
The Neural Correlates of Navigation: Do Head Direction and Place Cells Guide Spatial Behavior?

Gary M. Muir
Jeffrey S. Taube
Dartmouth College

Head direction (HD) and place cells are thought to represent the neural correlates of processes underlying navigation. At present, however, a large gap exists in our knowledge as to how the firing characteristics of HD and place cells relate to performance in a navigational task. The purpose of this review is to evaluate critically the current evidence that such a relationship exists by examining the studies that have directly addressed this issue. The results of these studies are consistent with the notion that behavior and perceived orientation (as represented in the firing of HD and place cells) can be independently controlled by different cues but, under certain conditions, are controlled by the same cue(s). Much work, however, remains to be done to clarify the role of the HD and place cell systems in the neurobiology of spatial cognition and navigation.

Key Words: head direction cells, hippocampus, navigation, place cells, single unit recording, spatial memory

NAVIGATION

Navigation is an important feature for survival of any species. Being able to locate one's nest or a food source or avoid the known location of predators will increase the longevity and breeding productivity of an individual animal and consequently improve the species' chances of success. Animals usually have simultaneous access to a wealth of different types of cues to use while navigating their surroundings. Allothetic cues can be defined as those cues external to the animal that can be used in determining its location. These allothetic cues can be further divided into extramaze and intramaze cues based on their proximity to the animal's immediate environment. For example, while an animal performs a radial arm maze task in the center of a large room, the posters and furniture around the walls of the room

would constitute examples of allothetic (extramaze) cues, whereas the surface texture and any olfactory or visual cues present in the maze itself would provide examples of allothetic (intramaze) cues. In contrast, idiothetic cues provide the animal with information about its movement and, potentially, its location based on the animal's self-motion. Vestibular, proprioceptive, optic flow, and motor efference copy information constitute examples of idiothetic cues. Given this abundance of both external and internal sources of information and that animals normally have simultaneous access to these sources during navigation, the possibility exists that different aspects of navigation may be controlled by different sources of information. For example, it is theoretically possible for an animal to rely on one cue to determine its perceived orientation while relying on another cue to guide its behavior.

This article reviews the relationship between the firing of spatial cells presumed to be involved in navigation and an animal's behavioral performance on a navigational task. Do these spatial cells guide behavior on navigational tasks? In evaluating these studies, we first examine the types of spatial cells thought to underlie navigational processes.

Authors' Note: This review was supported by National Institute of Mental Health Grants MH48924 and MH01286. The authors would like to thank Russell Frohardt, Joshua Bassett, and Fay Guarraci for helpful discussions and the reviewers for their valuable comments.

Behavioral and Cognitive Neuroscience Reviews
Volume 1 Number 4, December 2002 297-317
DOI: 10.1177/1534582302238339
© 2002 Sage Publications

FIRING PROPERTIES OF HEAD DIRECTION CELLS

Head direction (HD) cells exhibit firing activity related to an animal's directional heading, independent of its location within the environment. The firing properties of HD cells have been characterized based mainly on the examination of HD cells in the anterior dorsal thalamic nucleus (ADN) (Taube, 1995) and postsubiculum (PoS) (Taube, Muller, & Ranck, 1990a, 1990b) of the rat, although HD cells are present in other brain regions, for example, the lateral dorsal nucleus of the thalamus (LDN), (Mizumori & Williams, 1993), the lateral mammillary nuclei (Stackman & Taube, 1998), the retrosplenial cortex (Chen, Lin, Green, Barnes, & McNaughton, 1994), and the dorsal striatum (Weiner, 1993) (for a review of HD cell firing properties, see Taube, 1998). Although stable for long periods within and between sessions in an unaltered environment, the preferred firing direction (i.e., the direction in which the cell fires maximally) of a given HD cell can be consistently altered by manipulations of the allothetic cues in the environment. One environment commonly used in studies of HD cell activity is a gray cylinder with a single white cue card affixed to the inside wall (e.g., Taube et al., 1990a). The cylinder is surrounded by a floor-to-ceiling curtain of uniform color. Under these conditions, rotation of the cue card while the animal is out of the cylinder will usually result in a corresponding shift of the HD cell's preferred firing direction when the rat is returned to the cylinder (Taube et al., 1990b). This finding demonstrates that environmental cues can control the firing activity of HD cells and suggests that allothetic cues may preferentially control the firing of HD cells over other types of available spatial cues (e.g., idiothetic) (see also Blair & Sharp, 1996; Goodridge & Taube, 1995). Removal of the cue card or darkening the environment, however, does not disrupt the directional firing properties of the HD cell (although the preferred direction is frequently shifted), suggesting that the cue card is not necessary to generate the HD signal (Goodridge et al., 1998; Taube et al., 1990b). Note that HD cells appear to retain their directional specificity under all conditions involving environmental manipulations (including being placed in a novel environment), although the cell's preferred firing direction may be altered. Importantly, if an environmental manipulation is conducted that shifts one cell's preferred direction, the preferred direction of all other simultaneously recorded HD cells shifts by a similar amount; thus, the preferred directions of different HD cells remain in "register" with one another and act together in a network (Taube, 1995; Taube et al., 1990b).

FIRING PROPERTIES OF PLACE CELLS

Place cells derive their name from the fact that they demonstrate location-specific firing. Thus, when the animal's head is in a specific location within the environment, the cell's activity will increase significantly relative to other areas of the environment where the firing rate is at or near zero (O'Keefe & Dostrovsky, 1971; for a review, see Muller, 1996). The area of increased activity is termed the cell's *place field*. Each place cell exhibits one and sometimes more place field(s) within an environment, and large numbers of place cells can be active in any given environment, each with a unique place field location (Wilson & McNaughton, 1993). Using the location-specific information provided by the distributed pattern of activity from large numbers of place cells, the animal can construct a spatial representation, or "cognitive map" (O'Keefe & Nadel, 1978), of its location within the environment, which can then be used for navigation. Although cells with location-specific firing have been found in other brain regions (e.g., entorhinal cortex, see Quirk, Muller, Kubie & Ranck, 1992; striatum, see Wiener, 1993), most studies have examined the properties of place cells within the hippocampus.

Similar to HD cells, the location of a cell's place field can be altered by manipulations of the environment. Rotation of a prominent cue while the animal is out of the apparatus will usually result in corresponding shifts of the place fields of simultaneously recorded place cells when the rat is returned to the cylinder (Knierim, Kudrimoti, & McNaughton, 1995; Muller & Kubie, 1987). Place cells also maintain their location-specific firing activity when the cue card is removed or the environment darkened (Markus, Barnes, McNaughton, Gladden, & Skaggs, 1994; Muller & Kubie, 1987; Quirk, Muller, & Kubie, 1990). In contrast to HD cells, however, a place cell in one environment may be completely silent or have a place field in an unpredictable location in another environment (a phenomenon known as "remapping") (Bostock, Muller, & Kubie, 1991), suggesting that the spatial information derived from these place cells can differentiate which environment the animal is in.

THE NEURAL CORRELATES OF NAVIGATION?

An extensive amount of research concerning the neural correlates of navigation has been conducted based on the following two assumptions:

Assumption 1: HD cells and place cells are neural correlates of the animal's orientation and spatial location, respectively. Thus, an animal's perceived orientation will be re-

flected in the preferred firing direction of HD cells and in the location and orientation of place fields.

Importantly, manipulations that cause shifts in the preferred firing direction of HD cells also cause equivalent shifts in the place field locations of simultaneously recorded place cells (Knierim et al., 1995). Lesions of the PoS and ADN, however, do not abolish hippocampal place cell activity (Calton et al., in press). Similarly, destruction of the hippocampus leaves HD cell activity relatively unaffected (Golob & Taube, 1997). Together, this provides support for the notion that the HD and place cell systems comprise distinct, albeit interrelated, parts of an overall navigational system.

Assumption 2: HD cells and place cells are actively involved in guiding the navigational behavior of the animal.

Support for this assumption comes, in part, from studies showing that lesions of brain areas containing HD cells (e.g., PoS, ADN) and place cells (e.g., hippocampus) lead to deficits in performance on spatial tasks (Aggleton, Hunt, Nagle, & Neave, 1996; Jarrard, 1993; Taube, Kesslak, & Cotman, 1992).

If HD cells and place cells are indeed neural correlates of the animal's orientation and location, respectively, and are actively involved in guiding the behavior of the animal, then we could expect to see a consistent relationship between the animal's behavior and the neuronal activity of these cells in tasks requiring spatial memory and navigation. Unfortunately, despite the large number of studies examining the properties of these two types of spatial cells, most studies have failed to employ a well-defined navigational task, preferring instead to use tasks solely designed to keep the animal locomoting randomly about the environment (e.g., the pellet-chasing task) (Muller, Kubie, & Ranck, 1987; Taube et al., 1990a), thereby keeping the animal's behavior constant. These studies have provided important information regarding the firing characteristics of HD and place cells, but a large gap exists in our knowledge as to how these firing characteristics relate to guiding the animal's behavior and affecting the animal's performance in a navigational task.

This article reviews the studies that have tried to establish a link between cell activity and the animal's behavior. To present the findings in their historical context, the studies are described in chronological order. Although specialized sensory abilities are used by some species for navigation (e.g., magnetoreception: navigation using the Earth's magnetic field), and these abilities, in some cases, have also been linked to neural correlates (Lohmann & Johnsen, 2000; Némec, Altmann, Marhold, Burda, & Oelschläger, 2001), the current review will only exam-

ine the neural correlates of navigation as represented by the activity of HD and place cells in rats as it relates to guiding behavior. More complete reviews of other properties of HD and place cells can be found elsewhere (e.g., Best, White, & Minai, 2001; Eichenbaum, Dudchenko, Wood, Shapiro, & Tanila, 1999; Muller, 1996; Redish, 1999; Sharp, Blair, & Cho, 2001; Taube, 1998; Weiner, 1996). As will become clear from reading this review, the relationship between the hypothesized neural correlates of navigation and navigational behavior is not as straightforward as would first appear. One aim of this review is to propose some explanation for this state of affairs.

HD CELLS AND PERFORMANCE ON NAVIGATIONAL TASKS

Given the notion that HD cells are the neural correlate of the animal's perceived directional orientation or "sense of direction," surprisingly few studies have addressed the relationship between HD cell activity and performance in a navigational task. Moreover, those studies that have addressed this issue have not always been in agreement. This section will first review each study and then pose an explanation for why disparate results have been reported.

Mizumori and Williams (1993)

Mizumori and Williams (1993) were the first to demonstrate that HD cell firing might be related to an animal's performance on a spatial task. HD cells were recorded from LDN in rats during a working memory version of the eight-arm radial maze. In this task, all arms of the maze were baited, and the rats were forced to go down four preselected arms that varied on every trial. Following these forced choices, all arms were made available, and the animals had to visit the four arms not previously entered to obtain a reward. Repeated trials were conducted in light and dark conditions. Mizumori and Williams recorded from two HD cells in different animals over a 2-week period during acquisition of the task. As the rats learned the task, a significant negative correlation developed between the mean directional specificity of the HD cells (i.e., the amount of directionality in the cell's firing) and the mean number of errors made by the animal across days. One notable exception to this pattern of results, however, was that rats made significantly more errors in dark trials that followed light trials, whereas the HD cell's directional specificity was unchanged across these two conditions.

The finding that HD cells' directional specificity scores changed during the course of learning the task might be considered surprising given the current conceptualization of how the HD system functions. Except for brief periods of disorientation (Steven & Taube,

2002), most researchers consider the HD network to be continually active, and it would therefore be operational throughout any learning period. Furthermore, as task acquisition proceeds, the animal learns to use the information provided by the directional network to guide its behavior and improve its performance on a spatial task (Dudchenko & Taube, 1997; McNaughton, Chen, & Markus, 1991; Redish, Elga, & Touretzky, 1996; Sharp, Blair, & Brown, 1996; Zhang, 1996). If this process were not the case, then groups of different HD cells might become active as an animal learns a particular spatial task. This notion, however, would require a neural network that contained a large capacity for storing all possible spatial tasks and environments that an animal was exposed to. In contrast to this latter notion, researchers have found that HD cell firing remains directionally selective and relatively constant (in terms of peak firing rate, signal-to-noise ratio, and directional firing range) throughout all recording sessions and different environments (Taube, 1995; Taube et al., 1990a, 1990b). Thus, this account would predict minimal changes, if any, in HD cell firing properties as a consequence of learning a spatial task.

