
Neuronal Implementation of Hippocampal-Mediated Spatial Behavior: A Comparative Evolutionary Perspective

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The hippocampal formation (HF) of mammals and birds plays a strikingly similar role in the representation of space. This evolutionarily conserved property, however, belies the contrasting spatial ecology of animals such as rats and homing pigeons, differing spatial ecologies that should have promoted the evolution of group-specific adaptations to the HF representation of space. However, the spatial response properties of pigeon and rat HF neurons reveal surprising similarity in the contribution of position, direction, and trajectory toward explaining spatial variation in firing rate. By contrast, the asymmetrical distribution of neuronal response properties in the left and right HF of homing pigeons, but not rats, indicates a difference in network organization. The authors propose that hippocampal evolution may be characterized by inertia with respect to changes in the basic spatial elements that determine the response properties of neurons but considerable plasticity in how the neuronal response elements are organized into functional networks.

Key Words: grid cells, place cells, animal navigation, hippocampus

The evolution of nerve cells and their organization into nervous systems can be traced to the selective advantage of detecting a range of environmental stimuli coupled with eliciting relatively simple but adaptive behavioral-motor responses. From this modest beginning, nervous systems have evolved increasingly complex organizations, with the vertebrate forebrain serving as a dramatic example. A notable example of behavioral complexity supported by the brain of both mammals and birds is memory-based, maplike navigation among goal locations and the representation of space as a defining feature of episodic memory, that is, the “where” in the “what, when, and where” that would characterize an episodic memory. The mammalian and

avian hippocampal formation (HF)—in mammals composed of the hippocampus proper, dentate gyrus, subiculum, presubiculum, parasubiculum, postsubiculum, and entorhinal cortex (together with additional limbic regions)—is generally viewed as a collection of brain structures necessary for the operation of this spatial behavior-cognitive system. By comparing the spatial response properties of HF neurons in rats and homing pigeons, it is the intent of this review to explore how viewing HF organization as an evolutionary adaptation to the spatial ecology of an animal group can lead to a better understanding of the relationship between HF-dependent spatial cognition and spatial representations as implemented at the HF neuronal level.

One common functional feature of modern mammals, birds, and reptiles is an HF that generally participates in the representation of space. As such, the hippocampal formation that we see in extant vertebrate groups is an ancient brain structure, a feature of the brain of vertebrates that roamed the earth more than 300 million years ago before the evolution of birds and mammals. There is also some evidence of a hippocampal-like structure in modern teleost fish (Rodriguez et al., 2002). If confirmed, this would suggest the presence of a hippocampal-like structure dating back to the first vertebrates. The crucial point is that the HF of modern

Authors' Note: This work was supported by the National Science Foundation Grant IBN-0075891 (V.P.B.) and National Institutes of Health Grants R01 NS35191 and R01 MH66460 (P.E.S.). Thanks to Mark Gerdeman, Kate Koester, and Shawnda Turner-Williams for help in data collection and analysis.

Behavioral and Cognitive Neuroscience Reviews

Volume 5 Number 2, June 2006 80-91

DOI: 10.1177/1534582306289578

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mammals and birds are separated by about 300 million years of independent evolution. It is therefore remarkable that despite this “evolutionary distance,” the hippocampal formation of modern mammals and birds plays a remarkably similar role in the representation of space. Perhaps the best illustrative example of this similarity is a comparison of the rats studied in the laboratory by Eichenbaum, Stewart, and Morris (1990) and the homing pigeons studied in the field by Gagliardo, Ioalé, and Bingman (1999). In both studies, control and HF lesioned animals were trained on a task in which alternative spatial representational strategies could be used to navigate to a goal location: a routelike strategy based on the association of the goal direction with fixed orientation response to a landmark(s) and a maplike strategy based on learning the spatial relationship among landmarks distributed in space and using that relational representation to navigate to the goal. During probe tests, it was revealed that in both rats and pigeons, the maplike strategy was abolished by HF lesion, whereas the routelike strategy was spared.

The first-order functional similarity in the representation of space in rats and homing pigeons cited above, however, belies a crucial adaptive contrast. (We will assume for the current discussion that the laboratory rat and homing pigeon can serve as prototypical mammalian and avian species, respectively. However, by embracing an adaptationist perspective [Healy, de Kort, & Clayton, 2005] and acknowledging the potency of natural selection in shaping brain-behavior relations in response to spatial ecology, we are obligated to admit that one should be cautious about generalizing our rat-homing pigeon contrast to other avian-mammalian comparisons; rats are very different from chimpanzees, and homing pigeons are very different from penguins.) The natural history of the Norway rat, and its inbred derivative the laboratory rat, is characterized by nocturnal activity, locomotion along well-defined environmental corridors, and a robust sense of smell. By contrast, the natural history of the Mediterranean rock dove, and its artificially selected derivative the homing pigeon, is characterized by diurnal activity, open-field flight of considerable range, and a robust sense of vision. It is almost axiomatic, even if one acknowledges some constraint on the range of adaptive of change, that during the millions of years of independent evolution, the HF system of the rat would have been shaped to participate in the representation of space suited to its particular spatial ecology, whereas the HF system of the homing pigeon would reflect its spatial ecology.

In our view, it is in the spatial response properties of HF neurons where the evolutionary pressure for adaptive specialization will be most apparent. As such, a comparison of the spatial response properties of rat

and homing pigeon HF neurons could reveal much about the evolutionary plasticity of HF organization. We begin with a review of the spatial response properties of HF cells in the rat, where these signals have been studied most intensively. We then follow with a review of what is known, so far, about spatial cells in the homing pigeon, offering comments on the similarities and differences between the two species.

