to successfully discriminate between pairs of stimuli (e.g., olfactory dimension instead of visual dimension). This is referred to as an extradimensional shift and normal subjects tend to learn the discriminations more slowly than the ones associated with an intradimensional shift. Using this procedure, Fox, Barense, and Baxter (2003) examined the effects of neurotoxic PPC damage on attentional set shifting in rats. Lesions of the PPC exaggerated the normal difficulty in learning produced by the extradimensional shift while leaving performance on the intradimensional shift intact. In other words, rats with PPC damage were slower in abandoning attention to the first stimulus dimension. Insofar as this task requires shifting attention similar to the Posner (1980) covert attention task in primates, these data support the notion that PPC may be involved in this aspect of attentional function in both rats and primates.

7. Sustained attention

Sustained and divided attention has been studied in rats using the five-choice serial reaction time task (Carli, Robbins, Evenden, & Everitt, 1983), which is similar to the Continuous Performance Test in humans (Mirsky & Rosvold, 1960). In this procedure, rats must monitor five locations (individual nosepoke holes) and respond when a light is randomly illuminated in one of the holes. A correct response is rewarded by delivery of a food pellet. Incorrect responses are defined as a poke into a non-illuminated hole. Additional responses after the light is extinguished are considered preservative responses and are followed by a brief time out. Performance in this task is evaluated by measuring accuracy (percentage of correct responses), speed of responding, anticipation (responses during the intertrial interval), preservative responses, and errors of omission (trials during which no response is made). Several permutations of the task can be used to alter attentional demand such as changing the stimulus duration or including distracter stimuli (e.g., white noise bursts).

Although no published studies have examined the effects of neurotoxic PPC damage on this task, Maddux, Kerfoot, Chatterjee, and Holland (2007) compared the effects of cholinergic denervation of PPC or prefrontal cortex on performance in the five-choice serial reaction time task. The lesion consisted of selectively removing only basal forebrain cholinergic projections to either cortical region. Cholinergic denervation of prefrontal cortex had specific effects on several measures of attention, similar to those produced by neurotoxic damage to prefrontal cortex (Muir, Everitt, & Robbins, 1996). However, removal of cholinergic input to PPC was without effect. Likewise, lesions of a larger region of parietal cortex that may have included just the most rostral part of PPC did not affect performance in this task (Muir et al., 1996). One of the few electrophysiological studies that investigated attention-related activity in PPC did find that PPC activity is associated with signal detection in a sustained attention task (Broussard, Sarter, & Givens, 2006). However, activity in PPC does not necessarily indicate that the region is essential for task performance. Thus, the available data suggest that PPC may not have a critical role in sustained attention. Yet, future studies need to be carried out to more definitely assess the involvement of the rat PPC in sustained attention using a complete neurotoxic lesion restricted to PPC.

8. Surprise-induced enhancements in learning

Contemporary theories of learning maintain that the predictive validity of a conditioned stimulus (CS) regulates the amount of attention that is allocated to that stimulus (e.g., Mackintosh, 1975; Pearce & Hall, 1980). According to one influential theory (Pearce & Hall, 1980), a CS will capture attention if its meaning surprisingly changes. This increase in attention to the CS enhances subsequent learning about that cue as demonstrated in a number of different paradigms. For example, in a serial conditioning procedure used by Wilson, Boumphrey, and Pearce (1992) and outlined in Table 1, rats first learn that presentation of a visual CS (a light) is always followed by an auditory CS (a tone). In subsequent training sessions, the reliable, predictive relationship between the stimuli is violated for one group of rats (the 'Surprise' group) in that the light no longer reliably predicts occurrence of the tone. Another group continues to receive the usual light-then-tone trials ('Consistent' group). According to the Pearce-Hall theory (1980), this manipulation increases attentional processing of the light in the Surprise group, which is manifest as enhanced learning compared to the Consistent group when the light is later paired directly with food (Table 1; Holland & Gallagher, 1993b; Wilson et al., 1992).