If HD cell activity remains constant across time and environments, then how can we account for the findings reported by Mizumori and Williams (1993)? Their negative correlation between directionality and the number of performance errors was based on calculating a directional specificity score for each cell at different times during task acquisition. However, a cell's directional specificity score may increase due to an increase in the firing rate in the cell's preferred firing direction without a concomitant increase in the background firing rate or as a result of an overall decrease in the cell's background firing rate. The implications regarding the mechanisms responsible for these changes differ, but it is unclear which of these two possibilities may have occurred from the results. For example, a change in the recorded cell's signal-to-noise ratio between recording sessions, due to a decrease in background firing rate as a result of improved recording isolation of the cell, could have increased the cell's apparent directionality. Another point to consider is that although it is technically commendable to record from the same cell across 2 weeks, the authors only have data from two cells, and for one of these cells (Mizumori & Williams, 1993, Figure 12), a number of data points have a directional specificity score of less than 3, a value that was their threshold score for defining whether a cell exhibited directional specific firing. Thus, by their own definition, the cell that is depicted regularly showed firing that was not sufficiently directional to warrant classification as an HD cell. Directional-

specificity scores for this cell ranged from ≈ 2 to 6—a threefold difference in signal-to-noise ratio. This variability in the cell's directionality is difficult to reconcile with the large number of studies showing that HD cells remain directionally selective throughout a variety of environmental manipulations (Taube, 1998). Finally, the only data presented are the average of 10 trials per day; therefore, the correlation between performance and directional specificity on individual trials during task acquisition cannot be determined.

One important caveat to note is that this study remains the only one to date that has recorded HD cells from LDN. All other studies that have explored HD cell activity and linkage to behavior have recorded from HD cells in the ADN and PoS, and it appears that LDN HD cells have somewhat different properties compared to HD cells in these other regions. For example, HD cells in LDN appear to rely more on visual input for establishing and maintaining stable directional firing activity than HD cells in the ADN or PoS (Goodridge, Dudchenko, Worbays, Golob, & Taube, 1998). Because Dudchenko and Taube (1997) did not find changes in directional specificity from HD cells recorded in the PoS and ADN during acquisition of a spatial task (see the next section), the possibility remains that the learning-associated change in firing rate reported by Mizumori and Williams (1993) may be a property of cells only in the LDN.

Dudchenko and Taube (1997)

The first study to examine in detail the relationship between HD cell activity and behavior in a spatial task was that of Dudchenko and Taube (1997), who trained rats to solve a reference memory version of the radial arm maze task for a water reward. In this procedure, one arm of the maze was repeatedly baited while all other arms remained unbaited. The maze was situated within a black-curtained circular enclosure with a large white sheet encompassing $\approx 60^\circ$ (the cue curtain) attached to the inside of the black curtain. This cue curtain served as the most salient orienting cue for the animal when on the maze. Head direction cells from the ADN and PoS were recorded during acquisition of the task and during cue rotation manipulations once performance had reached criterion. During cue rotation manipulations, the white cue curtain was rotated 90° counterclockwise (CCW) or 180° while the animal was placed in one of three locations outside the curtained enclosure. The animal was then reintroduced to the center portion of the maze in one of four pseudo-randomly varied orientations. If the cue was influencing the animal's perceived location of the reward, then rotations of the cue should result in corresponding shifts in the maze arm chosen.

Similarly, if the preferred firing direction of the HD cell represents the animal's perceived orientation and this sense of direction is under control of the cue, then shifts of the cue curtain should also result in equivalent shifts of the cell's preferred firing direction.

Dudchenko and Taube (1997) showed a number of important results. First, during cue rotation manipulations, both the arm chosen and the preferred firing direction of the HD cell almost always shifted in register with one another (see Figure 1) (Dudchenko & Taube, 1997, Figures 3 and 5). Therefore, when the cue curtain was rotated 90° CCW, the animal selected a maze arm that remained in alignment with the cue curtain and was thus also rotated 90° CCW relative to the room's reference frame. During these "correct" rotational shifts in behavior, the HD cell also shifted its preferred firing direction 90° CCW. Importantly, on occasions when the animal's behavioral choice did not shift correctly following rotation of the cue curtain, the preferred firing direction of the HD cell also did not shift (Dudchenko & Taube, 1997, Figure 9A). Taken together, these results showed that the cell's preferred firing direction was strongly correlated with the animal's eventual maze arm choice. One animal made a large number of incorrect responses during 180° cue curtain rotation sessions (Dudchenko & Taube, 1997, Figure 9B). In this condition, the animal sometimes made rotationally equivalent responses that were correct, whereas at other times it selected maze arms that were incorrect (usually 90° shifted CW or CCW). Whereas the preferred firing direction of the HD cell shifted ≈180° on correct trials (thus maintaining strong linkage to the animal's behavioral choice), it also shifted ≈180° on incorrect trials, indicating little evidence that the HD cell network was guiding the animal's behavioral choice on these trials. Why was the HD cell's response not coupled to the animal's behavioral choice on these 180° rotation sessions? Interestingly, the rat did not consume the water reward during the 180° cue rotation sessions in which it selected the incorrect arm, although it did consume water during the standard prerotation sessions. It is possible that on the 180° cue rotation trials, the rat was less motivated to seek the water reward and selected different maze arms regardless of the cue curtain's position while continuing to maintain its orientation relative to the cue curtain.

A second finding was that during task acquisition, HD cell properties, including preferred firing direction, peak firing rate, and directional firing range, were generally unchanged from the initial session to when the rat reached criterion performance. Given that the animals were making many more errors at the start of training than at the end, the authors suggested that performance

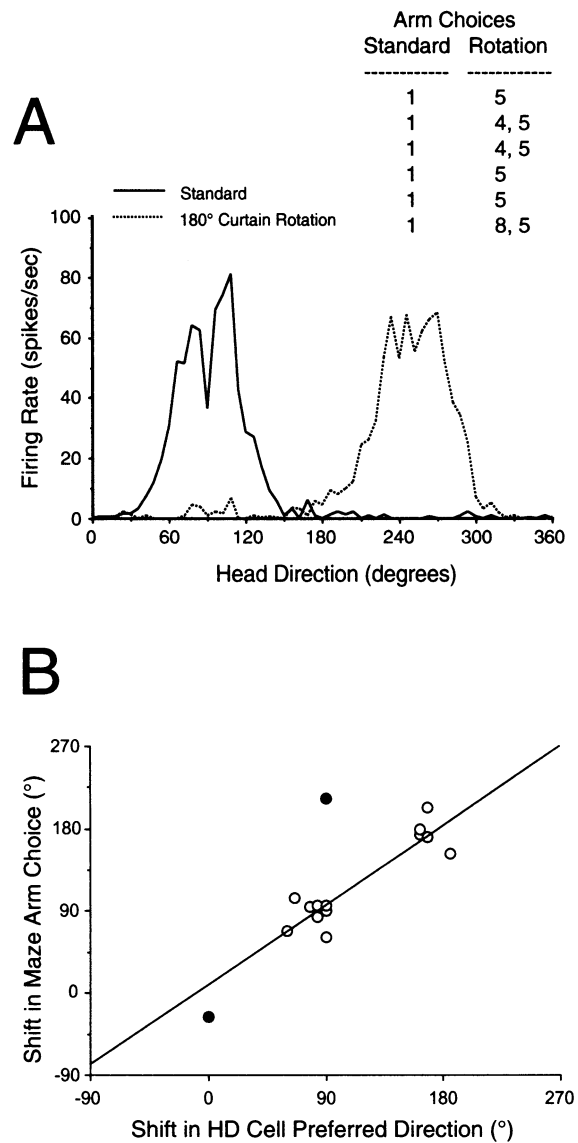


Figure 1: Dudchenko and Taube (1997) Generally Found Concordance Between the Amount of Shift in the Head Direction (HD) Cell's Preferred Firing Direction and the Amount of Shift in Behavior.

SOURCE: Figures reproduced with permission from Dudchenko and Taube (1997).

NOTE: A. The preferred firing direction of this HD cell rotated ≈180° from the standard session (solid line) to the rotation session (dashed line) following a 180° rotation of the cue. Similarly, the behavior of the animal (i.e., arm choice) also typically shifted by 180° from the arm reinforced in the standard session (Arm 1) to the rotationally appropriate arm (Arm 5). B. Correlation between shift in preferred firing direction and shift in arm choice during a session following a cue rotation. With the notable exception of the two filled circles on the plot, both the preferred firing direction of the HD cell and the arm choice usually rotated by a corresponding amount ($r = .816, p < .01$). The two filled circles represent data points from two instances in which an 180° rotation of the curtain was not associated with a corresponding shift in the HD cell's preferred firing direction.

accuracy was not related to stable HD cell activity observed across acquisition, but rather that animals were learning to use the information provided by the HD cell network when making a behavioral choice.

A third finding was the results from one cell where the animal was trained to go to a new arm on the radial maze following completion of the initial cue rotation trials. Despite the change in the location of the reward relative to the cue curtain and a corresponding change in correct maze arm selection, the HD cell's preferred firing direction remained unchanged from that observed during trials for the first reward location. Subsequent rotations of the cue curtain, however, still resulted in corresponding shifts in maze arm selection and in the preferred firing direction of the HD cell. This finding provides evidence that the HD cell's preferred firing direction is not directly related to the location of the reward.

In summary, Dudchenko and Taube (1997) concluded that their data support the hypothesis that "HD cells contribute to a representation of the animal's orientation within its environment which can then be used to guide its spatial behavior" (p. 18). This interpretation is consistent with the notion that HD cells represent the animal's perceived directional heading, but direct evidence that HD cell activity actually guides behavior remains equivocal because it is possible that both the HD cell's activity and the neural systems responsible for the animal's behavior were independently linked to the cue curtain but that they were not necessarily linked or causally related to one another. Thus, the appearance of linkage comes about because they were both responsive to the same stimulus—the cue curtain.

If this notion were true, then we might expect to find instances where HD cell activity may rely on one set of cues (either allothetic or ideothetic) for orientation, whereas the neural systems guiding behavior rely on other cues. This possibility may account for the results observed with the 180° cue curtain rotation in which the HD cell remained in alignment with the cue, but the animal's behavior must have been guided by a different cue because it did not select the 180° rotated maze arm. It is important to note that the procedures used in this study did not necessarily disorient the animal between trials because the animal was carried in an open cage into the recording room, and although placed in an opaque box in one of three locations between trials, the animal was not spun in the box before being returned to the maze. Thus, during training the animal had access to vestibular and optic flow cues as it was carried into the room and to a consistent entry point into the circular enclosure. Previous studies have shown that animals can effectively use the point of entry (POE) as an orienting cue (Hynes, Martin, Harley, Huxter, & Evans, 2000; Sharp, Kubie, &

Muller, 1990). Consequently, the animal may have initially oriented using these POE cues and then maintained its orientation within the curtain by using idiothetic cues when it was in the opaque box between trials. Thus, the animal may not have required the cue curtain for orientation while performing the task. This point may explain their findings when the cue curtain was removed; under these conditions, the animal continued to select the originally correct maze arm, and the HD cell maintained its preferred firing direction with respect to the room (Dudchenko & Taube, 1997, Figure 10).

The fact that the animal may be well oriented with regard to the environment, however, may not necessarily assist it in learning the radial arm maze reference memory task—a task that can be solved by simply learning the association between the cue curtain location and the reward location. It is possible that the animal's direction sense was under the control of the cue curtain from the moment of initial exposure to the maze, but that the animal slowly learned to use the cue to guide its maze arm selection behavior. By this account, both the preferred firing direction of HD cells and the maze arm selection of the animal would appear causally related to the location of the cue curtain following a rotation. Thus, it does not necessarily follow from this result that HD cell activity and maze arm selection are causally related to each other.

