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A Neural Systems Analysis of Adaptive Navigation

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Abstract

In the field of the neurobiology of learning, significant emphasis has been placed on understanding neural plasticity within a single structure (or synapse type) as it relates to a particular type of learning mediated by a particular brain area. To appreciate fully the breadth of the plasticity responsible for complex learning phenomena, it is imperative that we also examine the neural mechanisms of the behavioral instantiation of learned information, how motivational systems interact, and how past memories affect the learning process. To address this issue, we describe a model of complex learning (rodent adaptive navigation) that could be used to study dynamically interactive neural systems. Adaptive navigation depends on the efficient integration of external and internal sensory information with motivational systems to arrive at the most effective cognitive and/or behavioral strategies. We present evidence consistent with the view that during navigation: 1) the limbic thalamus and limbic cortex is primarily responsible for the integration of current and expected sensory information, 2) the hippocampal-septal-hypothalamic system provides a mechanism whereby motivational perspectives bias sensory processing, and 3) the amygdala-prefrontal-striatal circuit allows animals to evaluate the expected reinforcement consequences of context-dependent behavioral responses. Although much remains to be determined regarding the nature of the interactions among neural systems, new insights have emerged regarding the mechanisms that underlie flexible and adaptive behavioral responses.

Index Entries: Navigation; spatial learning; place cells; head direction cells; systems analysis.

Introduction

There is a wealth of data from a broad range of neuroscience fields indicating that the adult brain is plastic. Neural plasticity has been described at many levels from the details of synaptic function to the reorganization of afference, and “metaplasticity,” which refers to the mechanism underlying the potential for plasticity (Abraham and Bear, 1966). These analyses have yielded important insights regarding the mechanism by which specific brain struc-

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tures, such as the hippocampus or cerebellum, contribute to learning. Also, these neurobiological data provide at least partial explanations for the neuropsychological consequences of brain injury, which in turn have resulted in the commonly held notions that there are multiple memory systems (e.g., Schacter and Tulving, 1994). The different types of memory are thought to be mediated by different brain structures (e.g., Squire et al., 1993; Eichenbaum, 1997; Kesner, 1998, in press). Building on this view, it is argued here that to understand brain mechanisms of the behavioral instantiation of complex cognitive processing, we should adopt a broader view of learning and memory. That is, we should consider perspectives that take into account the possibility that a single behavior of an intact, healthy brain is mediated by multiple neural regions. Here we apply this type of analysis to a behavioral model of complex learning: experience-dependent visuospatial navigation by rodents. Based on data obtained from this and other laboratories, we suggest that a broad neural systems perspective on adaptive navigation has led to new hypotheses regarding the dynamic nature of the integration of environmental context information with motivational and behavioral control systems.

Adaptive Navigation as a Model System for a Neural Systems Analysis of Behavior

The ability to interpret one's external sensory environment in terms of existing and predicted spatial relationships is fundamental for the survival of all vertebrate species. Consequently, flexible integration between multiple sensory systems as well as between sensory and motor systems is highly adaptive. Such integration is likely mediated by complex and dynamic interactions between multiple neural systems of the brain. That spatial processing is distributed throughout the brain is clear; injury to a variety of brain structures can result in spatial impairments, and neurophysiological evidence shows spatially correlated discharge by cells located in a large number of brain structures (summarized in Colby and Olson, 1999). Close inspection of the details of spatial-behavioral impairments or spatial-discharge patterns of neurons reveals some regional variation, suggesting that spatial information is not redundantly represented across the brain. Rather, different neural systems may be using similar information in different ways.

Adaptive navigation involves the coordination of many processes. Initially, external environmental information must be processed via sensory input systems. According to a number of studies, representations of sensory information are in a continuous, dynamically changing state depending on internally generated variables such as attention or motivation (*see* Merzenich and deCharms [1996] for further discussion). This continuous reorganization of representations is observed to occur in a systematic fashion across many levels of sensory processing. Given that an essential component of visuospatial navigation is the processing of external sensory information, it seems reasonable that the fundamental principles of sensory integration and organization can be extended to the case of adaptive navigation.

The process of adaptive navigation is likely to be a highly dynamic, multidimensional and integrative event. This aspect of the navigational circuitry endows animals with the ability to use flexible behavior to solve environmentally based problems. The rules that determine appropriate overt behavior (e.g., right turn at the street light) are referred to here as one's "behavioral strategy." Flexible behavior is presumably mediated via flexible cognitive processing. Optimal cognitive flexibility could be achieved if multiple domains of sensory information are processed simultaneously, and if there are mechanisms that allow animals to switch quickly between different modes of sensory or mnemonic operation, hereafter referred to as "cognitive strategy."

These are seen as necessary features of an adaptive navigation circuit.

Despite the apparent complexity of the navigational system, one can identify and study discrete cognitive components and search for their neurobiological mechanisms. Here we divide the process of adaptive navigation as follows:

1. The evaluation of the relevant external sensory (visual) environment;
2. The evaluation of the internal sensory environment;
3. The integration of external and internal sensory conditions;
4. The influence of internal state information (i.e., motivational factors); and finally
5. The translation of the integrated sensory contextual and motivational information into cognitive or behavioral strategies that guide behavior.

This article concludes with the presentation of a working neurobiological model of the contributions of different neural systems to these aspects of experience-dependent navigation.

Evaluating the External (Visual) Sensory Environment

Visual spatial learning in the rat has been largely attributed to hippocampal processing. Such a conclusion is based on reports that hippocampal lesions seem to produce rather selective visuospatial impairments while leaving behavioral performance by the same rats on nonspatial visual tasks unimpaired (e.g., Morris et al., 1982; Olton et al., 1979). Also, since the early 1970s, it has been known that hippocampal pyramidal neurons selectively and reliably discharge when animals occupy specific locations within a familiar environment (O'Keefe, 1976; O'Keefe and Dostrovsky, 1971; Olton et al., 1978; Ranck, 1973). That is, a majority of hippocampal output neurons (referred to as *place cells*) exhibit "place fields." O'Keefe and Nadel (1978) put forth the very influential notion that the hippocampus represents a cognitive map for use in flexible sensory-based navigation. Such an interpretation implied that the hippocampus is specialized for processing spatial information, and there have been a number of theories that describe how place cells might contribute to these special computations. Although debates as to whether the hippocampus processes only spatial information continue (e.g., Eichenbaum, 1996), it seems clear that within the domain of spatial learning, the hippocampus plays an important role. So as not to be redundant with the many existing reviews on place cells (McNaughton et al., 1996; Muller et al., 1996; O'Keefe and Burgess, 1996b; Redish, 1999; Sharp et al., 1996; Wiener, 1996), the present description of the place-cell phenomenon will be selective.

It is well-known that hippocampal place cells are responsive to changes in a familiar visual environment. Place fields rotate in accordance with the rotation of distal visual cues (Muller and Kubie, 1987; Knierim and McNaughton, 1995). Also, relatively minor changes in the spatial organization of visual aspects of a familiar environment may induce changes in place-field properties (Muller and Kubie, 1987; O'Keefe and Burgess, 1996). Moreover, place fields recorded from rats performing a radial-arm maze task are almost always modulated by the direction from which the rat enters the field (McNaughton et al., 1983; Mizumori et al., 1989; Mizumori et al, 1999b). Although the significance of such directional firing remains debated (Muller et al., 1994), it indicates that these cells do not represent absolute locations in space.

An animal's representation of current visual information relevant for hippocampal processing may be derived from at least two sources. One source is via neocortical input that passes geniculostriate information on to hippocampus. In this system, entorhinal cortical afferents relay information gathered from pre- and parasubiculum (van Groen and Wyss, 1990a,b), which receive visual information from retrosplenial cortex (Wyss and van Groen, 1994). Retrosplenial cortex receives visual afferents from a secondary visual sensory cortical region, Area 18 (van Groen and Wyss, 1990c, 1992a).

Neural representations of space vary somewhat across structures that mediate geniculostriate information. Entorhinal and subicular regions contain visually sensitive spatial codes in the form of location-specific firing (Quirk et al., 1992; Mizumori et al., 1992). In addition, the subicular complex and retrosplenial cortex contains neurons that preferentially discharge when animals orient their heads in a particular direction in space, referred to as "head direction cells." Hippocampal place fields differ from entorhinal and subicular location codes in that the latter appear less directly related to the current external sensory environment (Quirk et al., 1992; Sharp and Green, 1994).