The results of several studies indicate that the rat PPC is part of a neural circuit that mediates these changes in attention. Using the task illustrated in Table 1, removal of cholinergic input to the PPC was shown to selectively impair learning in the Surprise group when the light was paired directly with food (Bucci, Holland, & Gallagher, 1998). Importantly, the lesion did not affect conditioning in the Consistent group. Similarly, a recent study in our laboratory revealed that neural activity is increased in PPC when the predictive relationship between stimuli is violated and attention is increased (Bucci & MacLeod, 2007). In that study, normal rats were trained in the task in Table 1 and sacrificed after one session of the Phase 2 procedures. An increase in immediate-early gene expression (a marker of neural activity) was observed in the PPC of rats in the Surprise group compared to the Consistent group. These data are also consistent with a study by Maddux et al. (2007), who used another paradigm designed to produce changes in attention and learning. In that study, removal of cholinergic input to the PPC eliminated surprise-induced enhancements in learning, but had no effect on performance when the same rats were tested in the five-choice serial reaction time task.

As mentioned previously, a study in our laboratory (Bucci & Chess, 2005) did not find an effect of neurotoxic PPC damage on orienting behavior (i.e., rearing on the hind legs) to presentations of a light when it was either presented alone (unconditioned orienting) or subsequently paired with food (conditioned orienting). Insofar as the orienting response reflects attentional processing of the stimulus, PPC lesioned rats did not exhibit a deficit in this form of attention. However, the lesioned rats in that experiment did exhibit impaired learning about the light as evidenced by decreased food-cup behavior (approaching the food cup in anticipating of receiving reward) when the light was paired with food. In contrast, normal learning was observed in a different set of PPC-lesioned rats that were not pre-exposed to the light (in other words, the light was always paired with food). These data indicate that PPC-lesioned rats were particularly sensitive to *changes* in the meaning of the light.

Interestingly, damage to the central nucleus of the amygdala, which has also been implicated in the pathway that mediates surprise-induced changes in attention and learning (Holland & Gallagher, 1993a, 1993b), had a different effect on orienting behavior. Like PPC-lesioned rats, those with central nucleus damage exhibited normal unconditioned orienting. However, re-emergence of the conditioned orienting response following reinforcement was impaired in central nucleus lesioned rats (Gallagher et al., 1990), but not PPC-lesioned rats (Bucci & Chess, 2005). This suggests that components of the central nucleus-PPC pathway have different roles in mediating changes in attention.

9. Working Memory

Many studies support the involvement of the primate PPC in working memory (Oztekin, McElree, Staresina, & Davachi, 2008; Ravizza, Delgado, Chein, Becker, & Fiez, 2004). Neuroimaging and lesion studies have demonstrated that PPC is involved in the ability to maintain task-relevant information during a delay (Champon & Petrides, 2007; Curtis, 2006; van Asselen, Kessels, Neggers, Kappelle, Frijns, & Potsma, 2006). By comparison, only a few studies to date have examined the role of the rat PPC in working memory. Kolb, Buhrmann, McDonald, & Sutherland (1994) used an aspiration lesion to remove the entire PPC and found no effects on performance of a radial arm maze task or either of two delayed non-match-to-sample tasks. In contrast, the same lesion produced deficits in spatial learning; thus, the lesions were not without effect. Using two versions of a food foraging task, Espina-Marchant, Pinto-Hamuy, Bustamante, Morales, Robles, and Herrera-Marschitz (2006) examined the effects of temporarily inactivating the PPC with lidocaine during the delay period in a working memory procedure. The authors found that inactivating the PPC only had an effect when the task demands required both working memory and reliance on long-term memory, but not working memory alone. Consistent with these data, Compton, McDaniel, and Dietrich (1994) tested rats with PPC lesions on a non-spatial serial learning task and found no effect on working memory. In summary, most of the studies that have examined a specific role for PPC in working memory, particularly in non-spatial tasks, have produced null results.