Golob, Stackman, Wong, and Taube (2001)

To clarify the issue further, Golob et al. (2001) conducted a series of experiments examining the relationship between ADN HD cell activity and behavior on tasks requiring navigation. In their first experiment, rats were initially trained to perform a reference memory task in a gray square environment that contained a fixed, white cue card against one wall. To perform the task correctly, rats had to go to the corner where a water reward was located relative to the cue card. For each trial, the animals were brought into the circular curtained enclosure and released into the apparatus from one of four start box locations (at the center of each wall) and facing one of the four chamber walls. Each session consisted of 16 such trials in two blocks of 8 trials, with each block preceded by a 4-minute baseline period where the animal could wander the apparatus freely. Following training, ADN HD cells were recorded while animals were tested in a series of sessions: standard, cue rotation, standard, and novel environment sessions. In the cue rotation sessions, both the cue and reward locations were rotated $\pm 90^\circ$ from the standard session and the animals were disoriented prior to entry. In the novel environment sessions, the square environment was replaced with a rectangular one with a cue card in the same location as the

standard session in the square. Changing from a square to a rectangular enclosure will usually induce a shift in the preferred firing direction of a HD cell (Golob & Taube, 1997; Taube et al., 1990b), but it was thought that the animal's ability to generalize what it had learned in the square would allow preserved performance on the task in the rectangle.

Results showed that animals were able to correctly locate the reward on $\approx 77\%$ of standard session trials, and the preferred firing direction of the HD cells showed no change from the baseline period to the standard trials in 77% of trials. In the remaining 23% of trials, the preferred firing direction shifted significantly, and these shifts tended to occur in multiples of approximately 90° . Examination of the data revealed that these shifts tended to occur on the first trial of a block of four following a shift in the start box location and persisted throughout the block until the start box was shifted again. For the cue rotation sessions, animals selected the correct corner 80% of the time, whereas the preferred firing direction of the HD cell between the baseline and rotation sessions was equivalent in only 64.6% of trials—not a particularly overwhelming value for concordance between behavior and cell activity. In the rectangle session, the preferred firing direction of HD cells almost always shifted by multiples of $\approx 90^\circ$ compared to the preferred firing direction in the square session. Despite these shifts between enclosures, the animals' behavior readily generalized to the new rectangular enclosure, with the correct corner chosen on 78% of trials. Thus, although the cue rotation experiments hint at a dissociation between HD cell activity and the animal's behavioral choice, the results from the square-to-rectangle experiment clearly demonstrate a strong dissociation. Finally, Golob et al. (2001) examined the concordance of HD cell activity with the animal's behavioral choice across individual trials in the standard (square) sessions. Results showed that on 22% of trials in which animals chose the correct corner, the HD cell's preferred firing direction shifted between the baseline period and the standard trial. Furthermore, the preferred firing direction of the HD cell was just as likely to be consistent with the behavioral choice on error trials as on correct trials. Similarly, animals performed equally well on the task regardless of whether the HD cell's preferred firing direction was consistent or had shifted between the baseline period and the standard trial. Taken together, the results of Golob et al.'s first experiment clearly fail to show a consistent relationship between HD cell activity and the performance of an animal on a spatial reference memory task.

In a second experiment, Golob et al. (2001) examined rats' performance on a spatial working memory task while simultaneously recording HD cell activity. The

task was similar to a task used by Margules and Gallistel (1988) whereby a rat was first given a sample trial in which it had to find a water reward in one of four corners in a rectangular enclosure that contained a prominent visual cue along one of the short walls. After the sample phase, the animals were removed and placed in an opaque box that was then gently spun to disorient them. They were then reintroduced into the rectangle from one of four entry points and had to go to the corner that was rewarded in the previous sample phase to receive a reward (test phase). Although the animals could easily solve the task by using the prominent visual cue, previous studies have shown that in an appetitive task, rats will ignore the visual cue and rely on the geometric shape of the environment for their orientation (Cheng, 1986; Margules & Gallistel, 1988). This use of geometric shape leads to rotational errors in which rats frequently select the 180° rotationally opposite corner instead of the correct corner. Note that the 180° opposite corner is the geometrically equivalent to the correct corner (e.g., the reward is in the corner with the short wall on the left and long wall on the right). Golob et al. were interested in determining whether the preferred firing direction of HD cells would shift back and forth 180° in correspondence with the corner they selected.

Golob et al. (2001) found that rats performed poorly on the task, choosing the correct corner on only 36% of trials (apparently disregarding the information provided by the cue card) and choosing the rotational (diagonally opposite) corner on 37% of trials. This result supports previous evidence that the geometry of the environment is used as a cue to guide behavior. Recording data showed that the preferred firing direction of HD cells between the sample and test phases were either consistent (i.e., unshifted) (56% of trials), shifted by 180° (25% of trials), or shifted by 90° or 270° (19% of trials). The most important finding, however, was a dissociation between the amount of shift in the preferred firing direction of the HD cell and the corner choice of the animal (see Figure 2). This dissociation was already hinted at by the fact that the preferred firing direction was consistent on 56% of trials, whereas animals only chose the correct corner 36% of the time. Indeed, the amount of shift in the HD cell's preferred firing direction from the sample to test phase only matched the shift in the animal's corner choice on 33% of trials. In addition, animals were equally likely to choose either the correct or rotational (diagonally opposite) corner on trials where the preferred firing direction remained stable between the sample and test phases. The dissociation between behavior and HD cell activity is highlighted by examination of the results in Table 5 of Golob et al. (2001) presented below (see Table 1). This table directly compares how much the preferred firing direction shifted between

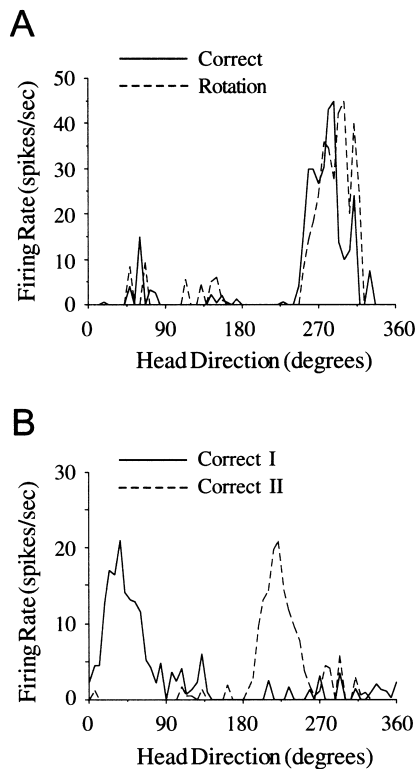


Figure 2: Examples of Discordance Between Preferred Firing Direction Shifts and Behavioral Shifts From Golob, Stackman, Wong, and Taube (2001).

SOURCE: Figure reproduced with permission from Golob et al. (2001).

NOTE: A. No change was observed in the preferred firing direction of this HD cell between trials when the corner choice was correct (solid line) or rotationally correct (dashed line). B. The preferred firing direction of this head direction cell shifted 174° between trials, whereas the animal's corner choice remained correct on both trials.

the sample and test phases and compares it to the animal's behavioral responses. If HD cell activity was routinely guiding behavior on this task, then one would expect most of the data points to fall along the 45° diagonal (from upper left to lower right) in which the preferred directional shift is associated with an equivalent behavioral response (i.e., $0-0^\circ$, $90-90^\circ$, $180-180^\circ$, $270-270^\circ$). However, examination of the table shows that data points fell along this diagonal on only 23 out of 70 trials (32.8% of the time)—a low value that is not indicative of a tight linkage between the two parameters.

Why was the animal's performance so poor on the spatial working memory task in the rectangle compared to performance in the rectangle on the reference memory task? In the reference memory task, as in the task used by Dudchenko and Taube (1997), the cue card location was a stable predictor of the reward location, and animals were able to perform the task well. In the working memory task, however, the location of the

TABLE 1: Preferred Firing Direction Shift (Sample vs. Test Trial) Versus Behavioral Response

Corner choice	Preferred Firing Direction Shift			
	0°	90°	180°	270°
0°	16	3	4	2
90°	2	0	0	1
180°	16	3	6	1
270°	5	2	8	1

SOURCE: Table reproduced with permission from Golob, Stackman, Wong, and Taube (2001).

reward relative to the cue card, although consistent from sample to test phases, differed on every new sample-test trial (a block consisting of two sample-test pairs), and animals therefore had to overcome interference between trials in order to perform well. In addition, the working memory task used procedures that intended to disorient the animal more between trials than in the reference memory task. The disorientation procedures may have made the task more difficult because there was an increased likelihood that information based on external cues (the cue card) was either inconsistent or in conflict with spatial information from idiothetic cues. Although one might argue that the animal should have relied on allothetic cues in this situation (given their higher level of stability), repeated disorientation has been shown to weaken an animal's reliance on the cue card as an orienting cue (Jeffery & O'Keefe, 1999; Knierim et al., 1995; but see also see Dudchenko, Goodridge, & Taube, 1997). Thus, animals may have continued using idiothetic cues or some other cue, such as the geometric shape of the enclosure, to guide their behavior. Consequently, animals would make an incorrect choice. The instability of these spatial relationships may also explain why the preferred firing direction of HD cells in the working memory task appeared to be modulated by the geometric shape of the environment, although independently of the animal's behavioral choice.

Why is there a difference between the findings of Golob et al. (2001) and Dudchenko and Taube (1997) on their spatial reference memory tasks? One contributing factor may be the different use of disorientation in the two procedures. Although Golob et al. did not intentionally disorient the animals between trials during training, the animals may have become somewhat disoriented after being released from four different start box locations throughout the course of a session. In contrast, Dudchenko and Taube did nothing to disorient their animals during training. The repeated disorientation in Golob et al. may have generated an inconsistent relationship between the animal's perceived orientation on

entry into the environment and the location of the allothetic cues, thereby weakening the animals' reliance on the cue card as an orienting cue. In this situation, the animal may have relied on idiothetic cues to orient itself upon entry to the enclosure and then used the shape of the environment, not the cue card, to correct for errors. This notion is consistent with Golob et al.'s finding that the preferred firing direction of the HD cell did not shift in register with rotation of the cue card in 35% of cue rotation sessions. Furthermore, the animal could still have learned to use the cue to guide its corner choice behavior, independent of its perceived orientation within the environment.

Muir and Taube (2001)

A more recent study (Muir & Taube, 2001) has examined whether the information provided by the HD system is used by the animal in guiding behavior when performing a navigational task that requires the use of a cognitive mapping strategy. The firing properties of ADN and PoS HD cells were examined in a navigational task based on Tolman, Ritchie, and Kalish (1946). Following training, animals ran three identical training trials along a maze route to locate a water reward in a fixed location, followed by a fourth ("sunburst") trial in which the normal route to the reward was blocked and a number of novel routes introduced, with one arm being a direct path (shortcut) to the reward's previous location. Animals that were able to use an accurate cognitive map of the environment should have been able to use the novel shortcut route to reach the reward. Results showed that throughout the sunburst trial, the preferred direction of both ADN and PoS HD cells remained stable relative to the training trials and was not related to the accuracy or inaccuracy of the behavioral choice(s) made by the animal. For example, when one animal was exposed to the sunburst maze for the first time and correctly selected the novel shortcut to the rewarded arm, the preferred firing direction of the HD cell did not shift compared to the training trials. Similarly, another animal that made seven errors before selecting the correct arm also showed stable HD cell activity, both compared to the training trials and to the sunburst trial. Although the animals may not have had sufficient experience with the task to perform well, the results clearly show that HD cell activity, at least in the PoS and ADN, remained robust throughout all phases of the task, whether the animal performed well or poorly. This finding stands in contrast to the results reported by Mizumori and Williams (1993), who suggested that HD cells in the LDN developed a more robust directional signal as an animal learned the task. In sum, our data are consistent with those already presented: The animal may know its orientation upon entry into the environment, but this infor-

mation may not necessarily be used to guide the animal's behavior to reach a goal.