SPATIAL RESPONSE PROPERTIES OF HF NEURONS IN FREELY MOVING RATS

Since the initial discovery of place cells in the hippocampus proper (O’Keefe, 1976; O’Keefe & Dostrovsky, 1971), cells with salient spatial response properties have subsequently been discovered throughout the HF. Indeed, spatial cells have been discovered in many extrahippocampal regions as well, and in fact, it appears that much of the rat limbic system and striatum may play a role in spatial signaling (see Sharp, 2002, for review).

In general, there are two forms of spatial correlates for cells in the rat HF. These are (a) location and (b) directional heading. Within each of these categories, there are variations in how the location and/or directional correlates are manifest, and many cells combine these two signals. Each subdivision within the rat HF appears to have a somewhat specialized (characteristic) set of place and/or directional cell types. These findings are reviewed briefly below.

Location-Related (Place) Signals in the Rat HF

Open-field recordings. Cells that fire in relation to a rat’s momentary position (location) in space are found nearly ubiquitously throughout the rat HF. However, as mentioned above, each subdivision within the HF has its own variant of this spatial signal.

Figure 1A shows the spatial-firing rate map for a classic hippocampal place cell recorded from the dorsal hippocampus (layer CA1). An overhead view is shown of the cylindrical chamber in which the rat foraged for food pellets throughout a 40-min recording session. The center map shows the firing rate as a function of the rat’s location for all samples throughout the session. Each of the maps in the circular array surrounding this show the data from a selected set of samples in which the rat happened to be facing in the direction indicated by the accompanying arrow. As can be seen, this cell showed a single region of high firing within the cylinder and was nearly silent in all other areas. From the array of direction-specific maps, it can be seen that the cell fired whenever the rat occupied this region, regardless of which direction it was facing. This direction-independent, location-specific firing field is typical for

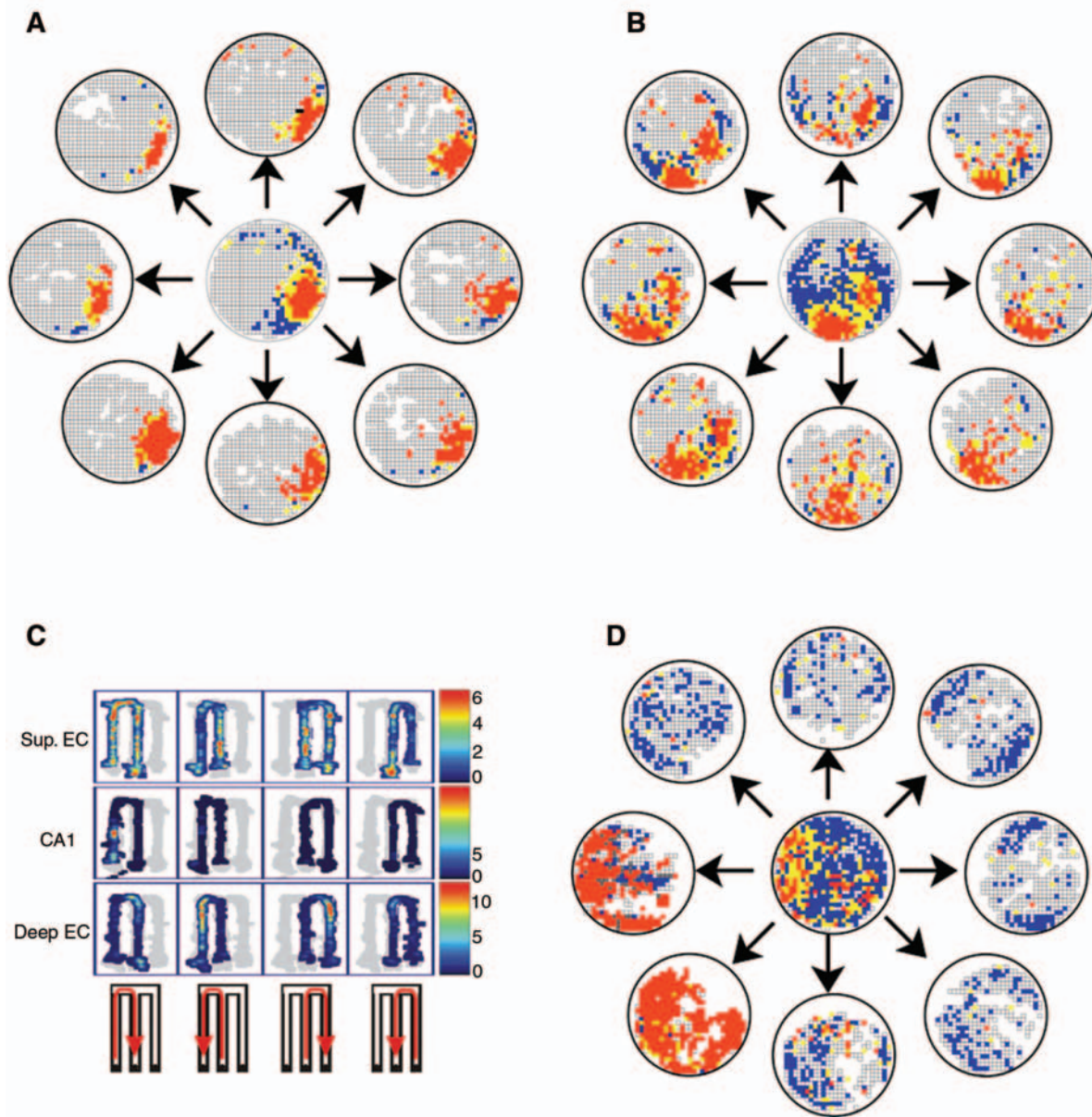


Figure 1: Spatial Firing Properties for Various Cell Types in the Rat Hippocampal Formation.