10. Summary and interpretation

The literature just reviewed appears to paint an inconclusive picture about the role of the rat PPC in attention and working memory and whether or not this region is functionally homologous to the PPC of primates. Indeed, damage that included PPC produced symptoms of contralateral neglect and inattention (Crowne et al., 1986; King & Corwin, 1993), but those studies did not restrict damage to PPC as it is currently defined and the effects could have been due to damage outside PPC. Lesions that were restricted to PPC did not produce somatosensory neglect (Ward & Brown, 1997). Similarly, PPC damage did not affect performance in a rat version of Posner's covert orienting task (Rosner & Mittleman, 1996; Ward & Brown, 1997), or in tasks that examined more overt forms of attentional orienting (Bucci & Chess, 2005; Tees, 1999). Likewise, the available data suggest that PPC does not have a significant role in sustained or divided attention (Maddux et al., 2007; Muir et al., 1996); although, the effects of neurotoxic damage restricted to PPC have yet to be examined in the five-choice serial reaction time task. In contrast, discrete neuronal damage to PPC did impair the ability to learn sensory discriminations when attention had to be shifted to from one stimulus dimension to another (Fox et al., 2003).

At this time, drawing conclusions about the functional homology (or lack thereof) between the rat and primate PPC with regard to attention may be premature. As mentioned above, only a few studies have examined the attentional effects of damage restricted to the PPC as it is currently defined. Moreover, there is a paucity of electrophysiological studies investigating neural activity in PPC during attentional manipulations. Such studies would complement those using lesion or imaging methods to identify the functional contributions of PPC. In addition, questions remain about whether the procedures used to measure attention in humans and monkeys have been adequately reproduced in rats.

Instead of focusing on the matter of functional homology between the PPC of rats and primates, it may be more instructive at this time to consider how the available data inform our understanding of the contribution of the PPC to behavior in rats. Consideration of the specific task demands in the studies that have focused on the PPC as it is currently defined may provide some resolution and explain the apparent contradictory findings regarding the role of the rat

PPC in attention. For instance, contemporary learning theories distinguish between attentional processing of stimuli that reliably predict outcomes and guide performance, and attention that is required when a stimulus is an unreliable predictor of future events and new information is acquired (Mackintosh, 1975; Pearce & Hall, 1980). A commonality between the covert orienting task (Rosner & Mittleman, 1996; Ward & Brown, 1997) and the 5-choice serial reaction task (Maddux et al., 2007; Muir et al., 1996) is the requirement to monitor several locations and respond when a target stimulus is detected. In both cases, attention is needed to direct performance on a well-learned task, and in both cases, damage to PPC was without effect. Instead, this type of attention has been shown to depend on frontal cortex systems in both rats (Gill, Sarter, & Givens, 2000; Maddux et al., 2007; Newman & McGaughy, 2008) and primates (Mesulam, 1981, 1990; Posner & Dahan, 1994).

In contrast, the perceptual set-shifting task (Fox et al., 2003) requires attending to a new stimulus dimension to successfully solve subsequent discriminations between pairs of stimuli (extra dimensional shift). The fact that PPC damage impaired discrimination after an extra dimensional shift suggests that it may be involved in attention that is required when the meaning of a stimulus has changed. This interpretation is consistent with the associative learning studies that demonstrate a role for PPC in mediating the effects of changes in attention on subsequent learning (Bucci & Chess, 2005; Bucci et al., 1998; Maddux et al., 2007). Interestingly, damage to prefrontal cortex does not affect this aspect of attentional function (Maddux et al., 2007). Likewise, our examination of cortical activity during a change in attention revealed activation in PPC but not prefrontal cortex (Bucci & MacLeod, 2007).

One role of the PPC may be to link attentional and associative learning mechanisms. As indicated in the study by Bucci and Chess (2005), orienting to a CS whose meaning has changed was unaffected by PPC lesions, but lesioned rats were unable to translate changes in attention to effects on subsequent learning. The anatomical connections between PPC and corticohippocampal pathways in the medial temporal lobe provide a clear pathway through which information processing in PPC may influence learning. As described previously, PPC is a major source of cortical input to the perirhinal cortex, which in turn projects to medial entorhinal cortex, perirhinal cortex, and the hippocampus (Burwell, 2000; Burwell & Amaral, 1998b; Furtak, Wei, Agster, & Burwell, 2007). Thus, PPC is likely to have a significant influence on the function of downstream medial temporal lobe regions that are explicitly involved in learning and memory, a notion supported by a recent study that disconnected PPC from hippocampus (Rogers & Kesner, 2007). Importantly, these connections between PPC and medial temporal lobe cortical regions are also reciprocated. This suggests that PPC may also have a role in subsequent stages of information processing, evidence for which is presented in other articles in this issue.