Summary: Toward an Account of HD Cell Function and Performance

Given these experimental findings, what can we conclude about the contribution of HD cell activity to navigation? One consistent feature appears to emerge from these studies: The relationship between HD cell activity and behavior is neither a direct nor simple one. We propose that several factors are important in determining the extent to which HD activity and behavior are in register. First, the animal's perceived orientation and its behavior can be independently controlled by cues. Thus, a given cue may control the animal's orientation, its behavior, or both on any given trial. Second, animals will rely, at least initially, on allothetic cues to guide their behavioral choice when the animal has learned that the spatial location of the goal is consistent with regard to the allothetic cues (Arolfo, Nerad, Schenk, & Bures, 1994; Maaswinkel & Whishaw, 1999; Packard, 1999; Packard & McGaugh, 1996; Rossier, Kaminsky, Schenk, & Bures, 2000). Third, if the animal has learned that the spatial information concerning the reward location and the allothetic cues are consistent and has learned that there is a consistent relationship between its perceived orientation on entry to the environment and the location of these allothetic cues, then HD cell activity will likely be in register with the animal's behavioral choice (see Figure 3A). Fourth, if an animal has learned that both of these relationships are stable and then subsequently learns that one of these relationships is unstable, it will attempt to maintain in its internal representation the consistent relationship it has learned between its perceived sense of direction and the location of the reward (see Figure 3B). Maintaining this consistency enables the animal to resolve cue conflict situations and requires the animal to either alter its perceived orientation upon seeing the location of the allothetic cues or alter its behavior to fit with its perceived orientation. In either case, HD activity and behavior in these situations would be in register whether or not the animal relied on the location of the allothetic cues. Finally, following repeated experience with inconsistency between the animal's perceived orientation and the location of the reward, the animal would no longer attempt to maintain this internal consistency (see Figure 3C). In this event, the animal's behavior and orientation would be guided independently by different cues, and it would be in these instances that we would expect to observe a poor correlation between HD cell activity and the animal's behavior. Note that in these cases, the allothetic cues would still most likely guide the animal's behavior because they would consistently predict the location of the reward,

and good performance on the task could still be maintained, but the animal's perceived direction would now be guided by a different set of cues (either allothetic, idiothetic, or POE). In instances in which the allothetic cues did not reliably predict the reward location and there was no consistent relationship between the animal's perceived orientation upon entry into the environment and the location of these allothetic cues, then some other cue (such as the geometric shape of the environment) would most likely guide the animal's behavior and orientation (see Figure 3D). In these cases, we would expect to observe not only no systematic relationship between HD cell activity and behavior but also poor performance on the navigational task.

Taken together, what information is conveyed by the HD cell signal when the animal appears not to use this information to solve navigational tasks? Throughout this review, the activity of HD cells has been postulated to represent the perceived directional heading of the animal, and the data presented here are not inconsistent with this notion. If this view is correct, then it appears that animals do not consistently rely on this sense of direction to guide their behavior on the spatial tasks described above. The HD signal may, however, be used to guide behavior in spatial tasks that can only be solved using the animal's internal sense of direction. It would be profitable for future studies to examine HD cell activity in a navigational task that involves path integration. Such a task would require the animal to rely on idiothetic, as opposed to allothetic, cues to locate a goal.

PLACE CELLS AND PERFORMANCE ON NAVIGATIONAL TASKS

Most studies that initially explored the relationship between place cell activity and behavior involved lesioning specific brain areas. In general, most of these studies showed that performance deteriorated when place cell activity was altered (Cooper & Mizumori, 2001; Leutgeb & Mizumori, 1999; Mizumori, Miya, & Ward, 1994), although not always in a consistent manner (e.g., Mizumori et al., 1994). Aging has also been shown to impair performance on a navigational task and decrease the spatial specificity scores of place cells (Mizumori, Lavoie, & Kalyani, 1996). Unfortunately, close examination of these studies shows that the place cell/performance relationship is not as clear as first appears. For example, Leutgeb and Mizumori (1999) demonstrated that the average number of errors per trial per animal was negatively correlated with the average stability of place cells between trials. It is important to note, however, that the place cell recordings were made after the behavioral data regarding the average number of errors was obtained during the reacquisition

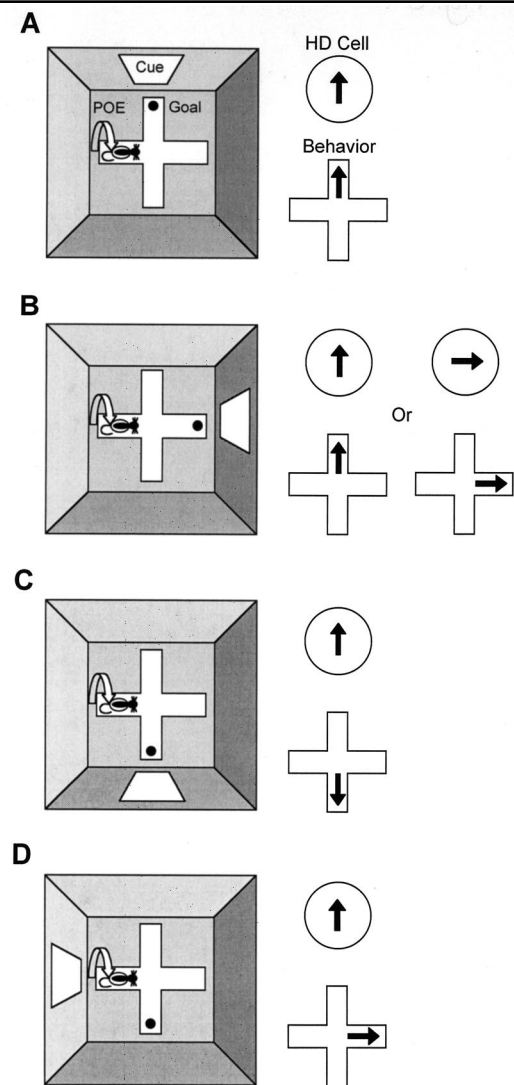


Figure 3: Diagrammatic Examples of Proposed Conditions Under Which the Relationship Between Head Direction (HD) Cell Activity and Navigational Behavior Will Be Consistent or Inconsistent.

NOTE: A. When trained in a situation where there is a stable relationship between its perceived sense of direction on point of entry (POE) to the environment and the allothetic cue(s), and given consistency between the allothetic cues and the reward location (goal), an animal will exhibit HD cell activity in register with its behavior (right panel). For B-D cue card, goal location, POE, HD activity, and behavior symbols are depicted as in A. B. If the animal is subsequently exposed to inconsistencies in either of these learned relationships (e.g., a shift in the location of the cues and goal location), it will attempt to maintain consistency of its internal representation by either altering its behavior to match its perceived orientation (center panel; incorrect choice) or altering its perceived orientation to fit with the location of the cue(s) (right panel). In either case, HD activity and behavior will remain in register, and performance can remain relatively good. C. Repeated exposure to inconsistencies between the animal's perceived orientation and goal location will cause the animal to abandon attempting to maintain the consistency of its internal representation. In this case, HD cell activity and behavior will not be in register, but performance may still be good if the allothetic cue remains an accurate predictor of goal location (right panel). D. If, in addition, the allothetic cue is also a poor predictor of goal location, then we would expect to observe not only no systematic relationship between HD cell activity and behavior but also poor performance on the navigational task (right panel).

phase and after the animals had been retrained to preoperative levels of performance and reacquired the task. Because place cell activity was not recorded during the reacquisition phase when performance was impaired, it is impossible to determine the relationship between place cell activity and performance during the reacquisition phase of the task. In contrast, data recorded during a session when the animals had reacquired the task showed no correlations between any location-dependent measures of place cell activity and working memory errors. Caution is therefore warranted when determining the strength of the place cell/performance relationship based on studies in which cell activity and performance were not monitored simultaneously.

As with HD cells, research conducted on place cells has focused primarily on holding the animals' behavior as constant as possible while characterizing the cells' firing properties in response to experimental manipulations. Such an approach, however, has the drawback that it becomes difficult to examine the relationship between the animal's behavior and place cell activity. Thus, it is necessary to conduct studies that simultaneously examine place cell activity and behavior in tasks requiring navigation. The animal's performance on these tasks can then be related to place cell activity on a trial-by-trial basis. If place cell activity is used to guide the animal's behavior and the location of the place field is representative of the animal's perceived spatial location, then we should observe corresponding shifts in the animal's spatial behavior (and hence performance) with shifts in the location of place fields.

O'Keefe and Speakman (1987)

The first account of a direct relationship between place cell activity and performance in a spatial memory task on a trial-by-trial basis was conducted by O'Keefe and Speakman (1987), who recorded hippocampal place cells while animals ran on a four-arm elevated plus maze. Rats were trained to go to the same rewarded arm, relative to a number of extramaze cues that surrounded the maze (e.g., a light, a fan, a white card). The start arm varied across trials, but the maze remained stationary throughout the experiment. Once the rats were performing this reference memory task well, a number of trials were conducted in which the extramaze cues were removed after the animal had been placed in the start arm for 30 to 120 seconds, before it was allowed into the maze to make its choice. These trials constituted the working memory task. In addition, a number of trials were conducted in which the extramaze cues were removed before the animal was placed in the start arm. Only data from correct trials were presented.

Confirming the findings of O'Keefe and Conway (1978), O'Keefe and Speakman (1987) reported that

the extramaze cues were the main factor in controlling the location of the place fields. Furthermore, static background cues that remained stable with the room throughout the trials (i.e., other uncontrolled cues, such as cues on the surface of the maze or curtain) also exerted some lesser control on place field location. During the working memory task, the location of the place fields in the start arm were usually stable following removal of the extramaze cues. During the control trials in which no cues were present, there was a strong correlation between the location of the place field and the animal's behavioral choice on the maze (see Figure 4). In fact, O'Keefe and Speakman stated that for some units, based on the unit's firing pattern in the start arm, they "were able to reliably predict the rat's choice of goal on these control trials during the experiment itself" (p. 21). This finding suggests that the animal's behavior and place cell activity may similarly reflect the animal's perceived location within the maze. Furthermore, exposure to part of the environment (the start arm) appears sufficient to activate the cognitive map for the entire environment. It is important to note, however, that the relationship between behavior and place cell activity may not be as straightforward as suggested by the authors. For example, in 10% of trials, the arm choice was correct, but the location of the cell's place field showed no correlation between the periods before and after the extramaze cues were removed. In these cases, it is possible that the place fields shifted following removal of the extramaze cues (as appeared to occur in the control trials), but then the animal's behavioral response should also have shifted by a corresponding amount. Thus, even in this study in which task performance is excellent, there is a hint that place cell activity does not always correspond to the animal's behavioral response.

Lenck-Santini, Save, and Poucet (2001a)

Following O'Keefe and Speakman (1987), almost 15 years were to lapse before other studies started to ascertain the relationship between place cell activity and trial-by-trial performance on a navigational task. Lenck-Santini et al. (2001a) recorded the activity of hippocampal place cells during a spatial memory task in a Y-shaped maze. Animals were trained to continuously alternate between the goal arm (which, in the standard session, was always in a consistent location relative to a large, white cue card) and the other two arms of the maze. Thus, accurate performance would be A-G-B-G-A-G-B-G and so forth, with G representing the goal arm and A and B representing the other two nongoal arms. Additional sessions were conducted in which (a) the rat was removed from the maze while the cue card and goal location were rotated clockwise (CW) together by 120°

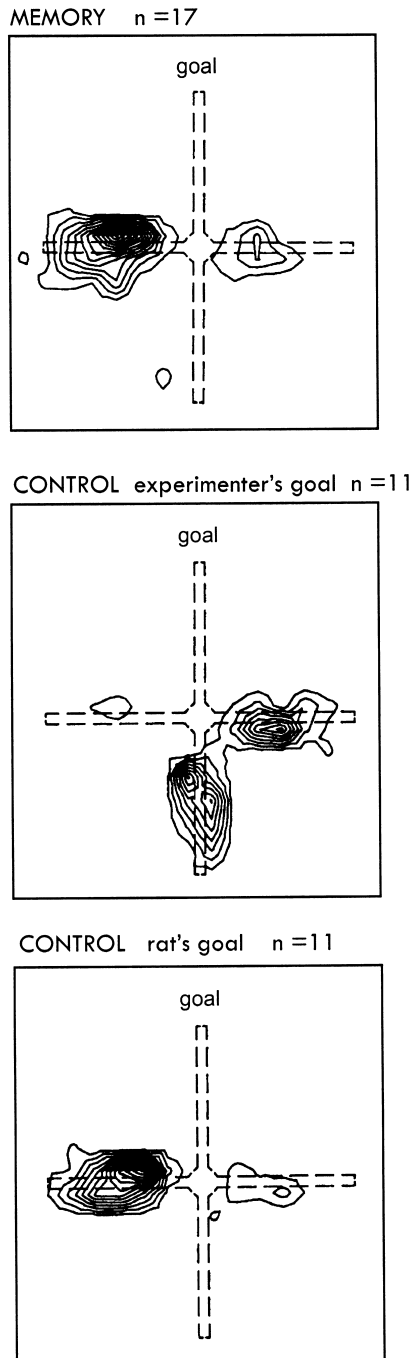


Figure 4: Firing Rate Contour Plots of a Place Cell From O'Keefe and Speakman (1987) Showing a Correspondence Between the Animal's Behavior and the Place Cell's Firing Location.