NOTE: (A) Example of a typical place cell recorded from the rat dorsal hippocampus. The central circle shows an overhead view of the cylindrical enclosure in which the rat continuously foraged for food throughout a 40-min recording session. The floor is divided into a series of 2.9×2.9 cm pixels, and the relative firing rate for each pixel is indicated using a color scale in which hotter colors indicate higher rates. White pixels are those that the rat visited but in which the cell never fired an action potential. The circular array of firing rate maps shows the same data as the center map but divided into samples taken when the rat was facing in each of eight directional bins, as indicated by the accompanying arrows. (B) Example of a typical place X direction cell recorded from the rat dorsal subiculum. Firing rate maps as in A. (C) Examples of trajectory-specific firing patterns recorded from cells in the superficial entorhinal cortex (EC), CA1 layer of the dorsal hippocampus, and deep layer of the EC. See text for an explanation of the behavioral task. (D) Example of a typical head direction cell recorded from the rat postsubiculum. Firing rate maps as in A.

SOURCE: Figure 1C is reprinted from *Neuron*, Volume 27, Frank, L. M., Brown, E. N., and Wilson, M., "Trajectory encoding in the hippocampus and entorhinal cortex," pp. 169-178, 2000, with permission from Elsevier.

dorsal hippocampal cells when recorded in the open field (Muller, Bostock, Taube, & Kubie, 1994).

Place-related signals in other parts of the HF tend to show larger firing fields than those in the dorsal hippocampus, and they often have more than one region of

relatively high firing (Hargreaves, Rao, Lee, & Knierim, 2005; Jung & McNaughton, 1993; Quirk, Muller, Kubie, & Ranck, 1992; Sharp & Green, 1994; Taube, 1995). Also, cells in the subicular complex are often influenced by the directional heading of the rat, in addition to location

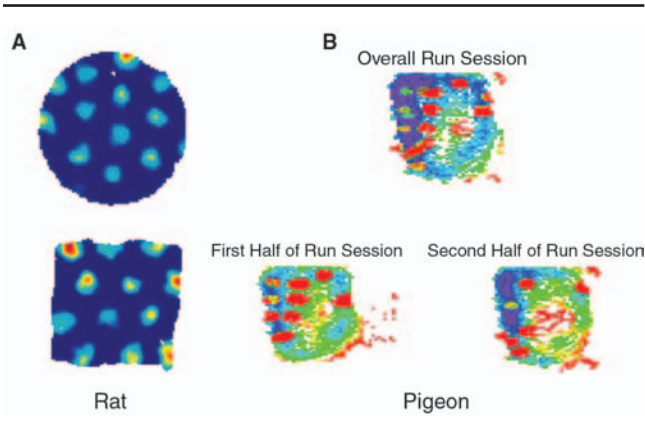


Figure 2: Rate Maps of a Rat Hippocampal Formation (HF) Grid Cell (A) and Pigeon HF Gridlike Cell (B).

NOTE: (A) Circular and square arena. (B) Overall rate map and separate rate maps for the first and second half of the recording session. Faster firing rates are associated with red/yellow and lighter blue; slower firing rates are represented by dark blue (rat) and purple/blue/green (pigeon). Note that in both rat and pigeon, regular, discrete patches of higher firing rate appear to form a gridlike pattern.

SOURCE: Figures courtesy of Edvard Moser (rat) and Meghan Kahn (pigeon).

(Cacucci, Lever, Wills, Burgess, & O'Keefe, 2004; Sharp, 1996; Sharp & Green, 1994; Taube, 1995). An example of this is shown in Figure 1B, which illustrates data from a cell recorded in the subiculum. Here, it can be seen that the cell was active over an area that covered approximately 60% of the cylinder. Within that region, there were two reliable "hot spots." In addition, firing rates across the firing field were modulated by the directional heading of the rat. Specifically, the cell fired at higher rates when the rat faced toward the southwest, as compared to the northeast.

Linear tracks. Interestingly, when rat HF cells are recorded in environments with structured, linear routes, such as the plus maze, eight-arm maze, or linear track, a somewhat different set of location-related properties emerges.

First, although the cells fire in a location-specific pattern, as described above, this place-specific activity is often also dependent on the particular trajectory taken through that place. This is true even for dorsal hippocampal cells, which typically show little or no directional modulation in the open field, as depicted in Figure 1A. For example, on a plus or eight-arm maze, a cell may fire only when the rat goes outward but not inward on a particular arm, or vice versa (e.g., McNaughton, Barnes, & O'Keefe, 1983; Muller et al., 1994). An example of this type of trajectory-specific pattern is provided in a recent study of cells in the entorhinal cortex and the hippocampal CA1 layer (Frank, Brown, & Wilson, 2000). In this

study, rats were trained to perform an alternation task on the W-shaped track depicted in Figure 1C. In this task, the rat was started in the center arm and then ran out to find a food reward at the end of either the left or right outer arm. Then, the rat returned to the center for another reward. Next, the rat would again leave the center arm, but this time it must choose the opposite outer arm to obtain reward. Thus, the well-trained rat went from center to left, to center to right, to center to left, and so on. Many cells in each region showed location-specific firing, but as shown in Figure 1C, the location-specific firing occurred only during the inward or outward trajectory through that region.

