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Navigation in Virtual Space: Psychological and Neural Aspects

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Glossary

Allocentric – A representation of a spatial environment referenced to an external coordinate system that is not dependent on the original view or direction navigated when first experiencing an environment.
Cognitive map – A representation of a spatial environment that contains information about the spatial layout of objects in that environment. By definition, cognitive maps are allocentric representations of space because they are not dependent on the original direction that a subject navigates and are instead general to any direction or viewpoint the observer experiences it from.
Egocentric – A representation of a spatial environment tied to a self or body-centered coordinate system.
Functional magnetic resonance imaging (fMRI) – A noninvasive method for looking at changes in neural activity in the human brain. It depends on changes in magnetic properties of deoxygenated hemoglobin, providing information on metabolic changes in various brain regions. fMRI is therefore an indirect measure for neural activity.
Hippocampal area – Comprises the hippocampus and surrounding cortical structures (i.e., parahippocampal region).
Hippocampus – A three-layered structure in the medial temporal lobes of the brain critically involved in memory and spatial navigation.
Parahippocampal cortex – Also known as 'posterior parahippocampal cortex.' Six-layered cortical tissue receiving strong input from visual areas; central to memory and spatial navigation.
Parahippocampal region – Cortical tissue surrounding the hippocampus, which is in turn composed of parahippocampal cortex, perirhinal cortex, and entorhinal cortex.
Lesion – Surgically or pathologically produced brain damage.
Place cell – A neuron that increases firing at specific spatial locations and not others. This increased firing is independent of the trajectory of the animal.
Place field – An area in space of increased firing of a place cell.
Path integration – Computation of the optimal, or shortest, path to a location based on previous paths.

Theories of Spatial Navigation and Navigation in Lower Mammals

Origin of the Cognitive Map Theory

How is it that we can return to a town we have not visited in many years and still have a feeling of where things are and the right way to go? When we learn the layout of one city, why is it we rarely confuse where things are in that city with a different city we know better? To explain these and other spatial memory phenomenon, in 1948, Edward Tolman proposed the idea that the brain forms comprehensive maps of a spatial environment, such that "the wider and more comprehensive. . .the more adequately it will serve . . . " He termed these representations 'cognitive maps,' basing his ideas on observations of rat maze learning. If a rat first learned to find a reward by entering a tunnel and turning right, and then found the entrance blocked and replaced by several tunnels branching toward and away from the reward, the rat quickly learned to take the arm that went most directly to the reward. Furthermore, when the entire maze was rotated, the rat still navigated around the obstruction to find where the food had been. These results could not be accounted for by classical learning theory, the dominant theoretical paradigm at the time, which explained rodent navigational behavior based on learning associations between stimuli and responses such as "white wall, turn right." Tolman's data suggested that the

rodent representation for space was not dependent solely on egocentric coordinates, which would be based on the original set of stimulus-responses pairings learned, but instead on allocentric coordinates, a novel type of representation that was direction independent and referenced to landmarks in the room.

Neural Basis of Cognitive Maps in Rodents

Since Tolman's proposal an extensive literature in the rat points to a critical role for the hippocampus, a three-layered structure in the medial temporal lobes, in allocentric spatial learning. Electrophysiological recordings from the hippocampus showed that as a rat foraged in an open area, a significant percent of cells robustly increased in firing rate for certain locations of the room. These place cells also showed direction independence, thus fulfilling the criteria for an allocentric representation of space. Furthermore, recordings from large numbers (>30) of hippocampal neurons simultaneously demonstrated that the firing field (or place field) of each place cell had a fairly sharp tuning for a certain region of the environment. These place fields had firing rates of up to 40–50 Hz which fell off rapidly with distance, thus coding for a certain region of the room quite sharply. The collection of place fields recorded during a single session was shown to comprise a spatial code of the entire room.

The presence of hippocampal place cells in the rodent led O'Keefe and Nadel in 1978 to propose the idea that the hippocampus computes cognitive maps of place, representations of location in an environment referenced to the position of external cues or landmarks. In the rodent, the predictions of the cognitive map model have proven (largely) correct. Cognitive maps, which can be thought as collections of place fields representing a spatial environment in its entirety, rotate with the environment and are environment specific, thus suggesting a map-like quality to these representations. Hippocampal computational models that implement cognitive maps quantitatively account for a large amount of spatial neurophysiological data on the rat.

While the evidence for the involvement of place cells and the hippocampus in cognitive map formation is well demonstrated in the rodent, it is important to note that the rodent hippocampus also plays roles in other behaviors. Examples of stimuli encoded by rodent hippocampal neurons include odors and conjunctions of odors and places. A situation in which these types of representations typically manifest involves training of a rat to associate smells in certain locations with food reward. In these situations, hippocampal neurons come to represent specific odors, while other neurons code combinations of odors and spatial locations. These findings suggest that the neural mechanisms involved in representation of place in the rodent may not be unique to spatial representation and suggest a role for the hippocampus in more than just spatial representation. Together, the place- and odor-representation findings suggest that the rodent hippocampus is important for representing stimuli in a manner that is task-driven and context dependent.