SOURCE: Figure reproduced with permission from O'Keefe and Speakman (1987).

NOTE: Following removal of the controlled cues surrounding the plus maze, alignment of the place cell's firing such that the goal location was always at the top of the panel (center panel) resulted in cell firing being poorly related to its previous firing location on the maze (top panel). In contrast, alignment of the firing of the cell according to the perceived goal location (as suggested by the animal's behavioral choice; see bottom panel) reinstated the previously observed firing pattern in the maze (bottom panel). Contour step = 1.5 spikes per second.

(card rotation session), (b) the cue card was removed with the animal still in the maze (card removal session), (c) the rat was removed and the entire maze rotated CW by a further 120° with no cue card present (goal rotation session), and (d) the rat was removed, the maze rotated CW by another 120° , thus returning it to its original orientation, and the cue card reinstated to its original location (final standard session). The relationship between place field location and the arm choice of the animal was examined in each of these session types during both correct and error trials.

Consistent with previous findings, rotations of the cue and goal location usually resulted in corresponding shifts in place field location. Of those place fields that did not shift with the cue, the clear majority remained unchanged from the previous standard session. These results suggest that static uncontrolled cues were controlling the location of the place fields and are therefore similar to the findings of O'Keefe and Speakman (1987). Removal of the cue card had no effect on place field location for most cells and the vast majority of place fields in the final standard session returned to the same location as in the initial standard session. In the goal rotation sessions, however, most place fields either returned to the same location as in the standard session (i.e., rotated 120° CCW) or maintained their location compared to the preceding card removal session (i.e., rotated 0° —with both consequences occurring about equally). Only a small proportion of place fields rotated with the goal arm (i.e., 120° CW shift).

Overall, the maze performance of the animals decreased progressively from the standard to the goal rotation sessions but returned almost to its original level in the final standard sessions. Session pairs from two contiguous sessions were categorized as consistent if the place field's location remained constant relative to the goal location from the first (reference) to the second (test) session in a pair or inconsistent if it did not remain constant. For example, a cell with a place field on the goal arm in the card removal session that rotated 120° CCW during the goal rotation session (while the maze itself was rotated 120° CW) would result in an inconsistent session pair. Although this comparison of session types was conducted independent of the specific session types involved, inconsistencies observed in the preceding goal rotation sessions made interpretation of the data from the final standard sessions difficult and these data were not included in their analyses. For inconsistent session pairs, the total number of errors was found to be significantly greater in the test session than in the reference session. For consistent pairs, however, no difference in performance between the reference and test sessions was evident, and performance on both the reference and test sessions was comparable to that

observed during the inconsistent reference sessions. Finally, a comparison of the number of errors made in the two nongoal arms during the test session revealed a strong, but not complete, bias for animals to incorrectly choose the arm consistent with the location of the cell's place field. In addition, if the arm predicted by the place field location was treated as the goal arm, performance was slightly but significantly better for that arm than for the other arm. It would have been interesting, however, to know whether the correspondence between place field location and arm choice pattern was more consistent for particular session types. For example, it may be the case that there was a tighter coupling of place field location and arm choice pattern on trials in which the extramaze cue was absent, as was observed by O'Keefe and Speakman (1987). Taken together, these findings support the notion that the location of the place field represents the animal's perceived location within the maze and its perception of the goal arm location. In general, the location of the place field was usually reflected in the pattern of the rat's arm choices, and performance declined during trials in which the place field location was not consistent with the goal arm location. These findings are consistent with the notion that animals do use the information encoded by place cells to guide their behavioral choices.

Huxter, Thorpe, Martin, and Harley (2001)

To determine the effects of using a fixed or variable POE into an environment on performance and place cell activity, Huxter et al. (2001) recorded hippocampal place cells from animals trained to find a baited corner of a box. The box was located within a white curtained area that had a large black cue attached to one side of the curtain, and the baited (correct) corner was always in the same location relative to the room. Animals received training either with entry through the curtain at only one point (fixed POE) or at multiple points (random POE). Following training, animals were given probe trials in which (a) the POE alone was rotated to one of the three other entry points, (b) the cue alone was rotated by 90°, 180°, or 270°, (c) the POE and cue were both rotated by a corresponding amount, (d) the animals were not allowed to view the room outside the curtain and were disoriented by rotation en route to the maze, and (e) the animals were disoriented and the cue rotated. Only animals trained with a fixed POE experienced probes involving rotation of the POE (i.e., POE rotation and POE + cue rotation). In these probe trials, the correct corner was always stable with respect to the room, the rotationally correct corner was the corner where the goal location should have been given the location of the cue or POE, and the incorrect corners were

the two remaining choices. Within a session, one probe trial was conducted along with seven control trials where the location of the POE and cue were the same as during training.

In contrast to their earlier findings (Hynes et al., 2000), Huxter et al. (2001) showed that animals in the random POE group were not impaired at learning the task relative to the fixed POE group. Furthermore, the combination of disorientation and cue rotation was the only probe trial manipulation that led to a decrease in the animal's performance and an increase in the number of rotationally correct errors compared to control trials. This result occurred regardless of whether the training POE was fixed or random. Thus, the animals appeared to rely more on the cue card to guide their corner choice following disorientation but used alternative cues (e.g., idiothetic) when they were not disoriented.

A number of probe trials, preceded by a baseline session, were conducted during the recording of place cells from three animals: two of whom had learned the task well (one trained with a random POE, the other with a fixed POE) and one animal that had not learned the task well (trained with a random POE). Results from the two learners showed an inconsistent relationship between the location of the place field and the animal's corner choice in the baseline, cue rotation, disorientation, and disorientation + cue rotation trials, but complete correspondence in the disorientation + no cue trials (whereby the animal was disoriented and the cue removed). Overall, for the learners, the location of the place field corresponded to the corner choice in 73% of trials (see Figure 5). With regard to behavior, the place field corresponded to the corner choice on 27 of 28 correct trials, 5 of 6 trials when the corner choice followed the cue, and only 6 of 18 trials when animals made incorrect responses. No consistent relationship was observed for the nonlearner animal between corner choice behavior and place field location, with the place field location usually remaining stable with respect to the room while the corner choice varied. Consistent with the behavioral data showing that POE was not the cue guiding the animal's corner choice, place field locations in the two random POE animals (one learner, one nonlearner) were also not dependent on the POE. The possibility remains, however, that as the animal entered the maze, place field locations were dependent on the animal's perceived sense of direction without being dependent on the POE. Thus, animals would have maintained their sense of direction by path integration as they were transported from the holding box, through the curtain, and into the maze. In this case, shifts in place field locations would only occur on trials where the animals were unable to maintain a stable sense of direction because of disorientation prior to maze entry—the disorientation would in

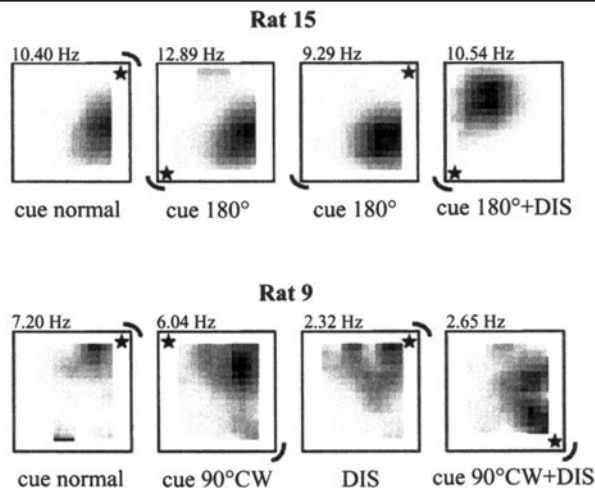


Figure 5: Firing Rate Maps of Place Cells From Huxter, Thorpe, Martin, and Harley (2001) Show Evidence That the Animal's Behavior and Place Cell's Firing Location Are Sometimes Not Related.

SOURCE: Figure reproduced with permission from Huxter et al. (2001).

NOTE: Each firing rate map from the two learners shows a recording trial, and firing rates are illustrated as a gray-scale percentage of the peak firing rate for that cell (indicated at the top of each rate map), with black representing the maximum firing rate (100%). The crescent represents the position of the cue panel, and the star indicates the rat's initial choice on each trial. The first panel of each row represents the baseline position for the place field and cue panel, and the corner choice corresponds to the correct choice for that animal. Place fields from both rats are often unaltered following cue rotation or disorientation (DIS) alone (Rat 15: middle panels, Rat 9: left middle panel) but rotate with the cue when the rat is also disoriented (Rats 9 and 15: right panels). Importantly, the behavioral response for both rats is often inconsistent with place field position. CW = clockwise.

turn necessitate a reorientation based on other available cues (e.g., the cue card, the geometric shape of the environment). Consistent with this notion, place field locations were based on POE cues on 30 of 33 trials that did not involve disorientation but only on 6 of 19 trials when animals were disoriented.

In sum, Huxter et al.'s (2001) findings showed that although there was often a correspondence between place field location and corner choice behavior, there was not perfect agreement. One interesting similarity between these findings and those of O'Keefe and Speakman (1987) was that in conditions where no extramaze cues were present, there was complete concordance between place field location and choice location, although performance accuracy was low. This finding suggests that allothetic and idiothetic cues can be independently used to control the perceived orientation and/or the animal's behavioral choice. Moreover, when the allothetic cues that the animal had previously relied on to guide choice behavior or perceived orientation are no longer available, the animal may be forced to rely on the same cue(s) to guide both its orientation and choice

behavior. This notion is consistent with their findings that disorientation was more likely to increase the animal's reliance on the cue card for its behavioral choice. In addition, subsequent removal of the cue following disorientation would likely force the animal to find another cue (e.g., idiothetic) to use in guiding its choice behavior, and this cue may already be used by the animal to orient itself. Although animals in the O'Keefe and Speakman study were not disoriented, the strong tendency for both choice behavior and place field location to follow rotation of the allothetic cues suggests that the animals considered those cues important to the task and perhaps used them for both orienting and guiding choice behavior. Removal of the allothetic cues would therefore force the animal to rely on another cue (e.g., idiothetic) to guide both parameters. In either case, poor performance results from requiring the animal to rely on a cue that was previously unused to guide its choice behavior. One implication of this view is that complete correspondence between the place field location and behavioral choice might be predicted only when animals rely on a single cue (e.g., idiothetic) to guide both its choice behavior and orientation, a notion similar to that mentioned earlier in the discussion of HD cells.

Jeffery, Gilbert, Burton, and Strudwick (in press)

Further evidence to suggest that the relationship between place cell activity and performance is not a simple one has been shown by Jeffery et al. (in press), who found preserved performance on a reference memory navigational task despite the remapping of hippocampal place cells. Rats were trained to go to the same corner of a square chamber (relative to the room cues) and lift a flap for food reward, the availability of which was signaled by a tone that was triggered when the animal entered a randomly selected region of the chamber. Animals were not disoriented prior to each trial. Manipulating the intramaze cues by changing the color of the walls and floor of a square chamber while leaving the extramaze cues and goal location intact led to a small decrease in performance (see Figure 6A) but a large change in the firing activity of most place cells. Place cells either ceased firing or shifted their place field locations, a response consistent with the animal having perceived the altered chamber as a novel environment (see Figure 6B). Performance was not preserved, however, after relocating the chamber to a new room containing different extramaze cues and retraining the rats to a new goal location.