In addition, several studies have now demonstrated that this type of trajectory-specific firing can be additionally dependent on the rat's recent past or future route (Ferbinteanu & Shapiro, 2003; Frank et al., 2000; Wood, Dudchenko, Robitsek, & Eichenbaum, 2000). For example, in the paradigm depicted in Figure 1C, a substantial portion of cells showed retrospective coding when traveling inward on the center arm so that they were active when traveling toward the center goal but, for example, only in cases when they had just come from the left outer arm. Similarly, some cells showed prospective coding so that they fired only when the rat was traveling outward on the center arm and was about to turn into, for example, the right outer arm. Note that the authors were careful to rule out the possibility that these results could be explained by details such as slight positional or directional differences between the two types of trial. Results such as these suggest that the cells are involved in planning future spatial trajectories and/or recalling recently experienced trajectories.

Finally, many of the entorhinal (but not hippocampal) cells recorded in this paradigm also showed "path equivalence" properties, so that, for example, a given cell may fire whenever the rat makes a left turn toward a goal, regardless of which loop of the W it is on (Frank et al., 2000).

Grid cells. Recent work in the medial entorhinal cortex has revealed a very exciting, novel type of location-related signal (Fyhn, Molden, Witter, Moser, & Moser, 2004; Hafting, Fyhn, Molden, Moser, & Moser, 2005). These cells have the remarkable property that they show a series of evenly spaced place fields that form a gridlike pattern that extends throughout the recording environment. An example of this cell type (kindly supplied by E. I. Moser) is shown in Figure 2A. This gridlike structure can also be observed when the same cells are recorded on linear tracks, so that an individual maze arm will have a series of evenly spaced fields.

A mapping study of the medial entorhinal cortex has shown that the spacing and field size for the individual

patches vary systematically across the extent of this region. Also, the cells are organized into clusters in which the cells within that local group show rotational alignment of their grid patterns (Hafting et al., 2005).

Head Direction Cells

An example of a classic head direction cell (Ranck, 1984; Taube, Muller, & Ranck, 1990) is depicted in Figure 1D. The defining characteristic of these cells is that they fire uniformly throughout the recording environment but do so only when the rat is facing in one particular direction (over a range of about 90°). Each head direction cell has its own directional preference, so that the entire 360° range of possible headings is uniformly represented.

These cells were initially discovered in the postsubicular region of the HF (Ranck, 1984; Taube et al., 1990) and have since been discovered in a limited portion of the hippocampus, as well (Leutgeb, Ragozzino, & Mizumori, 2000). In addition, they have been documented in a number of extrahippocampal regions, including the anterior thalamus, lateral mammillary bodies, retrosplenial cortex, medial precentral nucleus, and striatum (for review, see Sharp, Blair, & Cho, 2001).

Note that the graded directional modulation of the subicular place cells (depicted in Figure 1B) is somewhat reminiscent of the directional signal shown by head direction cells (Figure 1D). It is generally assumed that the directionality shown by the former cell type is likely imparted by these head direction cells, which are in a position to provide either direct or indirect input to most other cells in the subicular and entorhinal regions. In anticipation of the discussion of spatial response properties of homing pigeon HF neurons, it should be noted that head direction cells of the type described here for rat have yet to be observed in the homing pigeon HF.

Stimulus Control of Location and Head Direction Firing Patterns

There has been a tremendous effort, across several laboratories, to determine the sensory and computational basis for the locational and directional signals reviewed above. The majority of this work related to location signals has been conducted on place cells in the hippocampus (see Knierim, 2002; Muller, Poucet, & Rivard, 2002, for review), whereas that for directional signals has been conducted on head direction cells in the postsubicular region of the HF, as well as the anterior thalamus (see Taube, 2002, for review). However, qualitatively similar results have been obtained in those few cases in which cells in other HF regions have been examined (e.g., Hafting et al., 2005; Sharp & Green; 1994).

In general, the firing patterns of both the place (location-related) and head direction cells are thought to be controlled by two basic influences. These are (a) environmental landmarks and (b) a path integration (dead reckoning) process.

Evidence for control by environmental landmarks comes from studies in which environmental stimuli are shifted in their position, to see whether this affects the position and/or directional preference of the cell under study. For this, cells are typically recorded in a circular environment equipped with a set of visually salient, experimenter-controlled distal stimuli placed around the perimeter. Great effort is made to minimize any uncontrolled background cues. During probe sessions, the position of the experimental cues is rotated, so that they are all, for example, 90° clockwise from their standard location. The cue rotations are conducted between sessions, when the animal is out of the room. Under these circumstances, rotation of the controlled cues will almost always result in an equal angular rotation of the position (for place cells) or directional preference (for head direction cells) of the spatial firing pattern.

Evidence for a path integration process in these spatial signals comes from studies in which cells are recorded in an environment in which either (a) all known environmental orienting cues (landmarks) have been removed, (b) salient environmental cues are present but are arranged in a repeating, symmetric pattern (e.g., vertical stripes) so that they are ambiguous with regard to absolute direction and position, or (c) salient environmental landmarks are rotated in the presence of the animal, so that the “world” appears to rotate in a manner not congruent with the animal’s own locomotor pattern. In each of these cases, the positional/directional pattern will be determined, at least in part, by the initial start position of the animal (either upon arrival into the environment or at the start of the cue rotation). Thus, it appears that they are part of a path integration network that is initialized by the animal’s start position and then updated based on the animal’s subsequent trajectory (path) through the space (for theoretical treatments of these issues, see McNaughton et al., 1996; Samsonovich & McNaughton, 1997; Skaggs, Knierim, Kudrimoti, & McNaughton, 1995).