Neural Basis of Cognitive Maps in Primates

The conditions under which monkeys are tested in navigational paradigms have often differed from those of rodents due to the greater mobility of monkeys overall, compared to rats. In one particular study, monkeys navigated on a track from a head-restrained, moveable chair guided and controlled by a joystick. Monkeys were tested both on a real movement task (reward destinations were indicated by pointers on a monitor and monkeys navigated on the track to this location) and a virtual movement task (reward destinations were indicated by pointers on a monitor and the monkey moved the cursor on the monitor to this location). The study found that nearly half of the hippocampal and parahippocampal neurons recorded fired selectively at specific spatial locations (using criteria similar to that used previously in the rodent) in the virtual and real movement tasks, with a significantly greater number of neurons showing selectivity in the real navigation task compared to the virtual navigation task. These data argued for the presence of place cells in the primate hippocampus as well as the presence of place cells during both real and virtual navigation.

Some laboratories have developed technology for recording from freely moving and behaving monkeys and report different findings than Matsumara and colleagues. In one study, monkeys were tested in an unrestrained testing environment. Recording head direction, eye position, location in space, and neural firing rate, the location that the monkey viewed in space drove the firing rate of neurons in the hippocampus and parahippocampal region rather than spatial location. A subsequent study, however, which also examined freely moving monkeys, reported robust firing at specific spatial locations, regardless of the view direction from which the monkey approached the location. Additional studies are needed to resolve some of the discrepancies in findings with navigating monkeys and spatial coding. Both the place- and view-coding findings, however, show that the primate hippocampus forms allocentric representations of space because both the place- and view-based representations were direction independent in the studies mentioned.

Spatial Navigation in Humans

Behavioral Studies: Do Humans Employ Cognitive Maps?

Somewhat surprisingly, one of the first studies to carefully look for the presence of cognitive maps in humans reported little evidence for allocentric coding in the

human brain. Wang and Spelke set out to test behaviorally whether subjects use primarily egocentric or allocentric representations of space by having them view items arranged on a table and point to their locations in a darkened version of the room following blindfolded rotation. Consistent with an egocentric model of spatial representation, Wang and Spelke found errors accumulated during rotations rather than remaining constant across positions, inconsistent with an allocentric, or equal viewpoint representation of space. Subsequent studies also showed that subjects performed most accurately on viewpoints they had already experienced when pointing to a specific object from an imagined orientation, and that experiencing more viewpoints did not improve pointing accuracy to novel viewpoints. These findings were initially heralded as support for the idea that humans preferentially form egocentric rather than allocentric representations of space.

Part of the reason why these studies may have found support for the presence of egocentric rather than allocentric coding in the human (in contrast to what had been shown in the rodent) likely had to do with the testing situations employed by these studies. For example, the two studies mentioned relied, to some degree, on a bias toward a spatial representation from a specific viewpoint and not on a holistic representation of the room. Indeed, subsequent studies that naturally resulted in subjects referencing viewpoints outside of those they initially learned tended to demonstrate the presence of more allocentrically based representations. For example, when a salient landmark is experienced during active navigation, this information could override what viewpoints were best remembered egocentrically.

Why did Wang and Spelke find little evidence for allocentric representations during their task? Waller and Hodgson suggested that this could have arisen because Wang and Spelke did not interrogate subjects on their relative knowledge of items in the room compared to their absolute positions. Similar to Wang and Spelke, Waller and Hodgson showed that pointing accuracy increased following blindfolded rotation. Waller and Hodgson then went on to show that variations in errors in judging the relative distances of objects actually decrease following disorientation. Thus, pointing to objects appears to preferentially involve egocentric coding systems because the objects were originally centered on the first view-point experienced. Judging positions of objects relative to other objects, however, preferentially invokes allocentric coding as this system is instead initially referenced to landmarks in the room. The findings of Waller and Hodgon thus support the idea that both systems are active during spatial learning and therefore that our brain, similar to the monkey and rodent, codes both allocentric and egocentric references frames.

Brain Structures Underlying Human Spatial Navigation

The human hippocampus consists of several important and highly interconnected nuclei. These include CA1-4, dentate gyrus, and subiculum, which receive input from both lower brain modulating centers, higher neocortical locations, and local interconnections. Based on the hippocampus' apparent position at the top of a pyramid of inputs, it is in a unique position to integrate inputs from a variety of different sensory modalities and output this information for immediate action to motor regions. The parahippocampal region, found between six-layered neocortex and three-layered hippocampus, consists of entorhinal cortex, perirhinal cortex, and parahippocampal cortex, appearing histologically to represent a transition from hippocampus to neocortex. It receives reciprocal connections from the hippocampus and provides the majority of neocortical input to the hippocampus, thus containing many of the same inputs as the hippocampus (with the relative exception of lower brain modulatory centers the hippocampus receives via the fornix). A major source of input to the parahippocampal region, the retrosplenial cortex (an area of posterior cingulate cortex) provides ~20% of the cortical inputs into the entorhinal cortex. Since retrosplenial cortex also receives input from prefrontal cortex, it represents a way station for processing of multimodal input.