Data illustrating individual trial paths show that rats sometimes approached an incorrect corner prior to choosing the correct one (see Figure 6B). In two of the eight trials depicted in the familiar (black) chamber, the

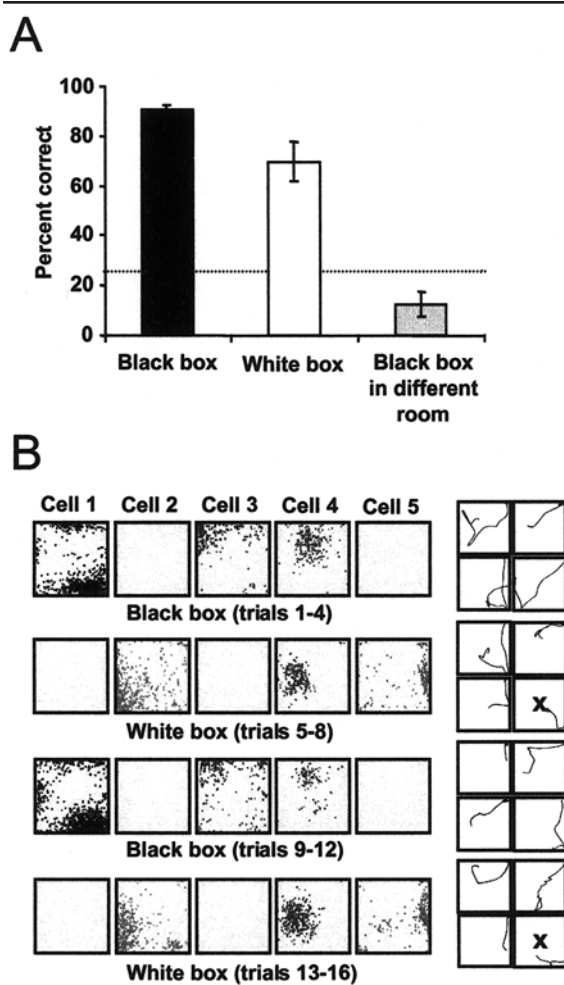


Figure 6: Jeffery, Gilbert, Burton, and Strudwick (2002) Showed That Performance on a Spatial Task Could Be Preserved Despite Place Cell Remapping.

SOURCE: Figures reproduced with permission from Jeffery et al. (2002).

NOTE: A. Mean (\pm SEM) performance accuracy in the black box (black bar) and white box (white bar). Whereas performance decreased from the black to white box, performance in the white box remained greater than chance (dotted line) and considerably better than in the black box in a different room (gray bar). B. Raw data from five place cells simultaneously recorded in alternating black and white box sessions (left) and individual trial paths of the animal during each session (right). Small squares indicate the location of the animal at the time a spike occurred. Note that cells that are active in the black box are either silent or shifted in the white box, and vice versa, indicating that remapping has taken place. The goal corner was the top right (southwest) corner of each box. The animal made no errors during the black box sessions and only one error in each of the white box sessions (indicated by a cross).

animal initially appeared to go to the incorrect northwest corner before choosing the correct southwest corner. Similarly, of the eight trials shown in the altered (white) chamber, the animal went once to the northwest corner before correctly choosing the southwest corner, and on the two occasions when the animals made errors, they were both to the northwest corner. These results

suggest that different cues were competing for control of corner choice behavior in both chambers and that the cue that was given more weight by the animal ultimately controlled the corner choice. It is important to note that even on the trials when the animals appeared indecisive in their choices and possibly required reorientation, place field locations remained stable throughout the entire trial. As no data were presented comparing the location of place fields on correct and error trials within a single environment, the possibility remains that the place cells may still have been responding in a manner consistent with the animal's navigational behavior in these two situations.

Previous studies have suggested that each place cell represents a specific location within the environment and that these locations are more or less evenly distributed over the environment (although there is a tendency for more place fields to be present adjacent to walls) (Hetherington & Shapiro, 1997). The location of some place fields would therefore correspond to the location of the reward. If the animal is using the location of these place fields to signal the reward location and to guide the animal's behavior to the reward, then performance should become random immediately following remapping of the environment, because the place cells signaling the reward location are now firing somewhere else or have ceased firing. So why was performance not impaired following remapping in the altered chamber? It is possible, of course, that the animals were not using the place cell information to guide their behavior on this task. Alternatively, the animals may have relearned the new relationship between place field locations and reward location very quickly, such that performance was disrupted only briefly. The authors attempt to discount this possibility by showing that animals did not relearn the task quickly when given a new reward location in the familiar chamber in a new room with different extramaze cues. Nonetheless, there is a considerable difference between the animal's ability to rely on previous experience to quickly relearn the task in the familiar chamber in the new room compared to learning the task in the altered chamber in the old room. Thus, we cannot totally rule out the possibility that rapid relearning of the relationships between place cell representation, extramaze cues, and goal location may have occurred over the first few trials in the white box; consequently, the place cells may still have been guiding behavior.

In summary, Jeffery et al.'s (in press) results unequivocally demonstrate that the intramaze cues controlled place cell activity, whereas the animal's behavioral responses must have relied (at least initially) on other cues (the authors argue that extramaze cues are responsible, but path integration could also have been used). Importantly, it was possible to manipulate place field

location independently of the animal's behavioral responses, suggesting that the two parameters are not always necessarily linked. These results are analogous to those of Golob et al. (2001) discussed earlier, who showed that changing the shape of the environment from a square to a rectangle usually resulted in a shift in the preferred firing direction of HD cells with no change in performance on the navigational task.

Lenck-Santini, Muller, Save, and Poucet (submitted)

Lenck-Santini et al. (submitted) examined the relationship between place field location and performance in rats trained to go to a goal zone in a cylinder to obtain a food reward. The animal's performance was monitored following 90° rotations of a cue card attached to the inside wall of the cylinder while the animal was either outside (hidden rotation) or still within the cylinder (visible rotation). In addition, the goal zone was either (a) far from the cue card and unmarked (far condition), (b) directly in front of the cue card and unmarked (near condition), or (c) marked by a black disk on the chamber floor (cue condition). The location of the goal zone was rotated equally along with the cue card in the far and near conditions, but in the cue condition the disk marking the goal zone did not rotate in alignment with the cue card. Hidden rotations of the cue card resulted in a corresponding rotation of the place field location in the vast majority of far and near sessions, but significantly fewer corresponding rotations were seen in the cue sessions. In contrast, and consistent with previous research (Rotenberg & Muller, 1997), visible cue card rotations usually failed to control place field location under all three conditions.

Importantly, performance in the far condition was generally preserved in trials when the place fields rotated consistently with the cue card regardless of whether the card rotations were hidden or visible. In contrast, performance declined significantly in trials in which the place field location was inconsistent with the cue card rotation, with animals usually searching for the goal in a region relative to the location of the place field rather than the cue card. In a notable exception, one animal maintained high performance accuracy during sessions when there was a dissimilar amount of rotation between the cue card and place field location. This animal continued to search for the goal zone relative to the cue card despite the information that was being conveyed by place cells. This dissociation between behavior and place cell activity indicates that this animal was using the cue card to determine its spatial behavior, but some other cue (perhaps idiothetic) was simultaneously determining the orientation of the place field representation.

Performance in the near condition remained relatively high whether or not place fields shifted a similar amount as the cue card rotation. Although these animals preserved their performance by mainly searching for the goal in a region relative to the cue card, they also searched a region relative to the field location more than a neutral area, suggesting that both strategies were influencing search behavior. Similarly, there was little relationship between place field/cue card consistency with respect to rotation and the performance accuracy of the animals in the cue condition.

Taken together, animals in the far condition relied strongly on the orientation of their place field representation to determine where they would search for the goal. In contrast, the near and cue condition results are consistent with the notion that animals were able to use the cue card or black disk as beacons and successfully use these cues to guide their behavior independently of the concurrent place cell representation.

Summary: Place Cells and Performance

What information are place cells signaling, and how is this information being used to guide the animal's behavior in a navigational task? The place cell studies described above all share one feature in common: an imperfect correspondence between the location of the place field and the behavioral choice of the animal while performing a navigational task. The assumption that the location of the place field within an unchanged environment is determined by the perceived orientation of the animal is still consistent with the results of these studies if, as we have noted earlier for HD cells, behavior and place field location can be independently controlled by different cues but under certain conditions are controlled by the same cue(s). If these processes were not independent and the animal's perceived orientation always controlled the location of place fields, then the behavioral choice of the animal would always remain in register with the location of the place fields. This situation did not occur. Close examination of the place cell studies described above indicates that each study contains data that to some degree supports this notion. Indeed, the existence of data showing that place field location and behavioral choice were not always in register was hinted at in an early study by O'Keefe and Conway (1978). They presented one example of an incorrect trial (see Figure 3F of O'Keefe & Conway, 1978) where, if the maze was rotated such that the correct goal arm was superimposed on the arm the rat incorrectly entered (presumably based on its perceived orientation and where it believed the reward to be located), the place cell did not fire where it should have on the maze.

To be able to use the location of place fields to guide behavior, an animal must first learn the relationship between specific locations and the representation of the environment contained in the activity of place cells. Thus, the cognitive map could never be used to guide behavior during the initial trials of a task, when animals were still learning these relationships. Because place field locations are usually stable in an unchanged environment for weeks (Thompson & Best, 1990), a recording demonstration showing that place fields are stable while animals are learning a spatial memory task would provide evidence that the cognitive map is not being used to guide behavior, at least until the map's relationship with other cues has been firmly established. The results discussed earlier from HD cells recorded during acquisition of a spatial memory task demonstrate such a dissociation (Dudchenko & Taube, 1997), but this relationship remains to be shown for place cells.

Place cells fire differently in different environments, suggesting they are critically involved in representing these environments as being different. Consequently, the locations of place cell place fields appear to reflect the environment that the animal perceives itself to be in. Does the location of the place field also reflect the orientation of the cognitive map (i.e., the animal's perceived orientation of the environment)? This notion is the implicit assumption underlying most of the studies described above and, if valid, means that place field locations should remain constant when the same task is repeatedly performed in an unchanged environment. However, two recent studies (Frank, Brown, & Wilson, 2000; Wood, Dudchenko, Robitsek, & Eichenbaum, 2000) have demonstrated that an animal's prior experience can alter the location of place fields under just these conditions. Both studies used continuous spatial alternation tasks and found that place cell activity in the part of the maze common to both leftward and rightward trials was different depending on where the animal had come from or where it was going. Unfortunately, neither study explicitly compared place cell activity during correct and incorrect trials. It is important to note that these studies differed from the ones discussed above in that the reward location varied depending on the previous trial. Because place cells can alter their locational firing characteristics with changes in task demand (Markus et al., 1995), it is plausible that in the spatial alternation task the animal may have treated the individual trials as components of different tasks, each associated with a different reward location. Although a subsequent study has failed to replicate the findings of Wood et al. (2000) in a Y-shaped maze (Lenck-Santini, Save, & Poucet, 2001b), these results still suggest that hippocampal place cells are encoding more than just the location of the animal within its environment. These data alone, however, do

not preclude the possibility that place cells may guide the spatial behavior of the animal but rather suggest a more complex relationship is present.

Finally, it is possible that the information provided by the place cell system may not be required for successful navigation in some circumstances, depending on the spatial demands of the task. For example, in conditions in which the animal can navigate to the goal by using a beaconlike cue, spatial performance can be preserved independently of changes in place cell activity (Lenck-Santini et al., 2002). In these cases, we would not expect to observe concordance between shifts in place cell activity and behavior.

HEAD DIRECTION, PLACE CELLS, AND PERFORMANCE ON A NAVIGATIONAL TASK

Very few studies have simultaneously recorded HD and place cells, and of those studies which have, only one recent study has examined the relationship between cell firing and behavior on a navigational task, although trial-by-trial data were not presented.