A second source of current visual information is the tectocortical visual system. In the rat, the tectocortical system is rather extensive (Linden and Perry, 1983; Sefton and Dreher, 1985), providing visual information via a pathway involving the superior colliculus, lateral dorsal nucleus (LDN) of the thalamus, subicular complex, and retrosplenial cortex (van Groen and Wyss, 1992b). The superior colliculus of freely behaving rats contains representations of current sensory information reflecting either the external environment or movement state of the animal (Cooper et al., 1998). The LDN contains head direction cells (Mizumori and Williams, 1993) that appear more visually dependent than head direction cells found in subicular areas. LDN projects largely to retrosplenial cortex, although there is also a minor projection to entorhinal cortex (van Groen and Wyss, 1992b). Thus, retrosplenial cortex seems strategically situated to integrate visual information obtained by both the geniculostriate and tectocortical systems before passing information on to hippocampus.

Despite the often clear sensitivity of place cells to current visual information, it is likely that hippocampal place fields do not reflect merely the visual receptive field of the cell being recorded because a significant proportion of place fields persist even when the room lights are turned off (*see* Fig. 1 for examples and details of the training procedure; McNaughton et al., 1989; Quirk et al., 1990). Interestingly, this persistence is observed if animals are allowed to first view an environment before the imposed darkness, but not when animals are placed initially into a dark room. Thus, hippocampal place cells appear to code visual and nonvisual information, and they seem to be influenced by an animal's past experience (or memory) of a particular environment (O'Keefe and Speakman, 1987). During navigation in darkness, animals presumably "path integrate," or monitor and control their own movements relative to a memory of the visual environment. The nonvisual cues to which hippocampal place cells are sensitive in darkness have been termed "idiothetic," and include self-generated information such as vestibular feedback, proprioceptive feedback, or motor efference copy.

Consistent with the view that hippocampal place cells represent information in an experience-dependent fashion is the suggestion that they represent spatial context information (Nadel et al., 1985). According to this view, hippocampal representations of a cue-rich environment may depend on the spatial organization of the visual environment and goals of the animal, and not on just the identification of individual visual cues. Indeed, removal of any one of the many available visual cues does not usually affect place-field characteristics (O'Keefe and Conway, 1978, but see Hetherington and Shapiro, 1997). Rather, recent reports from different laboratories have shown that more dramatic changes in the visual environment produce substantial changes in hippocampal place fields (e.g., Hetherington and Shapiro, 1997; Kubie and Ranck, 1983; Muller and Kubie, 1987; O'Keefe and Burgess, 1996a; O'Keefe and Conway, 1978; Tanila et al., 1997a,b; Wilson and McNaughton, 1993). A common response is a change in the topography of place fields across the population of cells being recorded. On an individual cell basis, it can be seen that one cell's response seems independent of the response of neighboring place cells. As an example, during per-

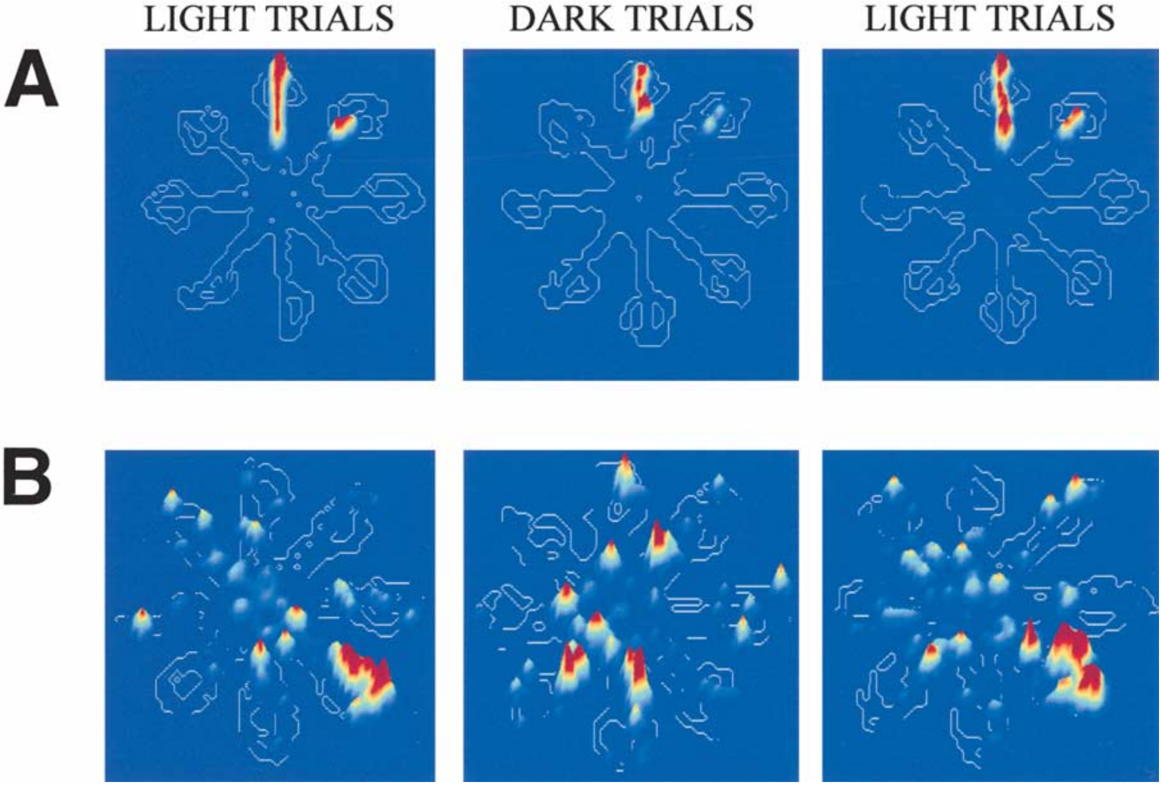


Fig. 1. Two examples (**A** and **B** of hippocampal place-field responses to changes in room illumination. Rats were trained to perform a standard spatial working-memory task on an eight-arm radial maze (Mizumori et al., 1999). For each trial, the rat was to retrieve chocolate milk reward found at the ends of the maze arms. Reentries into the same arm were counted as errors. Each color-density plot reflects the average firing-rate distribution of a hippocampal neuron recorded for five successive trials. The white lines show the extent of the rat's movement on the maze surface; red colors show the locations associated with the highest firing rates. Rats first performed the five trials with the lights turned on (left plot). During the 2-min intertrial interval between trials 5 and 6, the room lights were turned off and the rat performed five additional maze trials in complete darkness (middle plot). The room lights were then turned on as the rat performed the last five maze trials in light conditions (right plot). The examples of this figure illustrate the two most common responses of hippocampal place cells to this dark trials manipulation. The first example (A) shows a place field that shows reliable location specific firing on the north-maze arm even when the lights are turned off. This is characteristic of about 40–60% of hippocampal place fields recorded across a number of animals. The remaining place fields show some sort of change in their place field during dark trials. The example in (B) is of a place field that changed the location of the place field in darkness. The original field location was re-established during the last set of light trials. Other place cells might lose place specificity altogether, or develop a place field in darkness when none had been observed during the light trials. Because these patterns of cell responses are observed even within the same recording session, they are taken as evidence that the hippocampus reorganizes its spatial representations when dramatic changes are detected in the spatial context.

formance of maze trials in darkness, one cell's place field may change its preferred location, others may show enhanced or reduced spatial specificity, and other cells may stop firing altogether. Also, cells that do not exhibit place fields in light conditions may show clear and reliable place fields in darkness (e.g., Mizumori et al., 1999b). If all cells of an ensemble show altered place-field responses, this is referred to as "complete reorganization" (often referred to as "remapping"), but if only a portion of the population changes, this is referred to as "partial reorganization." Complete or partial reorganization has been demonstrated when the distal visual cues are randomly scrambled, when animals are placed in novel visual environments, and when the relationship between intramaze and extramaze cues is disrupted.

Another form of representational reorganization occurs when the task demands change in a familiar sensory environment (Mizumori et al., 1996). In this situation, one observes a change in the relative specificity of CA1 and CA3/hilar place cells when the task is shifted from a task in which rats do not have to recall the location of food, to a task that involves remembering rewarded locations. In addition to changing the topography of place representations, place fields demonstrate plasticity by switching between visual and idiothetic information codes depending on the task demands and availability of cues (Jeffery and O'Keefe, 1999; Markus et al., 1994, 1995). The latter finding demonstrates that dynamic sensory codes in hippocampus exist not only within the visual domain, but also across sensory modalities.