11. Conclusions and Future Directions

The goal of this article was to review the evidence of a role for the rat PPC in attention and working memory. Special emphasis was placed on studies that used tasks outside of the realm of spatial learning, as that topic is the subject of other articles in this issue. In addition, the focus was on the PPC as it has most recently been defined based on thalamic and cortical connectivity and cytoarchitecture (Chandler et al., 1992; Reep et al., 1994). Defined in this way, the PPC is the cortical region located 3.5 to 5.0 mm posterior to bregma and 1.0 to 5.0 mm lateral from the midline.

The rat and primate PPC have very similar patterns of thalamic and cortical connectivity, suggesting that these areas may also be functional homologues. Yet, the current data do not entirely support the notion that PPC has a similar role in attention or working memory in rodents and primates. However, only a few studies have examined the attentional effects of damage

restricted to the PPC as it is currently defined. Moreover it is difficult to ensure that the procedures used to measure attention in humans and monkeys have been adequately reproduced in rats. Thus, additional research is needed to resolve this question. Future studies might give special attention to translating tasks between species and also employing a variety of approaches including experimental lesions and neural activations methods as well as neurophysiological procedures. Indeed, there is a paucity of electrophysiological studies investigating neural activity in PPC during attentional manipulations.

While it may not yet be clear whether the PPC in rats and primates are functionally homologous, the existing data do suggest a particular role for the PPC in rat behavior. Several pieces of evidence converge to indicate that PPC may be important for regulating changes in attention that affect learning. A role for PPC in mediating the interactions between attention and learning may provide a valuable model in which to study the neural mechanisms that are at the interface between these functions. Understanding the interaction between attention and learning processes has been highlighted in several recent articles (Chun & Turk-Browne, 2007; Awh, Vogel, & Oh, 2006; Olivers, 2008). Indeed, Kandel (2006) has opined that one of the most important problems for 21st century neuroscience is to understand how attention regulates memory.

Another area of interest for future research is how the rat PPC interacts with other components of a proposed cortical attention network in rats (Burcham et al., 1997) and primates (Heilman et al., 1993; Mesulam, 1981; 1990). A few studies have begun to investigate this using lesions that disconnect PPC from other regions of cortex (Burcham et al., 1997). A recent study examined interactions between prefrontal cortex and PPC and found that prefrontal neurons regulate the release of acetylcholine in PPC (Nelson, Sarter, & Bruno, 2005). This is particularly noteworthy since removal of cholinergic input to PPC has been shown to produce deficits in attention in associative learning paradigms (Bucci et al., 1998; Maddux et al., 2007). Finally, it will be important to determine if the proposed subregions of rat PPC (Palomero-Gallagher & Zilles, 2004; Pérez-Clausell, 1996; Swanson, 1998) make unique functional contributions to behavior.

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References

- Awh E, Vogel EK, Oh SH. Interactions between attention and working memory. *Neuroscience* 2006;139:201–208. [PubMed: 16324792]
- Baizer JS, Ungerleider LG, Desimone R. Organization of visual inputs to the inferior temporal and posterior parietal cortex in Macaques. *Journal of Neuroscience* 1991;11:168–190. [PubMed: 1702462]
- Baleydier C, Mauguière F. Network organization of the connectivity between parietal area 7, posterior cingulate cortex and medial pulvinar nucleus: A double fluorescent tracer study in monkey. *Experimental Brain Research* 1987;66:385–393.
- Brain WR. Visual disorientation with special reference to lesions of the right cerebral hemisphere. *Brain* 1941;64:244–272.
- Broussard J, Sarter M, Givens B. Neuronal correlates of signal detection in the posterior parietal cortex of rats performing a sustained attention task. *Neuroscience* 2006;143:407–417. [PubMed: 17045755]
- Bucci DJ, Chess AC. Specific changes in conditioned responding following neurotoxic damage to the posterior parietal cortex. *Behavioral Neuroscience* 2005;119:1580–1587. [PubMed: 16420161]