Many studies of this kind are designed to be “confusing” for the spatial system, so that different types of cues are pitted against one another. For example, sometimes subsets of previously stable environmental landmarks are counterrotated in relation to one another (i.e., half the stimuli rotate clockwise, whereas the other half rotate counterclockwise). Or, in other cases, the environmental cues as a whole are pitted against the dead reckoning system (e.g., the rat is introduced into the arena from a different start position than the one

TABLE 1: Comparison of the Spatial Firing Properties, as Well as Overall Firing Rate, for Hippocampal Complex Spike Cells Recorded in Each Hemisphere of Rats

	<i>Left Hemisphere</i>		<i>Right Hemisphere</i>	
	M	SE	M	SE
Spatial coherence	0.64	0.02	0.65	0.05
Reliability	0.35	0.03	0.37	0.03
Information/spike	1.46	0.10	1.35	0.15
Firings rate (spikes/s)	1.43	0.17	1.66	0.30

used for all previous sessions). Under these confusing conditions, the hippocampal place cells can show a variety of responses. Often, they retain a place field similar in size, shape, and distance from a wall as in previous sessions but in a rotational position that is in alignment with either one particular cue set or with the start position. In other cases, however, the cell may stop firing entirely or may generate a completely novel firing field (different in shape, size, and eccentricity).

When head direction cells are tested under these confusing conditions, in contrast, they will always continue to fire in a direction-specific pattern, just as before the manipulation (i.e., they never stop being head direction cells). However, they are similar to the place cells in that, for any one such probe trial, they may rotate so that they maintain their standard relationship to either the environmental cues or the start position.

Spatial Signals in the Rat Show No Evidence of Hemispheric Lateralization

As reviewed below, spatial signals recorded from the pigeon hippocampal region show evidence for some degree of specialization in terms of the types of signals found in the HF of each hemisphere. As far as we are aware, there have been no data that suggest any lateralization of spatial signals in the rat.

To test for this possibility, we have examined data from a set of hippocampal cells recently recorded in the context of a separate study (P. Sharp & K. Koester, unpublished observations). In this study, 7 rats were implanted with recording electrodes in each of the right and left hippocampi. To date, data have been collected from a total of 78 complex spike cells (these are the cells thought to be the excitatory projection cells that exhibit the place cell properties) in the left hemisphere and 19 complex spike cells in the right hemisphere. (We are uncertain as to why we have happened to collect data from so relatively few cells on the right. One possibility has to do with the fact that our visual display of the recording channels places the left hemisphere channels above those on the right. This may create a bias in the

experimenter to examine these channels first on each recording day, and this may, in turn, increase the probability of seeing cells in this hemisphere.) We have used several of the most common measures of location-related firing to test for possible hemispheric differences. Specifically, we have used (a) spatial coherence, which is a spatial autocorrelation designed to test the strength of the correlation between firing rates in neighboring pixels; (b) reliability, which consists of a cross-correlation of the spatial firing patterns from the first half versus the last half of each session; and (c) location information (in bits) per spike. In addition, we have examined overall firing rate. These results are shown in Table 1. It is clear that this data set yields no evidence of any hemispheric differences in the hippocampal place cell signal.

SPATIAL RESPONSE PROPERTIES OF HIPPOCAMPAL NEURONS IN FREELY MOVING HOMING PIGEONS

The medial-dorsomedial pallium of birds was identified as the homologue of the mammalian hippocampal formation by comparative anatomists near the beginning of the 20th century. The homology was inferred, despite considerable differences in cytoarchitectural appearance, based on a similar topological relationship to the lateral ventricle. Since then, numerous developmental, pathway connectivity, neurochemical, and electrophysiological studies have overwhelmingly demonstrated that the intuitions of the early anatomists were correct: The mammalian and avian HFs are indeed homologous (Bingman, Hough, Kahn, & Siegel, 2003; Puelles et al., 2000; Siegel, Nitz, & Bingman, 2002). However, despite the demonstration of homology, the cytoarchitectural organization of the avian HF is notably different from the mammalian HF. In contrast to the distinct layers of cell bodies and fiber tracts that make the mammalian HF so distinctive, the distribution of cell bodies and fiber tracts in the avian HF is much more diffusely organized. This is important for our discussion of avian HF neuron response properties. To date, it has not been possible to determine with any precision whether any neuronal spatial response property (location, direction, or trajectory signal) is prevalently found in a particular cell layer or subdivision within the pigeon HF (although some subdivisional segregation of baseline electrophysiological properties, e.g., waveform, has been reported; Siegel et al., 2002). Therefore, in cataloging the different response properties of homing pigeon HF neurons, in contrast to what is routinely done in rat, we cannot claim that any type of spatial response localizes to any particular HF subdivision other than the relatively crude dorsal/ventral segregation described in Hough and Bingman (2004). However, our understanding of the

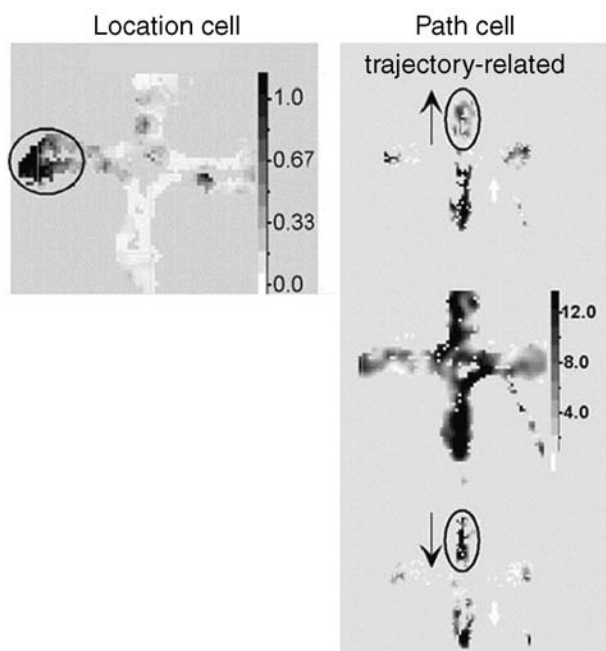


Figure 3: Rate Maps of a Hippocampal Formation Location Cell (Left) and Path Cell (Right) Recorded from a Freely Moving Pigeon in a Plus-Maze Environment.