The reorganization phenomenon in general can be taken as evidence that the hippocampus differentially represents distinct environmental contexts, perhaps to facilitate its role in episodic memory. The phenomenon of partial reorganization is a particularly revealing one. When this occurs, by definition, some place fields remain constant across changing environmental contexts and other fields change. A current interpretation of this pattern is that hippocampus contains neurons that code constant or common features across environments while other neuronal firing patterns reflect aspects that are different across environments (Eichenbaum et al., 1999; Mizumori et al., 1999b). Specifically, we proposed that the hippocampus processes contextual information by distinguishing between "expected" and "current" spatial context. "Expected spatial context" refers to a mnemonically driven information packet that is shaped by past knowledge (i.e., memory) of the spatial relationship between salient (visual and nonvisual) features of a familiar environment, knowledge of the appropriate cognitive/behavioral strategy for solving the task, and knowledge of the motivational significance of discrete locations within the environment. Such information may generalize across environments perceived to be similar in terms of one or more of the context attributes, resulting in place fields that persist across similar, yet different, environments. In contrast, "current spatial context" reflects the animal's currently active sensory spatial perception. Place fields that are sensitive to changes in the visual environment (such as moving a wall of the test apparatus, O'Keefe and Burgess, 1996a) may encode such current information. A specific function of hippocampus may be to compare the memory-driven knowledge of what to expect in a particular environment with the current perception of that environment. If there is no discrepancy, the message from hippocampus back to neocortex serves to "consolidate" memory representations, perhaps by strengthening current synaptic patterns of activity. If a discrepancy is found, the hippocampal signal destabilizes, or changes, previously stable neocortical networks such that another (presumably closely related) stable state emerges. In this case, another representational pattern (or memory) would determine the expected spatial context for the next trial. The destabilizing signal could be derived at least in part from the approach-consummate-mismatch cells that increase firing when animals do not find the expected reward at a particular location (Ranck, 1973).

The hippocampus may accomplish the goal of spatial context comparison in more than one stage (Mizumori et al., 1999b). According to our hypothesis, the dentate gyrus/CA3 region contributes most to the process of comparing expected and current contexts. Then, CA1, upon receiving the CA3 information, temporally organizes information in a manner consistent with past expectations. In this way, CA1 defines the temporal extent of a meaningful episode. This formulation of two-stage processing is based on several empirical observations. First, compared to the CA3/hilar region, CA1 contains a greater proportion of cells with place fields that persist across test conditions (Mizumori et al., 1999), indicating that there is greater representation of past knowledge in CA1. Also, CA1 place fields tend to be more broad (i.e., less specific to a particular location) than CA3 or dentate gyrus place fields (Barnes et al., 1990; Jung and McNaughton, 1993; Mizumori et al., 1989, 1996, 1999b) suggesting that CA1 fields incorporate more than just location information. Individual CA1 place cells might relay location information that has been integrated over a period of time, thereby providing a temporal context for spatial information. In this way, CA1 may have a preferential role in temporal processing (Mizumori et al., 1999b; Wiener and Korshunov, 1995).

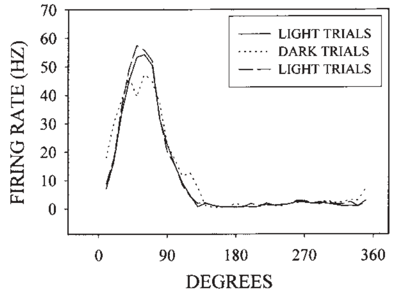
Hippocampal place-cell research has shown that even though hippocampus represents spatial aspects of a visual environment, other information is considered as well during adaptive navigation. As described earlier, hippocampal processing likely also incorporates sensory events generated from within the animal, such as idiothetic information about an individual's movement state (Knierim et al., 1998; Sharp et al., 1995; Whishaw et al., 1995, 1997). The following describes a likely source of idiothetic input.

Evaluating the Internal Sensory Environment

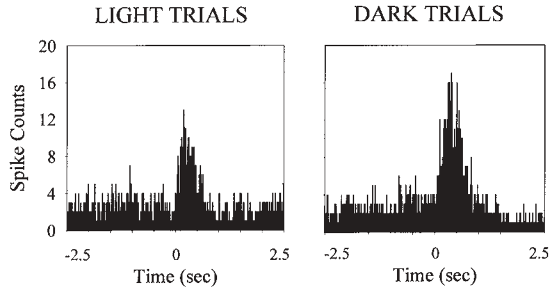
The internal sensory systems relevant to navigation consist of information detailing the current state of an animal's movement. Knowledge of self-generated motion is based on the combined input from the vestibular system, proprioceptive feedback, and motor efference copy. (In lighted environments, optic flow likely also plays a role.) Computational models show that movement information can, in theory, make critical contributions to knowledge of directional heading within a defined environmental structure (Blair, 1996; Skaggs et al., 1995; Redish and Touretzky, 1997; Zhang, 1996). Head direction cells, those neurons that selectively discharge according to the orientation of an animal's head (e.g., Fig. 2), are thought to carry such directional heading information. That is, the directional nature of these cells may be driven, at least initially, by idiothetic input. Because there are several excellent discussions of head direction cell properties (e.g., McNaughton et al., 1996; Muller et al., 1996; Taube, 1998; Redish, 1999; Sharp et al., 1996), this summary will be somewhat judicious.

Head direction cells were initially recorded in many structures afferent to hippocampus. They were first described in the postsubiculum (Ranck, 1984; Taube et al., 1990a,b). Since then, they have been discovered in limbic thalamic regions, such as the LDN (Mizumori & Williams, 1993) and the anterior nucleus (ATN) of the thalamus (Taube, 1995; Blair and Sharp, 1995), as well as the limbic cortical region of the retrosplenial cortex (Chen et al., 1994a,b; Cho et al., 1998). Relative to the other brain areas, head direction signals of the LDN seem to be more easily disrupted by changes in visual input. This is evidenced by the fact that dramatic shifts in the directional preference of the LDN neurons are observed 2–3 min after an animal begins performing maze trials in darkness (Mizumori and Williams, 1993). Head direction cells recorded in other limbic regions appear essentially unaffected by darkness, suggesting a greater dependence on idiothetic information (e.g., Blair and Sharp, 1996; Stackman and Taube, 1997; Taube and Burton, 1995). The greater visual sensitivity of LDN head direction cells likely reflects the fact that LDN is situated early in the tectocortical visual pathway (Linden and Perry, 1983; Sefton and Dreher, 1985), and the greater reliance on idiothetic cues by ATN head direction cells is consistent with ATN's relatively close proximity to vestibular input (Seki and Zyo, 1984; Shibata, 1992). Functionally, the differential sensitivity of the LDN and ATN directional systems may confer greater flexibility on the navigational system.

A. Head Direction Cell



B. Turn Cell



C. Forward Movement Cell

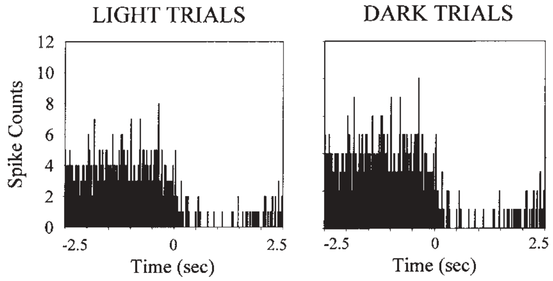


Fig. 2. In addition to hippocampal place cells, other spatial and movement-related neurons have been tested during performance of five maze trials in each of the light-dark-light phases of the recording session. Head direction cells recorded in many brain areas (except the LDN) typically retain the same directional preference during dark trials. Occasionally only a slight reduction in firing rate is observed during dark trials, as shown by the dorsal striatal head direction cell in **(A).** Mean firing rate is presented as a function of orientation on the maze. Dorsal striatal neurons that are sensitive to right or left turns made by the rat **(B),** or to forward motion through space **(C),** are not affected by turning the lights off. This is also true regardless of the brain area being recorded, suggesting that these representations reflect self-generated motion information. For **(B),** T_0 corresponds to the onset of turns made at the arm ends. For **(C),** T_0 corresponds to the time when the rat ceased outbound forward movement on the maze arms.

For all populations of head direction cells, however, it is thought that visual input that exists serves to anchor idiothetic information to specific aspects of the visual environment (Goodridge and Taube, 1995; Knierim et al., 1998; Mizumori and Williams, 1993). Indeed, analogous to the response of hippocampal place fields, the directional preference of head direction cells rotate in accordance with the rotation of extramaze visual cues (Chen et al., 1994a,b; Taube et al., 1990b; Taube, 1995). Also, a given head direction cell may show different directional preferences (e.g., north, then south) across environments (Taube et al., 1990b; Taube, 1995). It is interesting to note that in contrast to place cells, which are unpredictable in terms of their response to different environments, head direction cells reliably display firing that is related to heading direction in all (lighted) spatial environments.