- Bucci DJ, MacLeod JE. Changes in neural activation during a surprise-induced enhancement of attention. *European Journal of Neuroscience* 2007;26:2669–2676. [PubMed: 17970737]
- Bucci DJ, Holland PC, Gallagher M. Removal of cholinergic input to rat posterior parietal cortex disrupts incremental processing of conditioned stimuli. *Journal of Neuroscience* 1998;18:8038–8046. [PubMed: 9742170]
- Burcham KJ, Corwin JV, Stoll ML, Reep RL. Disconnection of medial agranular and posterior parietal cortex produces multimodal neglect in rats. *Behavioral Brain Research* 1997;86:41–47.
- Burwell RD. The parahippocampal region: corticocortical connectivity. *Annals New York Acad Sciences* 2000;911:25–42.
- Burwell RD, Amaral DG. Cortical afferents of the perirhinal, postrhinal, and entorhinal cortices of the rat. *Journal of Comparative Neurology* 1998a;398:1–27.
- Burwell RD, Amaral DG. The perirhinal and postrhinal cortices of the rat: Interconnectivity and connections with the entorhinal cortex. *Journal of Comparative Neurology* 1998b;391:293–321. [PubMed: 9492202]
- Burwell RD, Witter MP, Amaral DG. Perirhinal and postrhinal cortices of the rat: A review of the neuroanatomical literature and comparison with findings from the monkey brain. *Hippocampus* 1995;5:390–408. [PubMed: 8773253]
- Carli M, Robbins TW, Evenden JL, Everitt BJ. Effects of lesions to ascending noradrenergic neurones on performance of a 5-choice serial reaction task in rats; implications for theories of dorsal noradrenergic bundle function based on selective attention and arousal. *Behavioural Brain Research* 1983;9:361–380. [PubMed: 6639741]
- Cavada C, Goldman-Rakic PS. Posterior parietal cortex in rhesus monkey: I. Parcellation of areas based on distinctive limbic and sensory corticocortical connections. *Journal of Comparative Neurology* 1989a;287:393–421. [PubMed: 2477405]
- Cavada C, Goldman-Rakic PS. Posterior parietal cortex in rhesus monkey: II. Evidence for segregated corticocortical networks linking sensory and limbic areas with the frontal lobe. *Journal of Comparative Neurology* 1989b;287:422–445. [PubMed: 2477406]
- Chamod AS, Petrides M. Dissociable roles of the posterior parietal and the prefrontal cortex in manipulation and monitoring processes. *Proceedings of the National Academy of Sciences* 2007;104:14837–14842.
- Chandler HC, King V, Corwin JV, Reep RL. Thalamocortical connections of rat posterior parietal cortex. *Neuroscience Letters* 1992;143:237–242. [PubMed: 1436673]
- Chun MM, Turk-Browne NB. Interactions between attention and memory. *Current Opinions in Neurobiology* 2007;17:177–184.
- Compton DM, McDaniel WF, Dietrich KL. Non-spatial learning following posterior parietal or hippocampal lesions. *Neuroreport* 1994;5:2189–2192. [PubMed: 7865774]
- Critchley M. The phenomenon of tactile inattention with special reference to parietal lesions. *Brain* 1949;72:538–561.
- Crowne DP, Richardson CM, Dawson KA. Parietal and frontal eye field neglect in the rat. *Behavioral Brain Research* 1986;22:227–231.
- Curtis CE. Prefrontal and parietal contributions to spatial working memory. *Neuroscience* 2006;139:173–180. [PubMed: 16326021]
- Espina-Marchant P, Pinto-Hamuy T, Bustamante D, Morales P, Robles L, Herrera-Marschitz M. Spatial cognition and memory: a reversible lesion with lidocaine into the anteromedial/posterior parietal cortex (AM/PPC) affects differently working and long-term memory on two foraging tasks. *Biological Research* 2006;39:601–609. [PubMed: 17657341]
- Farah MJ, Wong AB, Monheit MA, Morrow LA. Parietal lobe mechanisms of spatial attention: Modality-specific or supramodal? *Neuropsychologia* 1989;27:461–470. [PubMed: 2733819]
- Fox MT, Barense MD, Baxter MG. Perceptual attentional set-shifting is impaired in rats with neurotoxic lesions of the posterior parietal cortex. *Journal of Neuroscience* 2003;23:676–681. [PubMed: 12533627]
- Furtak S, Wei S, Agster K, Burwell R. Functional neuroanatomy of the parahippocampal region in the rat: The perirhinal and postrhinal cortices. *Hippocampus* 2007;17:709–722. [PubMed: 17604355]