Ragozzino, Leutgeb, and Mizumori (2001)

Ragozzino et al. (2001) simultaneously recorded HD cells from the dorsal striatum and hippocampal place cells while rats performed the same spatial working memory radial-arm maze task as described for Mizumori and Williams (1993). In addition to the standard version of the task, a number of environmental manipulations were conducted: (a) The lights were turned off while animals were on the maze, (b) the lights were turned off and the maze rotated before the animals entered the maze, (c) the extramaze cues were rotated 180° prior to maze entry, (d) animals performed the same task in a novel room with novel extramaze cues, and (e) the familiar environment was altered either by allowing access to additional extramaze cues or by rearranging the familiar extramaze cues. Overall, Ragozzino et al. (2001) reported no significant correlation between hippocampal place field specificity or reliability and performance on the task. In contrast, a significant negative correlation was found between the directional specificity of HD cells and the number of errors, similar to the earlier findings of Mizumori and Williams (1993). Unfortunately, no data regarding the relationship between HD cell and place cell activity and performance were presented on a trial-by-trial basis. It is important to note that Dudchenko and Taube (1997) and Golob et al. (2001) both failed to observe the systematic relationship between the directional specificity of HD cells and the animal's performance reported by Ragozzino et al. and Mizumori and

Williams. Although counter to current conceptions, this difference may be a consequence of different properties of HD cells across different brain regions or the specific tasks used in these studies.

Simultaneously recorded HD and place cells did not always change in register in response to the various manipulations mentioned above. In particular, cue or maze rotations, which generated cue conflicts between the expected extramaze and intramaze cues, and exposure to a novel environment tended to evoke different responses for HD and place cells within the same recorded session. In contrast, HD and place cells usually responded similarly to changes in illumination or alterations of the familiar environment. Furthermore, no relationship was observed between performance and HD and place cell activity, independent of whether cells responded similarly or dissimilarly. Although these results appear to stand in contrast to those of Knierim et al. (1995), the two studies recorded HD cells from different brain regions (ADN vs. dorsal striatum) and employed different manipulations (disorientation vs. various cue manipulations). Thus, the two studies may not be directly comparable.

CONCLUSIONS AND CAVEATS

We have suggested that much of the data supports the notion that different cues may be simultaneously used by the animal to guide different aspects of navigation—in particular, the animal's perceived orientation and its behavioral response. These aspects may also be supported by different kinds of cues (e.g., allothetic vs. idiothetic) depending on their availability and salience. For example, results showing that lesions of the vestibular apparatus abolish the directional specificity of HD cells in the ADN, PoS, and location-specific place cell activity in the hippocampus (Stackman, Clark, & Taube, 2002; Stackman & Taube, 1997) provide evidence that idiothetic input is critical for enabling the generation of both directional heading and place codes and may therefore play an important role in guiding spatial behavior. Alternatively, brain systems beyond the HD and place cell systems (e.g., motivational or reinforcement systems) (Mizumori, Cooper, Leutgeb, & Pratt, 2000) may be responsible for guiding spatial behavior, although these alternative systems would still presumably receive information from HD and place cells. In addition, it may still be possible for one set of cues to guide both neuronal activity and spatial behavior if inconsistencies between them were the result of computational errors in other brain systems involved.

It is also noteworthy that most of the tasks used in the experiments described here, although spatial, have contained relatively low navigational demands. For exam-

ple, rats trained to go to the corner of a box for a reward have been trained to go to a specific spatial location, and therefore, it is a spatial associational task. This type of associational task may not require considerable processing in terms of navigation. The activity of HD and place cells may be less important for navigation during these relatively simple associational tasks, and if so, little relationship between neuronal activity and the behavior of the animal might be expected in these cases. Employing spatial tasks with increased navigational demands may reveal a tighter coupling of neuronal activity and behavior.

A better understanding of the precise information HD and place cells are encoding is required before we can begin to determine how that information can be used by the animal during navigation. Given our relatively poor understanding of what HD and place cells are encoding at a deeper level, it is extremely difficult to know if our expectations regarding the behavioral outcomes of experimental manipulations are realistic. For example, Zinyuk, Kubik, Kaminsky, Fenton, & Bures (2000) showed that two separate reference frames could simultaneously control place cell activity during a place-preference navigational task. This finding raises the possibility that a manipulation of one reference frame (e.g., the extramaze cues) may still leave the place cell under the control of cues from another reference frame. In such cases, changes in place cell activity would therefore not be expected to simply mirror the manipulation, and it would be difficult to predict the resulting spatial behavior of the animal. Similarly, findings showing that simultaneously recorded place cells do not always respond to environmental changes in the same way (i.e., partial remapping) (Knierim & McNaughton, 2001; Shapiro, Tanila, & Eichenbaum, 1997; Skaggs & McNaughton, 1998) and that place cells can sometimes exhibit activity related to the spatial location of a start box or goal (Breese, Hampson, & Deadwyler, 1989; Gothard, Skaggs, & McNaughton, 1996; Gothard, Skaggs, Moore, & McNaughton, 1996; Gothard, Hoffman, Battaglia, & McNaughton, 2001; Hollup, Molden, Donnett, Moser, & Moser, 2001; but see Speakman & O'Keefe, 1990) suggest that we might not always expect to see simple geometric transformations of the cognitive map following certain environmental manipulations. Future studies that determine what HD and place cells are encoding by examining the dynamic changes in HD and/or place cell activity within a trial while simultaneously monitoring behavior will provide a more solid base from which to explore the role of these systems in navigation and behavior.

In summary, the studies that have examined the relationship between HD and place cell activity and performance on a navigational task have shown that the link

between the two is not as straightforward as initially thought and that the presence or absence of a link will depend on several variables, including the nature of the task, available cues, and the response strategies employed by the animal. The historical approach we have taken in this review has, we hope, highlighted the encouraging observation that there has been a recent and long overdue increase in interest in this area. Although it seems reasonable that the information from cells that signal the directional heading and location of the animal would somehow be used in performing a spatial task, to date this underlying notion has only been an assumption. Cautionary tales against such assumptions come from many quarters within neuroscience, where neuronal correlates of behaviors have been observed in brain regions that have subsequently been shown to be unimportant in performing those very same tasks (e.g., hippocampal neurons and delay eye-blink conditioning) (Berger, Rinaldi, Weisz, & Thompson, 1983; Kim, Clark, & Thompson, 1995). In the future, it will be essential that such assumptions be critically tested so that we can move closer toward our goal of better understanding the role of the HD and place cell systems in the neurobiology of spatial cognition and navigation.

REFERENCES

- Aggleton, J. P., Hunt, P. R., Nagle, S., & Neave, N. (1996). The effects of selective lesions within the anterior thalamic nuclei on spatial memory in the rat. *Behavioral Brain Research, 81*, 189-198.
- Arolfo, M. P., Nerad, L., Schenk, F., & Bures, J. (1994). Absence of snapshot memory of the target view interferes with place navigation learning by rats in the water maze. *Behavioral Neuroscience, 108*, 308-316.
- Berger, T. W., Rinaldi, P. C., Weisz, D. J., & Thompson, R. F. (1983). Single-unit analysis of different hippocampal cell types during classical conditioning of rabbit nictitating membrane response. *Journal of Neurophysiology, 50*, 197-219.
- Best, P. J., White, A. M., & Minai, A. (2001). Spatial processing in the brain: The activity of hippocampal place cells. *Annual Review of Neuroscience, 24*, 459-486.
- Blair, H. T., & Sharp, P. E. (1996). Visual and vestibular influences on head-direction cells in the anterior thalamus of the rat. *Behavioral Neuroscience, 110*, 643-660.
- Bostock, E., Muller, R. U., & Kubie, J. L. (1991). Experience-dependent modifications of hippocampal place cell firing. *Hippocampus, 1*, 193-205.
- Breese, C. R., Hampson, R. E., & Deadwyler, S. A. (1989). Hippocampal place cells: Stereotypy and plasticity. *Journal of Neuroscience, 9*, 1097-1111.
- Calton, J. L., Stackman, R. W., Goodridge, J. P., Archey, W. B., Dudchenko, P. A., & Taube, J. S. *Hippocampal place cell instability following lesions of the head direction cell network*. Manuscript submitted for publication.
- Chen, L. L., Lin, L. H., Green, E. J., Barnes, C. A., & McNaughton, B. L. (1994). Head-direction cells in the rat posterior cortex. I. Anatomical distribution and behavioral modulation. *Experimental Brain Research, 101*, 8-23.
- Cheng, K. (1986). A purely geometric module in the rat's spatial representation. *Cognition, 23*, 149-178.
- Cooper, B. G., & Mizumori, S. J. Y. (2001). Temporary inactivation of the retrosplenial cortex causes a transient reorganization of spatial coding in the hippocampus. *Journal of Neuroscience, 21*, 3986-4001.
- Dudchenko, P. A., Goodridge, J. P., & Taube, J. S. (1997). The effects of disorientation on visual landmark control of head direction cell orientation. *Experimental Brain Research, 115*, 375-380.
- Dudchenko, P. A., & Taube, J. S. (1997). Correlation between head direction cell activity and spatial behavior on a radial arm maze. *Behavioral Neuroscience, 111*, 3-19.
- Eichenbaum, H., Dudchenko, P., Wood, E., Shapiro, M., & Tanila, H. (1999). The hippocampus, memory, and place cells: Is it spatial memory or a memory space? *Neuron, 23*, 209-226.
- Frank, L. M., Brown, E. N., & Wilson, M. (2000). Trajectory encoding in the hippocampus and entorhinal cortex. *Neuron, 27*, 169-178.
- Golob, E. J., Stackman, R. W., Wong, A. C., & Taube, J. S. (2001). On the behavioral significance of head direction cells: neural and behavioral dynamics during spatial memory tasks. *Behavioral Neuroscience, 115*, 285-304.
- Golob, E. J., & Taube, J. S. (1997). Head direction cells and episodic spatial information in rats without a hippocampus. *Proceedings of the National Academy of Sciences, 94*, 7645-7650.
- Goodridge, J. P., Dudchenko, P. A., Worboys, K. A., Golob, E. J., & Taube, J. S. (1998). Cue control and head direction cells. *Behavioral Neuroscience, 112*, 749-761.
- Goodridge, J. P., & Taube, J. S. (1995). Preferential use of the landmark navigational system by head direction cells in rats. *Behavioral Neuroscience, 109*, 49-61.
- Gothard, K. M., Hoffman, K. L., Battaglia, F. P., & McNaughton, B. L. (2001). Dentate gyrus and CA1 ensemble activity during spatial reference frame shifts in the presence and absence of visual input. *Journal of Neuroscience, 21*, 7284-7292.
- Gothard, K. M., Skaggs, W. E., & McNaughton, B. L. (1996). Dynamics of mismatch correction in the hippocampal ensemble code for space: Interaction between path integration and environmental cues. *Journal of Neuroscience, 16*, 8027-8040.
- Gothard, K. M., Skaggs, W. E., Moore, K. M., & McNaughton, B. L. (1996). Binding of hippocampal CA1 neural activity to multiple reference frames in a landmark-based navigation task. *Journal of Neuroscience, 16*, 823-835.
- Hetherington, P. A., & Shapiro, M. L. (1997). Hippocampal place fields are altered by the removal of single visual cues in a distance-dependent manner. *Behavioral Neuroscience, 111*, 20-34.
- Hollup, S. A., Molden, S., Donnett, J. G., Moser, M. -B., & Moser, E. I. (2001). Accumulation of hippocampal place fields at the goal location in an annular watermaze task. *Journal of Neuroscience, 21*, 1635-1644.
- Huxter, J. R., Thorpe, C. M., Martin, G. M., & Harley, C. W. (2001). Spatial problem solving and hippocampal place cell firing in rats: Control by an internal sense of direction carried across environments. *Behavioral Brain Research, 123*, 37-48.
- Hynes, C. A., Martin, G. M., Harley, C. W., Huxter, J. R., & Evans, J. H. (2000). Multiple points of entry into a circular enclosure prevent place learning despite normal vestibular orientation and cue arrays: Evidence for map resetting. *Journal of Experimental Psychology: Animal Behavior Processes, 26*, 64-73.
- Jarrard, L. E. (1993). On the role of the hippocampus in learning and memory in the rat. *Behavioral & Neural Biology, 60*, 9-26.
- Jeffery, K. J., Gilbert, A., Burton, S., & Strudwick, A. (in press). Preserved performance in a hippocampal dependent spatial task despite complete place cell remapping. *Hippocampus*.
- Jeffery, K. J., & O'Keefe, J. M. (1999). Learned interaction of visual and idiothetic cues in the control of place field orientation. *Experimental Brain Research, 127*, 151-161.
- Kim, J. J., Clark, R. E., & Thompson, R. F. (1995). Hippocampectomy impairs the memory of recently, but not remotely, acquired trace eyeblink conditioned responses. *Behavioral Neuroscience, 109*, 195-203.
- Knierim, J. J., Kudrimoti, H. S., & McNaughton, B. L. (1995). Place cells, head direction cells and the learning of landmark stability. *Journal of Neuroscience, 15*, 1648-1659.