A search for the source of the head direction signal has led to the suggestion that dorsal tegmental nuclei pass on a head direction signal to the lateral mammillary nucleus. In the latter structure, one finds head direction cells that show anticipatory discharge about 38–95 ms prior to the arrival at a particular head orientation (Blair et al., 1998; Stackman and Taube, 1998). Lateral mammillary afferents then project to the ATN where head direction cells show anticipatory firing of about 20–25 ms (Blair and Sharp, 1995; Blair et al., 1997; Taube and Muller, 1998). Retrosplenial cortical head direction cells also show anticipatory firing by about 23 ms (Cho et al., 1998). In contrast, postsubicular head direction cells do not show such anticipatory discharge (Blair and Sharp, 1995; Taube and Muller, 1998). The main conclusion from these data has been that current heading direction can be derived by progressively aligning internal (i.e., idiothetic) sensory information to the expected directional orientation. Precisely how each structure in the circuit contributes to the calculation of current directional orientation remains to be delineated.

Although not often discussed in this way, it is important to note that other forms of idiothetic representation have been reported in freely navigating rats (Fig. 2). These are derived from cells whose firing rates are sensitive to right or left whole-body turns, and cells that change firing rates as a function of velocity or whole-body forward motion through space (e.g., McNaughton et al., 1994; Ranck, 1973; McNaughton et al., 1983). Computational models propose mechanisms by which at least some of these forms of idiothetic representation contribute to the computation of directional heading (Blair, 1996; Skaggs et al., 1995; Redish and Touretzky, 1997; Zhang, 1996). In addition, it is possible that in rats, turn, velocity, or forward movement cells provide a more general code for self-generated motion because they are found across multiple brain regions such as the prefrontal cortex, retrosplenial cortex, posterior parietal cortex, hippocampus, septum, striatum, and the amygdala (Jog et al., 1999; King et al., 1998; McNaughton et al., 1994; Pratt and Mizumori, 1998; Poucet, 1997; Ranck, 1973).

Integrating External and Internal Sensory Information

To interpret our external sensory environment, allocentric (world-centered) information must be transformed or mapped into an egocentric (self-centered) coordinate system. This has been elegantly demonstrated in studies of, for example, sensory and motor integration by superior colliculus (Meredith and Stein, 1985; Stein and Meredith, 1993). In the context of unrestrained exploration of a novel environment, animals may correlate external environmental information with the knowledge structure of the idiothetic system (Knierim et al., 1995). Efficient integration of input from these multiple sensory modalities ultimately confers the behavioral flexibility necessary to survive ever-changing natural environments. This form of integration may underlie the finding described earlier that hippocampal place cells appear to be sensitive to different sensory modalities, depending on the availability of cues (or sensory context). Thus, it becomes important to understand how external sensory and internal idiothetic sensory information becomes integrated to implement accurate behavior.

When animals initially explore a maze such as the radial maze, they first learn the motor coordination skills necessary to navigate the many narrow arms of the maze. Over time, the significance of specific behavioral acts performed in a specific spatial context becomes embedded within knowledge about the appropriate behavior repertoire. Cooper and Mizumori (1999a) hypothesized that the context-dependent mnemonic association of visuospatial and idiothetic information may be a special contribution of the retrosplenial cortex.

The proposal that the retrosplenial cortex serves to integrate mnemonically visual and idiothetic information was initially based on anatomical and behavioral evidence. The retrosplenial cortex is strategically situated to receive both visual and idiothetic information, presumably from Area 18 and anterior thalamus, respectively. Efferent pathways of the retrosplenial cortex enter the hippocampal system via the parasubiculum, presubiculum, and postsubiculum (Wyss and van Groen, 1994), allowing for reasonably direct influence over hippocampal processing. Chen et al. (1994 a,b) reported that compared to other brain regions in which head direction cells are found, the retrosplenial cortex contains a head direction cell population that is more diverse. During radial-maze performance, some retrosplenial head direction cells are visually sensitive (as are LDN head direction cells), whereas others appear driven by idiothetic cues (as are ATN head direction cells). Behavioral evidence that the retrosplenial cortex is involved in spatial learning comes from studies showing spatial memory impairments following retrosplenial cortex lesions in rodents and humans (Sutherland and Hoesing, 1993; Takahashi et al., 1997).

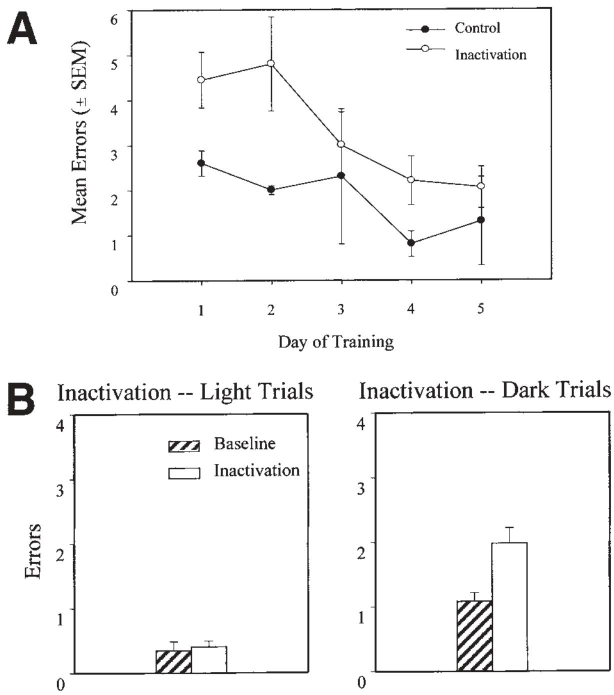


Fig. 3. **(A)** The effects of reversible inactivation of the retrosplenial cortex on acquisition of a spatial working-memory task on a radial-arm maze. Animals received daily bilateral injections of either tetracaine or a vehicle-control solution into retrosplenial cortex just prior to maze training. Retrosplenial cortex inactivated rats performed significantly worse than controls ($p < 0.05$). **(B)** In contrast to the behavioral deficit observed above, retrosplenial cortex inactivation did not affect choice accuracy after the task was learned (B, left). However, the inactivation of retrosplenial cortex resulted in significantly more errors during performance of the same task in darkness (B, right; $p < 0.05$). This pattern suggests a different contribution of the retrosplenial cortex during acquisition and asymptote performance.

We hypothesized that upon initial exposure to a new environment, the retrosplenial cortex may place visual context information within a framework of idiothetic knowledge. If, however, animals are required to learn a spatial working-memory task in this new environment, a new dynamic may take over. As learning progresses, retrosplenial cortex uses the new knowledge of the expected definition of the spatial context to guide behavior accurately. Accordingly, visual spatial information exerts a progressively greater influence over ongoing behavior as well as the neural representation of relevant sensory events. If this is true, then disrupting retrosplenial cortex function during the acquisition of a spatial memory task should impair choice accuracy. Indeed, Fig. 3 shows this to be the case. Importantly, however, visual dominance does not necessarily mean that idiothetic processing ceases. Rather, it seems more plausible that visual-idiothetic integration continues during the learning process to allow behavioral flexibility in the event that environmental conditions change. For this reason, when animals are experts in a particular navigation task, they have the potential to use multiple behavioral/cognitive strategies to ensure successful performance. Retrosplenial cortex inactivation in well-trained rats, then, would be expected not to impair choice accuracy on a radial maze.

Evidence that animals can use different cognitive strategies to navigate successfully a radial maze comes from behavioral observations. In our hands, animals proceed slowly through the maze during their first exposure to the task, often pausing at the maze center between choices. As training progresses, however, the behavior becomes more continuous and the time required to complete a trial drops from several minutes to less than one minute (Mizumori and Kalyani, 1997). This change in behavioral patterns and speed is what might be expected as animals become expert performers. Different cognitive strategies also appear to be used when animals perform a radial-maze task in light and dark conditions (Brown and Bing, 1997; Brown and Moore, 1997; Save, 1997). There is a greater reliance on idiothetic information in darkness. Thus, continued experience with the radial-maze task appears to encourage the integration of multiple sensory modalities.