- Gallagher M, Graham PW, Holland PC. The amygdala central nucleus and appetitive pavlovian conditioning: Lesions impair one class of conditioned behavior. *Journal of Neuroscience* 1990;10:1906–1911. [PubMed: 2355257]
- Gill TM, Sarter M, Givens B. Sustained visual attention performance-associated prefrontal neuronal activity: evidence for cholinergic modulation. *Journal of Neuroscience* 2000;20:4745–4757. [PubMed: 10844044]
- Heilman, KM.; Watson, RT.; Valenstein, E. Neglect and related disorders. In: Heilman, KM.; Valenstein, E., editors. *Clinical Neuropsychology*. Vol. 3. New York: Oxford University Press; 1993. p. 279–336.
- Holland PC. Conditioned stimulus as a determinant of the form of the Pavlovian conditioned response. *Journal of Experimental Psychology: Animal Behavior Processes* 1977;3:77–104. [PubMed: 845545]
- Holland, PC. Origins of behavior in Pavlovian conditioning, *The Psychology of Learning and Motivation*. Vol. 18. Academic Press; 1984. p. 129–174.
- Holland PC. Brain mechanisms for changes in processing of conditioned stimuli in Pavlovian conditioning: implications for behavior theory. *Animal Learning and Behavior* 1997;25:373–399.
- Holland PC, Gallagher M. The effects of amygdala central nucleus lesions on blocking and unblocking. *Behavioral Neuroscience* 1993a;107:235–245. [PubMed: 8484889]
- Holland PC, Gallagher M. Amygdala central nucleus lesions disrupt increments but not decrements in CS processing. *Behavioral Neuroscience* 1993b;107:246–253. [PubMed: 8484890]
- Kadson DL, Jacobson S. The thalamic afferents to the inferior parietal lobule in the rhesus monkey. *Journal of Comparative Neurology* 1978;177:685–706. [PubMed: 415071]
- Kandel, E. *Search of Memory: The Emergence of a New Science of Mind*. New York: W.W. Norton; 2006.
- Kaye H, Pearce JM. The strength of the orienting response during Pavlovian conditioning. *Journal of Experimental Psychology: Animal Behavior Processes* 1984;10:90–109. [PubMed: 6707583]
- King VR, Corwin JV. Comparisons of hemi-attention produced by unilateral lesions of the posterior parietal cortex or medial agranular prefrontal cortex in rats: Neglect, extinction, and the role of stimulus distance. *Behavioral Brain Research* 1993;54:117–131.
- Kirvel RD, Greenfield RA, Meyer DR. Multimodal sensory neglect in rats with radical unilateral posterior isocortical and superior collicular ablations. *Journal of Comparative Physiology and Psychology* 1974;87:156–162.
- Kolb B, Buhmann K, McDonald R, Sutherland RJ. Dissociation of the Medial Prefrontal, Posterior Parietal, and Posterior Temporal Cortex for Spatial Navigation and Recognition Memory in the Rat. *Cerebral Cortex* 1994;4:664–680. [PubMed: 7703691]
- Kolb B, Walkey J. Behavioral and anatomical studies of the posterior parietal cortex in the rat. *Behavioral Brain Research* 1987;23:127–145.
- Kosel KC, Van Hoesen GW, Rosene DL. A direct projection from the perirhinal cortex (area 35) to the subiculum in the rat. *Brain Research* 1983;69:347–351. [PubMed: 6883086]
- Krieg WJS. Connections of the cerebral cortex: I. The albino rat. A. Topography of cortical areas. *Journal of Comparative Neurology* 1946;84:221–275.
- Lang, PJ.; Simons, RF.; Balaban, M. *Attention and Orienting: Sensory and Motivational Processes*. Lawrence Erlbaum Assoc.; Mahwah, NJ: 1997.
- Mackintosh NJ. A theory of attention: Variations in the associability of stimuli with reinforcement. *Psychological Review* 1975;82:276–298.
- Maddux JM, Kerfoot EC, Chatterjee S, Holland PC. Dissociation of attention in learning and action: effects of lesions of the amygdala central nucleus, medial prefrontal cortex, and posterior parietal cortex. *Behavioral Neuroscience* 2007;121:63–79. [PubMed: 17324051]
- Mesulam MM. A cortical network for directed attention and unilateral neglect. *Annals of Neurology* 1981;10:309–325. [PubMed: 7032417]
- Mesulam MM. Large-scale neurocognitive networks and distributed processing for attention, language, and memory. *Annals of Neurology* 1990;28:597–613. [PubMed: 2260847]
- Mesulam MM, Van Hoesen GW, Pandya DN, Geschwind N. Limbic and sensory connections of the inferior parietal lobule (area PG) in the rhesus monkey: A study with a new method for horseradish peroxidase histochemistry. *Brain Research* 1977;136:393–414. [PubMed: 411543]