- Knierim, J. J., & McNaughton, B. L. (2001). Hippocampal place-cell firing during movement in three-dimensional space. *Journal of Neurophysiology*, *85*, 105-116.
- Lenck-Santini, P.-P., Save, E., & Poucet, B. (2001a). Evidence for a relationship between place-cell spatial firing and spatial memory performance. *Hippocampus*, *11*, 377-390.
- Lenck-Santini, P.-P., Muller, R. U., Save, E., & Poucet, B. (in press). *Relationships between place cell firing fields and navigational decisions by rats*. Manuscript submitted for publication.
- Lenck-Santini, P.-P., Save, E., & Poucet, B. (2001b). Place cell firing does not depend on the direction of turn in a Y-maze alternation task. *European Journal of Neuroscience*, *13*, 1055-1058.
- Leutgeb, S., & Mizumori, S. J. Y. (1999). Excitotoxic septal lesions result in spatial memory deficits and altered flexibility of hippocampal single-unit representations. *Journal of Neuroscience*, *19*, 6661-6672.
- Lohmann, K. J., & Johnsen, S. (2000). The neurobiology of magnetoreception in vertebrate animals. *TINS*, *23*, 153-159.
- Maaswinkel, H., & Whishaw, I. Q. (1999). Homing with locale, taxon, and dead reckoning strategies by foraging rats: Sensory hierarchy in spatial navigation. *Behavioral Brain Research*, *99*, 143-152.
- Margules, J., & Gallistel, C. R. (1988). Heading in the rat: Determination by environmental shape. *Animal Learning Behavior*, *16*, 404-410.
- Markus, E. J., Barnes, C. A., McNaughton, B. L., Gladden, V. L., & Skaggs, W. E. (1994). Spatial information content and reliability of hippocampal CA1 neurons: Effects of visual input. *Hippocampus*, *4*, 410-421.
- Markus, E. J., Qin, Y. L., Leonard, B., Skaggs, W. E., McNaughton, B. L., & Barnes, C. A. (1995). Interactions between location and task affect the spatial and directional firing of hippocampal neurons. *Journal of Neuroscience*, *15*, 7079-7094.
- McNaughton, B. L., Chen, L. L., & Markus, E. J. (1991). "Dead reckoning," landmark learning, and sense of direction: A neurophysiological and computational hypothesis. *Journal of Comparative Neuroscience*, *3*, 190-202.
- Mizumori, S. J. Y., Cooper, B. G., Leutgeb, S., & Pratt, W. E. (2000). A neural systems analysis of adaptive navigation. *Molecular Neurobiology*, *21*, 57-82.
- Mizumori, S. J. Y., Lavoie, A. M., & Kalyani, A. (1996). Redistribution of spatial representation in the hippocampus of aged rats performing a spatial memory task. *Behavioral Neuroscience*, *110*, 1006-1016.
- Mizumori, S. J. Y., Miya, D. Y., & Ward, K. E. (1994). Reversible inactivation of the lateral dorsal thalamus disrupts hippocampal place representation and impairs spatial learning. *Brain Research*, *644*, 168-174.
- Mizumori, S. J. Y., & Williams, J. D. (1993). Directionally selective mnemonic properties of neurons in the lateral dorsal nucleus of the thalamus of rats. *Journal of Neuroscience*, *13*, 4015-4028.
- Muir, G. M., & Taube, J. S. (2001). Who's reading the cognitive map? Head direction cell activity and behavior in a spatial navigation task. *Society for Neuroscience Abstracts*, *27*, 953.1.
- Muller, R. (1996). A quarter of a century of place cells. *Neuron*, *17*, 813-822.
- Muller, R. U., & Kubie, J. L. (1987). The effects of changes in the environment on the spatial firing of hippocampal complex-spike cells. *Journal of Neuroscience*, *7*, 1951-1968.
- Muller, R. U., Kubie, J. L., & Ranck, J. B., Jr. (1987). Spatial firing patterns of hippocampal complex-spike cells in a fixed environment. *Journal of Neuroscience*, *7*, 1935-1950.
- Némec, P., Altmann, J., Marhold, S., Burda, H., & Oelschläger, H. H. A. (2001). Neuroanatomy of magnetoreception: The superior colliculus involved in magnetic orientation in a mammal. *Science*, *294*, 366-368.
- O'Keefe, J., & Conway, D. H. (1978). Hippocampal place units in the freely moving rat: Why they fire where they fire. *Experimental Brain Research*, *31*, 573-590.
- O'Keefe, J., & Dostrovsky, J. (1971). The hippocampus as a spatial map. Preliminary evidence from unit activity in the freely-moving rat. *Brain Research*, *34*, 171-175.
- O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map*. Oxford, UK: Clarendon Press.
- O'Keefe, J., & Speakman, J. (1987). Single unit activity in the rat hippocampus during a spatial memory task. *Experimental Brain Research*, *68*, 1-27.
- Packard, M. G. (1999). Glutamate infused posttraining into the hippocampus or caudate-putamen differentially strengthens place and response learning. *Proceedings of the National Academy of Sciences*, *96*, 12881-12886.
- Packard, M. G., & McGaugh, J. L. (1996). Inactivation of hippocampus or caudate nucleus with lidocaine differentially affects expression of place and response learning. *Neurobiology of Learning and Memory*, *65*, 65-72.
- Quirk, G. J., Muller, R. U., & Kubie, J. L. (1990). The firing of hippocampal place cells in the dark depends on the rat's recent experience. *Journal of Neuroscience*, *10*, 2008-2017.
- Quirk, G. J., Muller, R. U., Kubie, J. L., & Ranck, J. B., Jr. (1992). The positional firing properties of medial entorhinal neurons: Description and comparison with hippocampal place cells. *Journal of Neuroscience*, *12*, 1945-1963.
- Ragozzino, K. E., Leutgeb, S., & Mizumori, S. J. Y. (2001). Dorsal striatal head direction and hippocampal place representations during spatial navigation. *Experimental Brain Research*, *139*, 372-376.
- Redish, A. D. (1999). *Beyond the cognitive map: From place cells to episodic memory*. Cambridge, MA: MIT Press.
- Redish, A. D., Elga, A. N., & Touretzky, D. S. (1996). A coupled attractor model of the rodent head direction system. *Network: Computation in Neural Systems*, *7*, 671-685.
- Rossier, J., Kaminsky, Y., Schenk, F., & Bures, J. (2000). The place preference task: A new tool for studying the relation between behavior and place cell activity in rats. *Behavioral Neuroscience*, *114*, 273-284.
- Rotenberg, A., & Muller, R. U. (1997). Variable place-cell coupling to a continuously viewed stimulus: Evidence that the hippocampus acts as a perceptual system. *Philosophical Transactions of the Royal Society of London: Series B, Biological Sciences*, *352*, 1505-1513.
- Shapiro, M. L., Tanila, H., & Eichenbaum, H. (1997). Cues that hippocampal place cells encode: Dynamic and hierarchical representation of local and distal stimuli. *Hippocampus*, *7*, 624-642.
- Sharp, P. E., Blair, H. T., & Brown, M. (1996). Neural network modeling of the hippocampal formation spatial signals and their possible role in navigation: A modular approach. *Hippocampus*, *6*, 720-734.
- Sharp, P. E., Blair, H. T., & Cho, J. (2001). The anatomical and computational basis of the rat head-direction cell signal. *TINS*, *24*, 289-294.
- Sharp, P. E., Kubie, J. L., & Muller, R. U. (1990). Firing properties of hippocampal neurons in a visually symmetrical environment: Contributions of multiple sensory cues and mnemonic processes. *Journal of Neuroscience*, *10*, 3093-3105.
- Skaggs, W. E., & McNaughton, B. L. (1998). Spatial firing properties of hippocampal CA1 populations in an environment containing two visually identical regions. *Journal of Neuroscience*, *18*, 8455-8466.
- Speakman, A., & O'Keefe, J. (1990). Hippocampal complex spike cells do not change their place fields if the goal is moved within a cue controlled environment. *European Journal of Neuroscience*, *2*, 544-555.
- Stackman, R. W., Clark, A. S., & Taube, J. S. (2002). Hippocampal spatial representations require vestibular input. *Hippocampus*, *12*, 291-303.
- Stackman, R. W., & Taube, J. S. (1997). Firing properties of head direction cells in the rat anterior thalamic nucleus: Dependence on vestibular input. *Journal of Neuroscience*, *17*, 4349-4358.
- Stackman, R. W., & Taube, J. S. (1998). Firing properties of rat lateral mammillary single units: Head direction, head pitch, and angular head velocity. *Journal of Neuroscience*, *18*, 9020-9037.
- Steven, M. S., & Taube, J. S. (2002). Head direction cell discharge during periods of disorientation. Program No. 584.3. *2002 Abstract Viewer/Itinerary Planner*. Washington, DC: Society for Neuroscience.
- Taube, J. S. (1995). Head direction cells recorded in the anterior thalamic nuclei of freely moving rats. *Journal of Neuroscience*, *15*, 70-86.

- Taube, J. S. (1998). Head direction cells and the neurophysiological basis for a sense of direction. *Progress in Neurobiology*, *55*, 225-256.
- Taube, J. S., Kesslak, J. P., & Cotman, C. W. (1992). Lesions of the rat postsubiculum impair performance on spatial tasks. *Behavioral & Neural Biology*, *57*, 131-143.
- Taube, J. S., Muller, R. U., & Ranck, J. B., Jr. (1990a). Head-direction cells recorded from the postsubiculum in freely moving rats. I. Description and quantitative analysis. *Journal of Neuroscience*, *10*, 420-435.
- Taube, J. S., Muller, R. U., & Ranck, J. B., Jr. (1990b). Head-direction cells recorded from the postsubiculum in freely moving rats. II. Effects of environmental manipulations. *Journal of Neuroscience*, *10*, 436-447.
- Thompson, L. T., & Best, P. J. (1990). Long-term stability of the place-field activity of single units recorded from the dorsal hippocampus of freely behaving rats. *Brain Research*, *509*, 299-308.
- Tolman, E. C., Ritchie, B. F., & Kalish, D. (1946). Studies in spatial learning: I. Orientation and the short-cut. *Journal of Experimental Psychology*, *36*, 13-24.
- Wiener, S. I. (1993). Spatial and behavioral correlates of striatal neurons in rats performing a self-initiated navigation task. *Journal of Neuroscience*, *13*, 3802-3817.
- Wiener, S. I. (1996). Spatial, behavioral and sensory correlates of hippocampal CA1 complex spike cell activity: Implications for information processing functions. *Progress in Neurobiology*, *49*, 335-361.
- Wilson, M. A., & McNaughton, B. L. (1993). Dynamics of the hippocampal ensemble code for space. *Science*, *261*, 1055-1058.
- Wood, E. R., Dudchenko, P. A., Robitsek, R. J., & Eichenbaum, H. (2000). Hippocampal neurons encode information about different types of memory episodes occurring in the same location. *Neuron*, *27*, 623-633.
- Zhang, K. (1996). Representation of spatial orientation by the intrinsic dynamics of the head-direction cell ensemble: a theory. *Journal of Neuroscience*, *16*, 2112-2126.
- Zinyuk, L., Kubik, S., Kaminsky, Y., Fenton, A. A., & Bures, J. (2000). Understanding hippocampal activity by using purposeful behavior: Place navigation induces place cell discharge in both task-relevant and task-irrelevant spatial reference frames. *Proceedings of the National Academy of Sciences*, *97*, 3771-3776.