Cooper and Mizumori (1999a) sought more direct behavioral evidence that the retrosplenial cortex is essential for the mnemonic association between visual and idiothetic cue-based strategies by examining spatial accuracy on a spatial working-memory (radial-maze) task by well-trained rats. As predicted earlier, bilateral reversible inactivation of the retrosplenial cortex selectively impaired spatial performance when maze trials were performed in darkness, but not in light conditions (Fig. 3). That performance in light conditions was intact shows that the procedure itself did not produce general sensory or motor impairments. The lack of behavioral effect during light trials at asymptote performance stands in contrast to the significant impairment observed when the retrosplenial cortex was inactivated during initial learning of the task in the light (Fig. 3). The differential effects suggest that the role of the retrosplenial cortex in spatial learning varies according to how well animals have learned a particular task. In the case of inactivation during asymptote performance in darkness, rats could not use preexisting knowledge of the expected spatial context to guide behavior according to the idiothetic system. Performance in light conditions was not disrupted by the inactivation perhaps because such performance could be maintained by predominantly visually based strategies that did not require integration with idiothetic information. If hippocampus evaluates the spatial context of an environment independent of the availability of specific sensory cues, it might be expected that retrosplenial cortex inactivation would result in significant changes in hippocampal place-field properties regardless of whether inactivation occurs in light or dark conditions.

Cooper and Mizumori (1999b) recorded hippocampal place cells during inactivation of the retrosplenial cortex in rats at asymptote performance during light or dark test conditions. Temporarily removing the influence of retrosplenial cortex resulted in significant reorganization of hippocampal place fields regardless of the lighting conditions (Fig 4). This result is consistent with the view that rats use different strategies to support similar behavioral performances in light and dark conditions (e.g., Brown and Bing, 1997; Brown and Moore, 1997; Save, 1997). Furthermore, although many would agree that hippocampal place-field organization reflects a constellation of attributes that define unique spatial contexts, it is important to point out that particular representational organizations do not necessarily correspond to improved or impaired behavioral accuracy. In the case of the retrosplenial cortex inactivation study, hippocampal place-field organization changed independently of changes in errors. Therefore, extrahippocampal factors must also contribute to successful performance.

The Influence of Internal State Information

An animal's interpretation of the current sensory (external and internal) environment depends not only on how it interacts with or behaves in the environment, but also on the current motivational status. When one is hungry, preferential attention will be paid to certain cues and behaviors that may otherwise be ignored if one is in the same environment but is searching for an escape route. Because of the well-known and dramatic influence that motivation can have on cognitive processing, models of adaptive navigation need to consider this variable more fully. Traditionally, the effects of motivational states on behavior have been studied either by considering the consequences of varying general homeostatic regulatory systems such as hunger or thirst, or by studying the effects of appetitive or aversive events. For decades, the hypothalamus has been considered an important regulator of homeostatic functions. Other neural systems have been argued to facilitate the formation of associations between specific external environmental cues and their reinforcement consequences (via the amygdala-prefrontal cortex circuit; Alheid et al., 1995). Both approaches to the study of motivation are rarely if ever considered within the behavioral context of adaptive navigation. A hypothalamic contribution to spatial learning is considered nonspecific

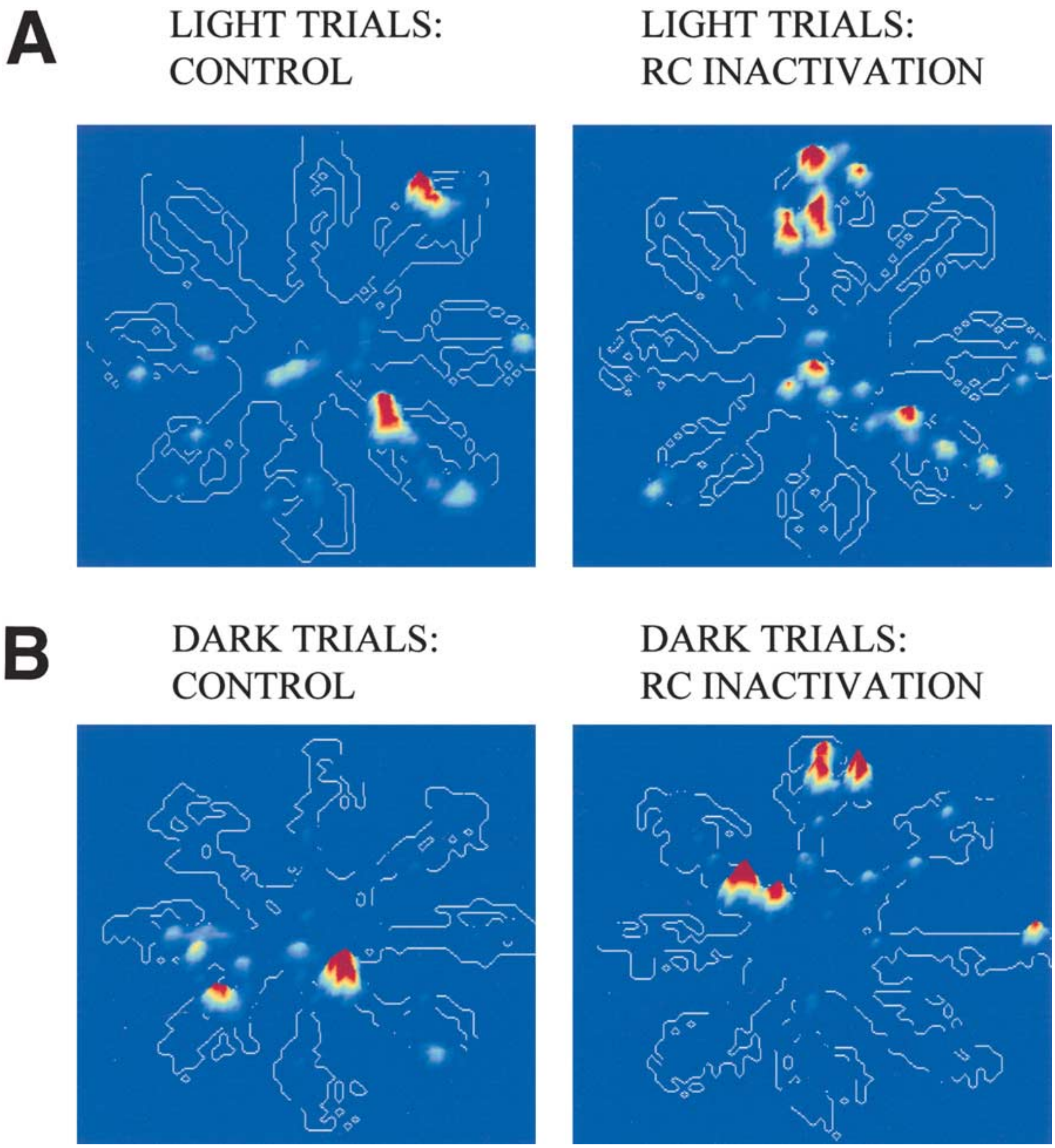


Fig. 4. Color-density plots showing reorganization of hippocampal place fields during reversible inactivation of the retrosplenial cortex (RC) in either light test conditions **(A)** or dark test conditions **(B).** It can be seen that the place fields changed in both illumination conditions. Perhaps this result is indicative of a change in spatial strategy induced by the retrosplenial cortex inactivation.

and indirect at best (e.g., stress effects), and the study of an amygdala contribution to behavior is typically in terms of conditioning phenomena (*see* Kapp et al., 1979; LeDoux et al., 1990). We argue here that by considering more precisely how motivation and incentive learning affect experience-dependent navigation, we can gain insight as to how animals eventually learn the significance of behaviors and cues available in specific spatial contexts.

Homeostatic Regulation

The neural circuitry discussed thus far emphasizes primarily limbic thalamus, hippocampus, and limbic cortical contributions to sensory processing aspects of adaptive navigation. However, a vast literature, based on neuroanatomical, behavioral, and neurophysiological evidence, indicates that several subcortical structures can exert powerful control over limbic structures, especially the hippocampus. The traditional interpretation of these subcortical influences has been that they somehow gate incoming cortical information (e.g., Winson, 1984). The gating hypothesis was based on findings that prestimulation of many subcortical areas, including the medial septum (e.g., Alvarez-Leefmans and Gardiner-Medwin, 1975; Bilkey and Goddard, 1985), supramammillary nucleus (Segal, 1979; Mizumori et al., 1989; Winson, 1984), nucleus raphe (Assaf and Miller, 1978), and the locus coeruleus (Dahl and Winson, 1985) facilitated perforant path-mediated synaptic transmission through the hippocampus. In all of these cases, the nature of the specific information being conveyed by the gating process was not clearly defined.