- Mirsky, AF.; Rosvold, HE. The use of psychoactive drugs as a neuropsychological tool in studies of attention in man. In: Uhr, I.; Miller, JG., editors. *Drugs and behavior*. New York: Wiley; 1960. p. 375-392.
- Muir JL, Everitt BJ, Robbins TW. The cerebral cortex of the rat and visual attentional function: dissociable effects of mediofrontal, cingulate, anterior dorsolateral, and parietal cortex lesions on a five-choice serial reaction time task. *Cerebral Cortex* 1996;6:470–481. [PubMed: 8670672]
- Naber PA, Caballero-Bleda M, Jorritsma-Byham B, Witter MP. Parallel input to the hippocampal memory system through peri- and postrhinal cortices. *NeuroReport* 1997;8:2617–2621. [PubMed: 9261838]
- Nelson CL, Sarter M, Bruno JP. Prefrontal cortical modulation of acetylcholine release in posterior parietal cortex. *Neuroscience* 2005;132:347–359. [PubMed: 15802188]
- Newman LA, McGaughy J. Cholinergic deafferentation of prefrontal cortex increases sensitivity to cross-modal distractors during a sustained attention task. *Journal of Neuroscience* 2008;28:2642–2650. [PubMed: 18322107]
- Olivers CN. Interactions between visual working memory and visual attention. *Frontiers in Bioscience* 2008;13:1182–1191. [PubMed: 17981622]
- Oztekin I, McElree B, Staresina BP, Davachi L. Working Memory Retrieval: Contributions of the Left Prefrontal Cortex, the Left Posterior Parietal Cortex, and the Hippocampus. *Journal of Cognitive Neuroscience*. 2008Epub ahead of print
- Palomero-Gallagher, N.; Zilles, K. Isocortex. In: Paxinos, G., editor. *The Rat Nervous System*. Elsevier Academic Press; San Diego: 2004.
- Pandya DN, Van Hoesen GW, Mesulam MM. Efferent connections of the cingulate gyrus in the rhesus monkey. *Experimental Brain Research* 1981;42:319–330.
- Pearce JM, Hall G. A model for Pavlovian learning: Variations in the effectiveness of conditioned but not of unconditioned stimuli. *Psychological Review* 1980;106:532–552. [PubMed: 7443916]
- Pérez-Clausell J. Distribution of terminal fields stained for zinc in the neocortex of the rat. *Journal of Chemical Neuroanatomy* 1996;11:99–111. [PubMed: 8877598]
- Petersen SE, Robinson DL, Currie JN. Influences of lesions of parietal cortex on visual spatial attention in humans. *Experimental Brain Research* 1989;76:267–280.
- Posner MI. Orienting of attention. *Quarterly Journal of Experimental Psychology* 1980;32:3–25. [PubMed: 7367577]
- Posner MI, Dehaene S. Attentional Networks. *Trends in Neuroscience* 1994;17:75–79.
- Posner MI, Walker JA, Friedrich FJ, Rafal RD. Effects of parietal injury on covert orienting of attention. *Journal of Neuroscience* 1984;4:1863–1874. [PubMed: 6737043]
- Price, JL. Thalamus. In: Paxinos, G., editor. *The Rat Nervous System*. Vol. 2. San Diego, CA: Academic Press; 1995. p. 629-648.
- Ravizza SM, Delgado MR, Chein JM, Becker JT, Fiez JA. Functional dissociations within the inferior parietal cortex in verbal working memory. *Neuroimage* 2004;22:562–573. [PubMed: 15193584]
- Reep RL, Chandler HC, King V, Corwin JV. Rat posterior parietal cortex: Topography of corticocortical and thalamic connections. *Experimental Brain Research* 1994;100:67–84.
- Roberts AC, De Salvia MA, Wilkinson LS, Collins P, Muir JL, Everitt BJ, Robbins TW. 6-Hydroxydopamine lesions of the prefrontal cortex in monkeys enhance performance on an analog of the Wisconsin card sort test: possible interactions with subcortical dopamine. *Journal of Neuroscience* 1994;14:2531–2544. [PubMed: 8182426]
- Rogers J, Kesner RP. Hippocampal-parietal cortex interactions: evidence from a disconnection study in the rat. *Behavioural Brain Research* 2007;179:19–27. [PubMed: 17336404]
- Rosner AL, Mittleman G. Visuospatial attention in the rat and posterior parietal cortex lesions. *Behavioural Brain Research* 1996;79:69–77. [PubMed: 8883818]
- Schmahmann JD, Pandya DN. Anatomical investigation of projections from thalamus to posterior parietal cortex in the rhesus monkey: A WGA-HRP and fluorescent tracer study. *Journal of Comparative Neurology* 1990;295:299–326. [PubMed: 1694186]
- Seltzer B, Pandya DN. Converging visual and somatic sensory cortical input to the intraparietal sulcus of the rhesus monkey. *Brain Research* 1980;192:339–351. [PubMed: 6769545]