NOTE: Firing rates can be read from the gray scales to the right. Note the linear quality in the vertical region of increased firing of the path cell's overall rate map (center). Importantly, note that the increased firing rate in the north and south arms depended on the direction of movement (higher firing rates in both the north and south arm when the pigeon was exiting; arrows identify direction of movement).
SOURCE: Figure courtesy of Jennifer Siegel.

response properties of homing pigeon HF neurons has advanced to the point at which comparisons with rat HF neurons are of considerable comparative interest. But it also must be acknowledged that understanding the spatial response properties of homing pigeon neurons and how response properties may be influenced by the characteristics of a recording environment and task demands is still at a very early stage. The summary offered in this review should be viewed as a first assessment that will grow as research progresses.

Location Cells

The avian HF has been demonstrated to participate in spatial behavior such as homing by familiar landmarks and recognizing goal objects by their position in space (Bingman et al., 2003; Colombo & Broadbent, 2000; Gagliardo et al., 1999; Sherry & Vaccarino, 1989; Smulders & DeVoogd, 2000). The dual role of the avian HF in goal recognition and navigational processes suggests that HF neurons would display response properties in support of these partially dissociable spatial functions.

One type of spatial response property routinely observed in pigeons navigating a plus maze (Siegel, Nitz, & Bingman, 2005, 2006) and analogue radial-arm maze (Hough & Bingman, 2004) belongs to what we have described as location cells (Figure 3). Location cells display statistically reliable (stable in time) local regions (patches) of higher activity that disproportionately, but not exclusively, occur at or near goal (food bowl) locations. The patches of higher activity that characterize location cells are typically less reliable and display relatively smaller increases from baseline firing rates compared to what is found in rat HF place cells. However, it is uncertain how seriously this impression of lower reliability should be taken. The experimental conditions and behavior of pigeons during recordings is not the same as what is usually found in rats. A 40-min recording session is routine in rat, whereas in pigeon, a 20-min recording session is the upper limit as a bird becomes satiated and no longer moves through an experimental environment. Therefore, the claim that the homing pigeon lacks place cells of the kind found in rat (Bingman, Siegel, Gagliardo, & Erichsen, 2006; Siegel et al., 2005;) may be premature. There have been location cells recorded that would appear to be bona fide place cells (Figure 3). Location cells can be found in both the right and left HF, and they have been hypothesized to represent the interaction between space and the events that occur in that space.

Arena-Off Cells

A common response property recorded from pigeons navigating a plus maze (Siegel et al., 2005) or analogue radial-arm maze (Hough & Bingman, 2004) belongs to what we have called arena-off cells. Arena-off cells have the curious property of displaying substantially higher firing rates as a pigeon is being held in a neighboring baseline recording space before being entered into a maze, when firing rates drop dramatically. Higher firing rates often reemerge when a pigeon is returned to the holding space after a maze-run period. Arena-off cells are similarly present in the left and right HF. Identifying a functional contribution of arena-off cells has proved challenging, not only because they have received less attention than location and path cells. Nonetheless, the temptation has been to assign arena-off cells some role in context setting prior to entry into a maze. However, it may well be that arena-off cells are just another example of a location cell with a preferred firing rate field positioned at the baseline recording space.

Path Cells

Another type of response property found in pigeons navigating a plus or radial-arm maze belongs to what we

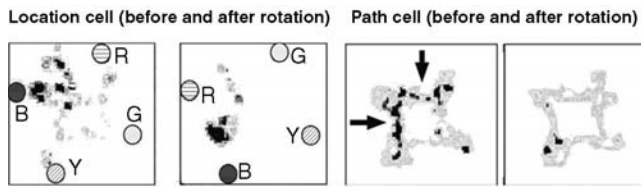


Figure 4: Rate Maps of One Location Cell (Two Left Maps) and One Path Cell (Two Right Maps) Before and After Rotation of Light Cues Recorded in a Modified Eight-Arm Radial Maze With Four Arms Baited.

NOTE: Local visual cues, colors B, Y, G, and R, are shown only for the location cell. Note the rotation of the patch of higher activity (tracking of blue bowl, indicated as B) regularly seen in location cells. Also note the disappearance of the regions of higher activity (corridors of higher firing rates in the prerotation map [arrows] disappear following rotation) regularly seen in path cells following rotation. Regions of higher firing rates are in darker gray and black.

SOURCE: Figure courtesy of Gerald Hough.

have described as path cells (Figure 3). Path cells display striking increases in activity when pigeons are moving along corridors that connect goal locations (Hough & Bingman, 2004; Siegel et al., 2006). Path cells display the interesting property of being directionally modulated in a way suggesting sensitivity to where a pigeon is going to or coming from, and they are almost exclusively found in the HF of the left hemisphere. Compared to location cells, the within-session reliability of path cells is typically higher and generally more comparable to rat HF cells (Hough & Bingman, 2004). Path cells appear to be well suited to participate in computational processes that would guide navigation among target locations. In many ways, the spatial response properties of path cells resemble some of the response properties of location-related HF cells recorded from rats on linear tracks (see above).