Of the brain structures known to modulate hippocampal neurotransmission, the septum is clearly strategically located to provide the navigational circuit with information concerning an animal's motivation state. The septum has extensive interconnections with hypothalamic motivational systems (Jakab and Leranth, 1995; Swanson and Cowan, 1979) as well as significant control over hippocampal plasticity. The hippocampal effects presumably occur via powerful GABAergic and cholinergic septal afferents (Freund and Buzsaki, 1996; Freund and Antal, 1988; Risold and Swanson, 1996). Examples of a septal influence over hippocampal function are many. Septal lesions or reversible inactivation not only impair hippocampal-dependent behaviors (e.g., Harzi and Jarrard, 1992; Mizumori et al., 1989, 1990; Winson, 1978) but also significantly attenuate septal-mediated hippocampal theta rhythm (Winson, 1978; Mizumori et al., 1989). Single-unit recording studies suggest that septal lesion or inactivation alters hippocampal place fields by decreasing responses to changed environments (Leutgeb and Mizumori, 1999; Mizumori et al., 1989). For example, septal lesions render place fields less prone to reorganization in novel visual environments (Leutgeb and Mizumori, 1999). Other evidence suggests that neural activity in septum and hippocampus can be temporally coordinated (Dragoi et al., 1999; O'Keefe and Reece, 1993). Also, acetylcholine (presumably from the septum) modulates hippocampal long-term potentiation (LTP, a synaptic model of plasticity), and there is growing evidence of significant acetylcholine release in hippocampus during new learning (e.g., Decker et al., 1988; Galey et al., 1989; Ragozzino et al., 1998b). Findings such as these suggest that the septum importantly regulates hippocampal neuroplasticity,

Although it has been known for some time that the septum can have powerful physiological effects on hippocampal systems, a satisfactory functional explanation for this control is lacking. One way to view a septal influence on hippocampal processing is that it identifies for hippocampus the appropriate internally defined perspective (or motivational state) within which to view the current spatial environment. If so, the septum needs access to information concerning the current visuospatial context. Because the septum does not have direct connections with visual areas of cortex (Jakab and Leranth, 1995), it stands to reason that its spatial context information may come from the extensive hippocampal CA3 efferent system. Indeed, Zhou et al. (1999) and Leutgeb et al. (1999) have shown that the lateral septum (the main cortical input area of the septal region) contains place-like neurons (Fig. 5). Leutgeb et al. (1999) further showed (with simultaneous recordings of hippocampal and lateral septal place cells) that both types of place cells show a mixture of place fields that persist or change in darkness. However, unlike hippocampal neurons, preliminary analysis

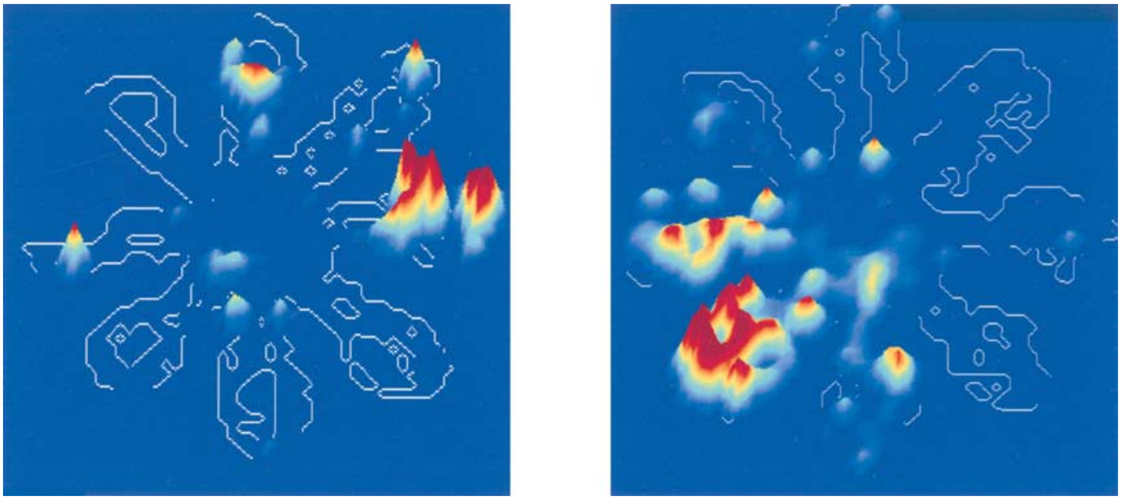


Fig. 5. Two examples of place fields recorded from the lateral septum of rats performing at asymptote on a spatial working-memory task. It can be seen that the septal place fields could appear as selective as some hippocampal place fields. It is suggested that this information could be used to inform hypothalamic motivational systems about the current spatial context.

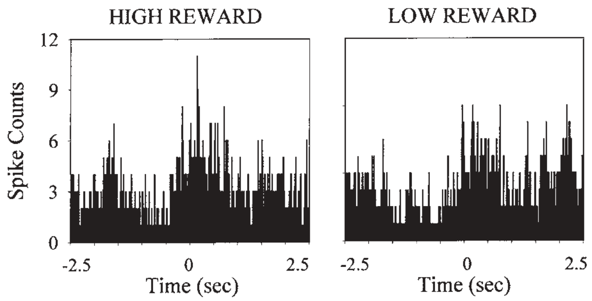
indicates that lateral septal place neurons showed greater sensitivity to idiothetic cues (e.g., velocity of movement) in darkness than in light conditions (Leutgeb and Mizumori, unpublished data). One interpretation of this pattern of greater responsiveness by septal place cells is that under normal conditions septum represents more information about the current spatial context, and less about the expected context. In addition, the functional contribution of lateral septal neurons may be directed by more than hippocampus.

Our current working hypothesis is that the lateral septum, via its extensive projection to various hypothalamic and mammillary structures, informs the motivational system of the current spatial context. In doing so, it biases the neural codes of hypothalamic neurons to reflect the appropriate motivational state. This bias in turn could dramatically shift hypothalamic control of the medial septum, which in turn would be expected to have consequences for hippocampal processing. In this way, the hypothalamo-septal informational system could be thought of as reflecting the motivational perspective within which hippocampus should interpret neocortical sensory information. This operation may serve to disambiguate, or selectively filter, incoming sensory information, perhaps in the manner suggested by Wallenstein et al. (1998).

Reinforcement-Cue Association

In addition to the influence of homeostatic regulatory systems on spatial processing, a number of studies describe structures such as the amygdala and connected cortical regions in terms of their role in identifying the reinforcement, or incentive, value of cues in the environment. For example, basolateral amygdala lesions impair fear conditioning (Kapp et al., 1979; LeDoux et al., 1990), second-order conditioning (e.g., Hatfield et al., 1996), and conditioned place preference (McDonald and White, 1993). We explored the possibility that the basolateral amygdala contributes to adaptive navigation, perhaps by contributing knowledge about the incentive value of reward (Pratt and Mizumori, 1998). Rats were trained to solve a spatial working-memory task in which alternating maze arms contained either a small amount of reward or a large amount of reward. Rats eventually learned to discriminate behaviorally these two types of arm choices by showing a preference for entering arms that reliably contained a large reward. About 30% of recorded amygdalar neurons showed reward-correlated discharge. Of these, about 60% showed anticipatory discharge in that they reduced or increased firing shortly before reward encounters. A subset of these differentially anticipated encounters of large or small amounts of rewards (Fig. 6). Control procedures illustrated that movement or gustatory aspects of reward consumption could not account for the anticipatory firing. Given that the basolateral amygdala receives hippocampal information from regions that show diffuse location codes such as the subiculum and entorhinal cortex (Mizumori et al., 1992; Quirk et al., 1992; Sharp and Green, 1994) it is likely that the amygdala does not receive a precise spatial code. Because amygdala lesions do not result in the consistent spatial learning impairment observed with hippocampal lesions (e.g., McDonald and White, 1993; Kesner and Williams, 1995), it appears that the amygdala makes a conditional contribution to navigation. That is, the amygdala may be recruited if distinguishing incentive values is a salient feature of the spatial context.