- Shi CJ, Cassell MD. Cortical, thalamic, and amygdaloid projections of rat temporal cortex. *Journal of Comparative Neurology* 1997;382:153–175. [PubMed: 9183686]
- Stanton GB, Cruce WLR, Goldberg ME, Robinson DL. Some ipsilateral projections to areas PF and PG of the inferior parietal lobule in monkeys. *Neuroscience Letters* 1977;6:243–250.
- Swanson, LW. *Brains Maps: Structure of the Rat Brain*. Vol. 2. Elsevier; Amsterdam: 1998.
- Takahashi T. The organization of the lateral thalamus of the hooded rat. *Journal of Comparative Neurology* 1985;231:281–309. [PubMed: 3968240]
- Tees RC. The effects of posterior parietal and posterior temporal cortical lesions on multimodal spatial and nonspatial competencies in rats. *Behavioral Brain Research* 1999;106:55–73.
- van Asselen M, Kessels RP, Neggers SF, Kappelle LJ, Frijns CJ, Postma A. Brain areas involved in spatial working memory. *Neuropsychologia* 2006;44:1185–1194. [PubMed: 16300806]
- Vogt BA, Pandya DN. Cortico-cortical connections of somatic sensory cortex (areas 3, 1 and 2) in the rhesus monkey. *Journal of Comparative Neurology* 1978;177:179–192. [PubMed: 413844]
- Vogt BA, Pandya DN. Cingulate cortex of the rhesus monkey: II. Cortical Afferents. *Journal of Comparative Neurology* 1987;262:271–289. [PubMed: 3624555]
- Ward NM, Brown VJ. Deficits in response initiation, but not attention, following excitotoxic lesions of posterior parietal cortex. *Brain Research* 1997;775:81–90. [PubMed: 9439831]
- Wilson PN, Boumphrey P, Pearce JM. Restoration of the orienting response to a light by a change in its predictive accuracy. *Quarterly Journal of Experimental Psychology* 1992;44B:17–36.

Table 1

Procedures designed to increase attentional processing

Group	Phase 1	Phase 2	Phase 3
CONSISTENT	L→T→food	L→T→food	L→food
	L→T→nothing	L→T→nothing	
SURPRISE	L→T→food	L→T→food	L→food
	L→T→nothing	L→nothing	

During Phases 1 and 2, rats in each group (Consistent and Shift) receive 4 randomly-intermixed trials of each type indicated in the table. During Phase 3, the light is followed by food on all 8 trials for rats in each group.