Stimulus Control of Location and Path Cells

We are tempted to speculate that location cells are more involved in goal recognition processes, whereas path cells are more involved in navigational processes. The proposed partial functional dissociation is supported by the findings of Hough and Bingman (2005) suggesting that visual landmark cues within an experimental environment have dissociable effects on the spatial response fields of location cells and path cells. Location cell patches of higher activity, particularly those located at or near goal locations, often rotate in parallel with the rotation of light cues (Figure 4). By contrast, the linear patches of higher activity that characterize path cells regularly disappear following light cue rotation (Figure 4). For location cells, a visual cue associated with a goal location seems to serve as a local reference determining increased activity independent of the spatial relationship between that local cue and the rest of the

environment. By contrast, path cells may be more sensitive to the spatial relationship of the local visual cues with the overall spatial properties of a test environment. When that relationship is disrupted upon rotation of visual landmark cues, the path sensitivity disappears, suggesting that path cells lose their spatial specificity (no longer coherently signal location) or they are more tuned to the context setting (Jeffery & Anderson, 2003) relationship between the local landmark cues and the overall properties of the environment.

Gridlike Cells

The vast majority of HF recordings conducted in freely moving pigeons have been carried out in the corridors created by a plus maze and analogue radial-arm maze, where goal locations (food bowls) were stable in space. Only recently have preliminary recordings been carried out in an open-field experimental environment where food is randomly distributed on the floor and a bird's movement would be unconstrained by corridor walls. In general, the overall location selectivity of neuronal spatial response properties appears to deteriorate in the goalless open-field environment; path cells have been virtually undetectable. However, one response property found during open-field recordings that was not found in the maze studies belongs to what we have called gridlike cells. Examining the rate map of a gridlike cell can be bewildering (Figure 2B). Typically, gridlike cells are characterized by numerous, almost square-shaped patches of higher activity. The transition in firing rate between the patches of higher activity and the surrounding space is often much more abrupt compared to the patches of location cells. Finally, the pattern created by the numerous patches of higher activity can appear symmetrically distributed over the experimental space. It is unknown whether it is the shape of the open-field environment, the absence of stable goal locations, or the interaction of these two factors that leads to the emergence of gridlike cells. We will speculate on the function of gridlike cells after they are explicitly contrasted with rat HF grid cells below.

Lateralization

As intimated above, the distribution of location and path cells in the left and right HF is asymmetrical. Path cells have almost exclusively been found in the left HF, whereas location cells seem to occur equally often in the left and right hemisphere. However, even among location cells, those found in the left hemisphere are more likely to have directionally modulated patches of higher firing rate (Siegel et al., 2006). It has been proposed that the asymmetrical distribution of response properties in the left and right HF reflects a partial

segregation of neuronal populations involved in goal recognition and navigational processes. The purpose of comparative research is to rely on differences among animal groups, as evolved adaptations to environmental contingencies, to better understand the operation of biological systems. Homing pigeons, and birds in general, are the animal world's supreme navigators, and their ability to recognize goals by their position in space is extraordinary. The partial segregation of neuronal response properties to the left and right HF, and the emergent lateralization of spatial information processing due to this segregation, may be one adaptive characteristic of the avian HF that confers on birds their seemingly special spatial cognitive abilities (Bingman et al., 2006).

CONSERVED FEATURES OF HF NEURON RESPONSE PROPERTIES

The bias taken in previous contrasts of rat and pigeon HF neuronal response properties has been to highlight differences rather than similarities (Bingman et al., 2006; Siegel et al., 2005). However, the explicit contrast presented in this article suggests the emphasis on difference may have been exaggerated and similarity may be more robust than previously appreciated.

Pigeon HF Location (and Perhaps Arena-Off) Cells and Rat Hippocampus Place Cells

Although the category of pigeon location cells may yet be found to include more than one dissociable response property (arena-off cells, cells with patches of higher activity at or remote from goal locations), these cells are unified by displaying restricted patches of higher activity in an experimental environment. Location cells may be typically less reliable than rat place cells and on average display more patches of increased firing rate, but it is uncertain if these differences reflect intrinsic differences in response property or emerge because of differences in any combination of behavior, the properties of an experimental environment, or the analyses used to extract a spatial signal. In our view, the important point is that increases in the firing rates of both location cells and place cells can potentially inform an animal, with some statistical certainty, of its location in space. Another similar feature of location and place cells is that both have been reported to disproportionately display increases in firing rate at goal locations (e.g., Hollup, Molden, Donnett, Moser, & Moser, 2001). We propose that the spatial response properties of pigeon HF location cells are analogous to rat hippocampus place cells and may reflect an evolutionarily conserved response property.

Pigeon HF Path Cells and Rat HF Cells Recorded on a Linear Track

The corridor-sensitive response properties of path cells reflect an interaction among a pigeon's location, movement, and direction. However, no one dimension can explain the firing pattern of a neuron. A path cell will fire when the pigeon is moving in a particular direction at a particular location (Figure 3). Directional tuning will additionally depend on where the animal is in an environment and is therefore relative. These complex, conditional spatial firing properties appear to be very similar to those reviewed above for the rat HF. It is clear that much more work is needed in both the rat and pigeon HF to more fully characterize and explain these firing patterns. However, based on the data presently available, it appears that both species show HF spatial response patterns that code for complex combinations of location, path, and additional task-related variables. It has been postulated that these signals could form the basis for episodic memories in which spatial context forms the background, as well as for navigational behavior itself.

Pigeon HF Gridlike Cells and Rat Entorhinal Grid Cells

Of the homing pigeon HF response property types, the least understood are the gridlike cells. It is worth repeating that gridlike cells have been observed only in a relatively open experimental space, where a pigeon's movement would be unrestrained by corridors. This may be because only an open field has the environmental features permissive for the expression of this response property or that the response properties of gridlike cells would transform into location or path cell-like in an environment characterized by corridors and fixed goal locations. However, the similarity in the distribution of patches of higher activity between gridlike cells and rat entorhinal grid cells can be striking (Figure 2). We propose that the spatial response properties of pigeon HF gridlike cells are analogous to rat entorhinal cells and may reflect an evolutionarily conserved response property.