A. Basolateral Amygdala



B. Prefrontal Cortex

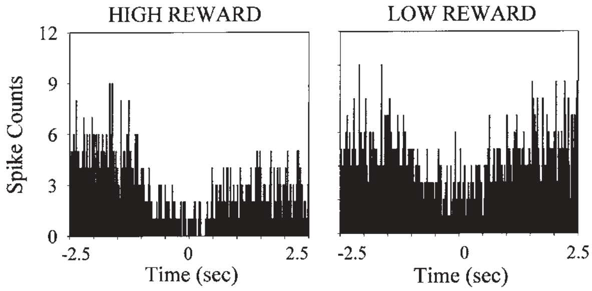


Fig. 6. Examples of anticipatory reward-related discharge by a basolateral amygdala **(A)** and a prefrontal cortical **(B)** neuron. T_0 corresponds to the time when the rat reached the end of the maze arm, or the onset of reward consumption. The amygdala neuron showed an increased rate just prior to reward consumption. The prefrontal neuron showed anticipatory inhibition just prior to reward consumption.

In contrast to the lesion literature involving the basolateral amygdala, lesion studies of rat prefrontal cortex suggest a more direct involvement in spatial processing. For example, prefrontal cortex lesions produce reliable impairments in tasks requiring flexible use of goal location information (e.g., Gemmell and O'Mara, 1999; Granon et al., 1996; Poucet and Herrmann, 1990). Also, prefrontal cortex inactivation impairs spatial working-memory performance (Seamans et al., 1995; Ragozzino et al., 1998a). Single-unit studies, however, reveal a paucity of obvious spatial correlates (Jung et al., 1998; Poucet, 1997; Pratt and Mizumori, 1998b). This was initially surprising in light of the results of lesion studies, and given that there is a direct connection between the CA1 region of hippocampus and the prefrontal cortex (Jay and Witter, 1991). The most consistent type of behavioral correlate of prefrontal neurons during active navigation is the reward correlate. Similar to basolateral amygdala, a significant portion of prefrontal cortical-reward cells anticipated reward encounters in predictable locations on the maze (Fig. 6; Pratt and Mizumori, 1998b). A comparison of the lesion data together with the finding of anticipatory reward correlates suggests that the prefrontal cortex may provide a prospective representation of the incentive value of different locations that is unique for different spatial contexts. This interpretation is consistent with the hypothesis of an orbitofrontal cortex contribution to olfactory learning (e.g., Shoenbaum et al., 1998). Such prospective coding may bias the response patterns of prefrontal efferent structures such as the striatum, thereby influencing the evaluation of response outcomes.

Translating Integrated Sensory Contextual and Motivational Information into Cognitive Strategies and/or Behavioral Acts

An important process that follows the integration of sensory and internal state information is the selection of effective cognitive or behavioral response strategies to be used when solving a navigational problem. In this section, we present evidence that the striatum is ideally suited to facilitate this process by providing the navigational circuit with a system whereby the expected reinforcement outcome of a particular behavior or cognitive strategy is compared to the actual reinforcement received. The expectation is based on past experience with a given spatial context. A more in-depth presentation of this hypothesis can be found in Mizumori et al. (1999a).

Behavioral studies suggest an important role for the striatum in adaptive navigation. Striatal lesions produce spatial deficits similar to those observed following hippocampal lesions in that spatial but not nonspatial learning is disrupted, and the behavioral deficits are most pronounced during new learning (e.g., Annett et al., 1989; Floresco et al., 1996; Gal et al., 1997; Ploeger et al., 1994). Anatomical evidence also suggests specificity of information processing because the most consistent impairments are observed following reversible or permanent lesion of the medial extent of dorsal striatum, or of the ventral striatum. Lesions of the dorsolateral region of dorsal striatum do not result in a spatial impairment, but instead produce impairments in tasks that require a type of learning for which flexible responding would not be adaptive, such as stimulus-response or response-response learning (Devan and White, 1999). This apparent separation of functional contributions to behavior can be explained by considering the afferent patterns of connections. The dorsolateral sector receives primarily topographically organized input from sensory cortical areas and motor cortex (Flaherty and Graybiel, 1993). In contrast, the ventral striatum and the dorsomedial sector of dorsal striatum receive extensive convergent input from multiple sensory and association areas of neocortex (McGeorge and Faull, 1989). Computationally speaking, topographically constrained patterns of input place a restriction on the number of combinatorial patterns that can result, resulting in well-defined stimulus-response relationships. In contrast, a highly convergent pattern is endowed with tremendous combinatorial power to produce the high degree of flexible processing needed to evaluate the reinforcement outcomes of the current spatial and behavioral contexts relative to those expected by experience.

Although there is a clear topographical organization to striatal afferent patterns, the intrastriatal computations appear relatively consistent across the structure. This is supported by investigations of the intrinsic organization of the striatum showing that all cortical afferents terminate on GABAergic medium spiny neurons, which exhibit a characteristic bistable membrane property (Wilson, 1995; Stern et al., 1998). Synaptic efficiency of these spiny neurons is modulated by dopamine signals that are thought to reflect the reinforcement conditions (Houk, 1995; Schultz, 1997; Schultz et al., 1995). Thus, the striatum as a whole may perform similar computations on diverse types of information.

Recently, we postulated that the striatum as a whole shapes the action patterns that are appropriate to a given spatial context (Mizumori et al., 1999a). According to this hypothesis, association areas of neocortex provide striatum with mnemonic information concerning the sensory, motor, and reinforcement attributes that define a given environmental context. Other more direct sensory and motor cortical-afferent systems inform striatum about the current sensory and behavioral status. By integrating cortical information with dopamine-mediated information about the actual reinforcement experienced, the striatum effectively relays to frontal cortex whether or not the reinforcing consequences of current behaviors or cognitive strategies match the expected outcome. That is, striatum may reveal to cortex the extent to which actual reinforcement consequences are consistent with the expectations of a given spatial context. If they are not, the efferent message may destabilize the current cortical network activity pattern so that a related, yet different, strategy emerges. Expectations based on the new strategy are then relayed to striatum via its cortical afferents. If reinforcements occur as expected, the message back to cortex could effectively strengthen the synaptic weights within the currently active cortical neural network. The process of comparing the expected success of learned strategies with the consequences of current behaviors is referred to as a "response reference system." It is a system that should be generally useful for multiple forms of learning including resource acquisition during spatial exploration, as well as the less-flexible processes of stimulus-response, habit, or egocentric-response learning.

The response reference-system interpretation of a striatal contribution to navigation is consistent with findings from lesion studies and with the anatomically defined patterns of connectivity (described earlier). Neurophysiological studies are also congruent with the response-reference hypothesis. In behaving rats, the dorsomedial aspect of dorsal striatum and the ventral striatum contain idiothetic-types of neural representations (e.g., turn cells, forward movement cells, and head direction cells) as well as spatial context representations (e.g., location-sensitive cells), some of which are modulated by reinforcement aspects of the task. Lavoie and Mizumori (1994) described movement, reward, and location-sensitive cells in the ventral striatum. Wiener (1993) and Mizumori et al. (1996, 2000) also found movement and location-sensitive neurons in the dorsal striatum. In addition, head direction cells were found, and these were located within the dorsomedial sector of dorsal striatum (which receives input from retrosplenial cortex, McGeorge and Faull, 1989). Furthermore, Mizumori et al. (1999a) found reward-sensitive neurons, some of which anticipated arrival at locations previously associated with different amounts of food reward. Examples of some of these dorsal striatal correlates can be found in Fig. 2. These correlate types have also been reported in nonhuman primate studies (Kawagoe et al., 1998; Schultz et al., 1995), with the exception of the location and head direction cells. This exception likely reflects the fact that the primates are not freely navigating their environment during the recording sessions. Interestingly, however, primate striatal neurons are sensitive to the location of stimuli, as well as the direction of stimulus movement, as they appear on a two-dimensional test screen (e.g., Kawagoe et al., 1998). Altogether, the information required for the operation of a response reference system appears to be represented by striatal neurons during navigation.

The hypothesis that striatum serves as a response-reference system predicts that at least some neural representations are sensitive to changes in behavioral or cognitive strategy. Using a behavioral paradigm that induces a change in cognitive strategy (i.e., the dark-trial procedure for the radial-maze task described earlier), we tested the sensitivity of different categories of dorsal striatal neurons. The location- and head direction-sensitive neurons showed clear responses to changes in darkness, but in different ways. The location cells almost always showed a different pattern of firing, either in terms of mean rate or spatial specificity. In contrast, striatal head direction cells remained directionally selective during dark trials (Fig. 2). However, the directional preference shifted from being visually determined in light conditions to being determined by nonvisual cues during dark trials (Mizumori et al., 2000). The differential response may relate to the fact that rats use predominantly a visual-based strategy in light conditions, and idiothetic strategies in darkness (Brown and Bing, 1997; Brown and Moore, 1997; Save, 1997). Turn and other movement correlates were never observed to change during dark trial performance. That spatial context and at least some aspects of the idiothetic system are sensitive to changes in cognitive strategy is consistent with the response-reference hypothesis.

Another prediction of the response-reference hypothesis is currently being tested. Our expectation is that the effects of a spatial context change should be observed for the behavioral correlates of striatal neurons regardless of whether the task is a spatial or nonspatial one. This prediction stands in contrast to the conclusions drawn form many striatal lesion studies (e.g., Cook and Kesner, 1988; Packard and McGaugh, 1996; McDonald and White, 1993), which suggest that the striatum should not be sensitive to changes in context especially if they occur during performance of a nonspatial response-learning task.

Dynamic Interactions across Neural Systems

Considering adaptive navigation from a broad neural and functional perspective has revealed the likely involvement of multiple neural systems. Interactions between systems, and hence the accuracy of behavioral choices, may vary as a function of many factors such as the particular external sensory context, the appropriate behavior for a given spatial context, the internal state of the animal, the particular task demands, and whether the animals is performing a new or familiar task. The multidimensional nature of adaptive navigation makes it a particularly attractive behavioral model for studying dynamic neural systems interactions.

Figure 7 summarizes the functional contributions of different neural systems to spatial learning as it is proposed to occur during active navigation. To simplify the presentation, the connectivity patterns and brain structures/systems shown were limited to those that were most directly relevant to this review. Certainly, there are many more interconnections than what are shown. Other brain regions may be added as more is discovered about their functional contributions. The general prediction is that if this system operates as a unified whole, there must be systematic alterations in information processing during shifts in attention, incentive, or spatial context.

When an animal enters a new environment, the spatial world may be viewed relative to the absolute location and behaviors of the animal. Having not yet developed knowledge of the significance of different aspects of the environment, the animal's most reliable strategy for organizing its world is relative to itself. A defined motivational perspective (i.e., input from hypothalamus) may determine the framework within which subsequent knowledge is acquired about relevant, stable aspects of the spatial context. That is, the framework within which new information is placed may shift slightly to include a world-centered framework. During the transition between framework types, it would be highly adaptive to create associative networks involving *both* external spatial and idiothetic information, thereby permitting memory-guided use of any sensory modality if environmental conditions change. If the ability to create such associations is removed (as in the case of retrosplenial cortex inactivation), behavior becomes less reliable because of the greater reliance on a single sensory modality (*see* Fig. 3). When animals expertly navigate familiar environments, then they potentially have access to multiple strategies including perhaps an egocentric response pattern. The latter algorithm may arise by default because of a striatal contribution to the initial learning process. By considering the environmentally defined reinforcement consequences (provided by the basolateral amygdala and the prefrontal cortex) of different response patterns, the striatum may have effectively strengthened the associative networks underlying behavioral acts that are repeatedly exhibited during maze performance. Anyone who has watched a well-trained rat perform a spatial working-memory task on a radial maze has undoubtedly noticed that maze-unique behavioral patterns such as making abrupt

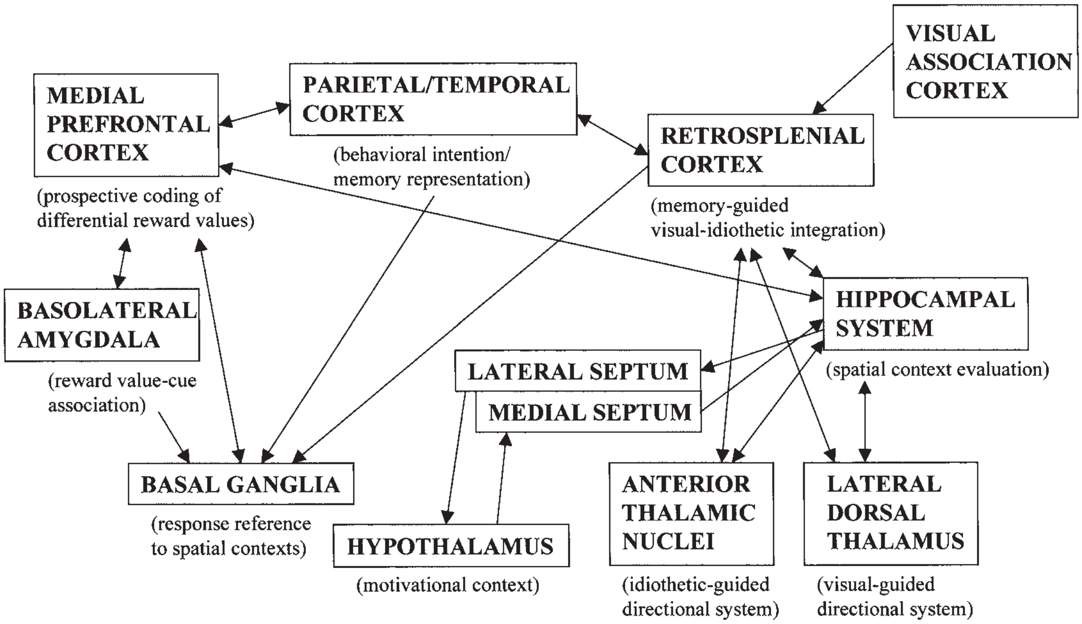


Fig. 7. A working hypothesis describing important components of the adaptive navigational circuit. The brain structures indicated in this figure are not meant to be inclusive. Other systems may contribute but their functional contribution is presently not clear.

180° turns at the arm ends become almost automatic and stereotypic. Thus, in healthy, brain-intact animals, it is probably the case that accurate performance on such mazes is under the control of multiple learning mechanisms. This would insure animals readily and dynamically adapt to ever-changing environmental conditions and demands, because altered cortical feedback from hippocampus or striatum would bias cortical activity patterns that reflect the current cognitive strategy. Also, the simultaneous activation of different learning algorithms during performance of a complex task may create a situation that encourages repeated response patterns to become habitual while *at the same time* retaining the flexibility to accurately make trial-unique choices. This combination should facilitate the efficiency with which new information is learned. We hypothesize that the striatum (perhaps by virtue of its unique afferent connections) plays a key role in coordinating simultaneously acquired *complementary* (rather than competitive) response and context-learning strategies.

Work with primates reveals the interesting possibility that parietal cortex plays a special role in spatial behaviors (Andersen, 1987, 1997) by coding the behavioral intention of future responses (Colby and Duhamel, 1995; Duhamel et al., 1992). In rat, the existing, though sparse, neurophysiological data suggest some parallels with the primate work. As rats perform a working-memory task on the radial-arm maze, some parietal neurons anticipate particular movements (such as turns) by several hundred milliseconds (McNaughton et al., 1994). These correlates could reflect intended behavioral acts and/or activated memory representations. Because these functions are clearly integral to the process of adaptive navigation, we include them in the model shown in Fig. 7.

In summary, the complex behavior of adaptive navigation is mediated by many parallel, yet interdependent neural systems. There is much to be learned about the mechanisms of their dynamic interactions. Computational models will undoubtedly make important contributions in this regard. However, most current computational models of navigation do not concern themselves with the influences of motivational status and strategy selection, processes mediated by extrahippocampal circuits. One exception to this statement is the Taxon Affordance-World Graph model of navigation described by Guazzelli et al. (1998; 1999), which considers the integration of internal and external sensory information together with motivational status across multiple neural systems. In the future, it would be of interest to compare directly predictions of the Taxon Affordance-World Graph model with those of the neurobiological model presented here.

Implications for Learning and Memory Systems in General

There is a striking, and initially somewhat surprising, feature of the empirical investigations that led to the navigational circuit proposed in Fig. 7. Although the specific proportions vary, spatial representations in the form of location-selective firing or head-direction discharge are found in a large number of brain structures. The hippocampal system and its afferents show the most impressive specificity of spatially related discharge. The hippocampal place fields often show mnemonic properties not observed in neocortex or striatum. Although these features may reflect a unique contribution of hippocampus to learning about changes in spatial context, it has become clear that other neural system incorporate similar forms of spatial information to guide their distinct computational missions. One interpretation of the widespread representation of spatial information is that for tasks involving navigating animals, spatial information serves as a common denominator to functionally link anatomically distinct brain systems. Effectively, this common denominator serves as a framework by which to organize multiple cognitive processes to enable adaptive behavioral responses. This interpretation may, in retrospect, not be too surprising given that the sensory and motor systems on which learning and memory systems are based have, as a fundamental principle, the spatial organization of information.

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