However, there is one fascinating difference in how these gridlike patterns are structured in the two species. Note that in Figure 2, the rat grid cells are organized in a hexagonal pattern, so that sets of neighboring patches form equilateral triangles. In contrast, the pigeon gridlike cells are arranged in rows, so that sets of neighboring patches form squares. It seems possible that this difference in the geometry of the gridlike pattern may have fundamental implications for possible avian/mammalian differences in how the gridlike structure is formed or for the functional role of these grid cells in the overall navigation system. One possibility is that the neural network architecture responsible for these gridlike patterns has

evolved independently in the two groups. This in turn suggests that there is some relatively universal adaptive advantage to the development of this type of rigid, two-dimensional, spatial metric.

Summary

Because of evolutionary distance and spatial ecology, in the beginning of this article we highlighted the expectation of differences in the neuronal implementation of HF-dependent spatial representations in pigeon and rat. At least to the surprise of the first author, a careful contrast of neuronal response properties has revealed substantial similarity in the contribution of position, direction, and trajectory toward explaining the differential firing rate of HF neurons. The degree of resemblance is reminiscent of the similar but not identical properties of theta rhythm found in rat and pigeon (Siegel, Nitz, & Bingman, 2000). This is not to say that the response properties of location, path, and gridlike cells in the pigeon are identical to place, linear track, and grid cells in rat. But what must be emphasized is that the pattern of similarity is sufficiently apparent that it becomes necessary to respect the possibility that the differences are not a reflection of variations in biological organization but emerge as a consequence of testing procedures and behavioral differences. What is needed now to better assess how similar (or different) homing pigeon and rat HF neuronal response property types are is the application of more similar testing and analysis procedures to the two species. For the moment, the working hypothesis that the same composite of neuronal response properties determines how the HF of pigeon and rat participates in the representation of space remains valid. If supported, it would demonstrate considerable resistance to evolutionary modification in the components of neuronal response properties that determine HF function.

DIVERGENT PROPERTIES OF HF ORGANIZATION

A comparative analysis of neuronal response property differences suffers from the same limitation as has historically plagued comparative studies of cognition. Are any noted differences a true reflection of variations in biological organization or are they simply a nonspecific consequence of differences in how cells and animals respond to different environments, different sensory sensitivities, or motivations? However, there is one difference in the organization of the rat and homing pigeon HF that can likely withstand this admonishment. If the component response properties of pigeon and rat HF neurons are found to be as similar as we suggest above, it

does not necessarily mean that their interactions are organized in the same way. The different response properties in rat HF neurons are easily localized to well-defined anatomical subdivisions (e.g., hippocampus, subicular complex, and entorhinal cortex). To date, a similar partitioning has not been detected in pigeon. Importantly, because of the contrast in the patterns of connectivity among HF subdivisions in rat and homing pigeon HF (Hough, Pang, & Bingman 2002; Kahn, Hough, Ten Eyck, & Bingman, 2003), it is very likely that the coupling of neurons with different response properties, and the emergent network of interactions, will differ between pigeon and rat.

In pigeon, the distribution of response properties among neurons in different HF subdivisions manifests itself most dramatically in the lateralized distribution of path cells and the lateralized sensitivity of neurons to relative direction of movement (Hough & Bingman, 2004; Siegel et al., 2006). To date, path cells have been reliably found only in the left HF of pigeons, and even the activity profile of location cells of the left hemisphere are more tuned to the relative direction of movement compared to location cells of the right hemisphere. Consistent with the notion of lateralization in homing pigeons are reports of left HF lesions producing behavioral performance deficits that do not occur with right HF lesions (see Bingman et al., 2006, for a review). By contrast, as discussed above, despite an industry of unit recording research in the rat HF, lateralized response properties have, to the best of our knowledge, never been reported.

In pigeon, the lateralized organization of HF neuronal response properties, as a reflection of how neurons with different response properties may be organized as an adaptive network, represents a dramatic difference compared to rat HF. We have proposed above that there may be constraints on how natural selection can modify the range of response properties of HF neurons. However, how neurons with different response properties are structured into networks does not appear to be under similar constraints and can apparently change in response to selective pressure in a way we would like to think resonates with spatial ecology. Consistent with this admittedly speculative notion is that HF lateralization is a well-described feature of the human HF. The similar lateralized characteristics of the human and avian HF have been discussed elsewhere (see Bingman et al., 2006; Bingman & Gagliardo, 2006). We wish to highlight here only that the convergent property of HF lateralization in human and pigeon (and other birds) supports the hypothesis of substantial plasticity in the evolution of HF network architecture constructed from component neurons with relatively conserved spatial response properties.

CONCLUSION

Any attempt to reconstruct the evolutionary history of brain-behavior relations is necessarily speculative. We began this article by noting the striking similarity in the role of homing pigeon (bird) and rat (mammal) HF in the representation of space. This observation supports the assumption of a common evolutionary ancestor with something like an HF that also participated in the representation of space. Perhaps the most surprising inference that emerges from the subsequent review is the unexpected similarity in how the spatial properties of location, direction, and trajectory determine the spatial response properties of neurons in both homing pigeon and rat HF. It would appear that whether an animal flies in the air during the day or navigates environmental corridors at night, some representation of location, direction, and trajectory is similarly adaptive. But for the adaptationist, there is solace in the observation that the presence of HF lateralization in homing pigeon but not rat, differences in anatomical organization, and possible differences in gridlike and grid cells all reflect variation on how the neuronal elements can be organized into functional networks. Spatial ecology as a selective agent determining HF evolution would appear to have a more potent effect on how neurons with different spatial response properties are organized into networks than on response properties per se.

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