Patient lesion work

Lesions to the hippocampus, parahippocampal region, and retrosplenial cortex in humans produce a variety of deficits, including impairments in spatial processing. In one particular study, patients with hippocampal area lesions attempted to locate a sensor hidden under a rug in a room and then find the sensor again after a 30-min delay. Bohbot and colleagues reported that patients with parahippocampal lesions performed significantly worse than controls on this task, while patients with right and left hippocampal lesions did not. In subsequent studies, patients with parahippocampal lesions also showed deficits when navigating virtual environments, performing worse on exploration of a virtual environment than patients with lesions limited to the hippocampus or anterior parahippocampal cortex (i.e., perirhinal and entorhinal cortices). These studies suggest that the human parahippocampal cortex, and not the hippocampus, plays an important role in both real and virtual spatial navigation.

What role then does the lesion literature suggest that the hippocampus plays in spatial memory? Studies of the classic patient HM, who had damage to his hippocampus (and some surrounding structures), but whose parahippocampal cortex was largely intact, suggested a potentially different story than the rat. In one study, HM was tested

in the same navigation task used by Bohbot and colleagues. HM showed intact navigation to the location of the hidden sensor, comparable to controls, although was impaired when required to remember more than one location. These data suggested that HM had some intact allocentric memory, despite a lesion to the hippocampus. His hippocampal lesion appeared to produce the most pronounced impairments when he was required to remember more than one spatial location. In line with these findings, other studies reported that patients with damage largely prescribed to their hippocampus were similarly impaired at recalling the locations of several objects that had been placed in an open arena but not at drawing these objects correctly on a map. These findings further suggested that hippocampal lesions resulted in deficit in integrating multiple representations of objects in space and not simply locating a single object on a map. Thus, together these findings suggest that the human hippocampus may be most critical for integrating multiple representations of space, especially within different contexts. The lesion data suggest that the human parahippocampal cortex may be more involved in actual spatial representation of visually encoded environments than the hippocampus.

Some limitations with patient lesion work warrant consideration when evaluating what brain regions underlie navigation. Lesions impair both the computations a structure performs as well as the input it provides to other structures. Thus, damage to a structure, such as parahippocampal cortex, removes strong inputs to the hippocampus, thus altering its normal functioning as well. In both developmental amnesiacs and patients with even relatively recent lesions, significant remapping in brain structures may occur, which may still involve individual variability. Thus, other measures of brain function, particularly in nonpathological brain structures, are necessary to accurately identify the brain systems involved in navigation.

Functional imaging and virtual reality navigation

Since its inception about two decades ago, functional magnetic resonance imaging (fMRI) remains the dominant method in healthy volunteers for investigating the brain systems involved in human behavior. This is primarily because fMRI is noninvasive yet provides excellent spatial resolution (up to 1 mm) and acceptable temporal resolution (on the order of seconds) for most memory paradigms. fMRI relies on changes in the magnetic properties of hemoglobin as oxygen is delivered to tissue in the brain, and thus is not a direct measure of neural activity. This potential limitation with fMRI, however, appeared initially of less concern because, at least in visual neocortex because there is significant coupling between the fMRI blood-oxygenated-level-dependent responses (BOLD), synaptic activity, and single neural firing. Unfortunately, the story in the hippocampal area appears more complicated. Current evidence suggests that activations in the hippocampal area largely reflect local field potential input from other brain regions rather than neural firing rate specifically, suggesting that the BOLD signal may largely represent input from nearby brain regions rather than the actual computations that structure performs. Despite this limitation, fMRI and positron emission tomorgraphy (PET) (which similarly measures changes in metabolism), remain a powerful technique for looking at changes in neural activity in brain regions and can provide valuable information about the types of information input for processing in a brain region.

Several fMRI and PET studies have looked specifically at the role of the hippocampal area in spatial processing. One of the first studies to look directly at virtual navigation using PET was a study by Maguire and colleagues, who looked at hippocampal activity as subjects navigated to spatial locations. Maguire and colleagues found that as subjects chose more accurate trajectories to locations, hippocampal, blood flow increased in a linear fashion to the hippocampus. They also found significant hippocampal activation as subjects successfully navigated to locations compared with following arrows to locations.

In a subsequent virtual reality (VR) study, however, it was reported that the parahippocampal region, but not the hippocampus, was active during spatial navigation involving way finding (navigation requiring use of novel paths) compared with a control condition in which subjects traversed a virtual corridor back and forth. Subsequent work also demonstrated parahippocampal activation simply when subjects viewed spatial scenes compared to viewing faces or objects. What then explains the discrepancy between studies showing parahippocampal activations and those of Maguire and colleagues?

One possible explanation lies with some of the ambiguity in interpreting the BOLD signal in the hippocampal area as structures that provide input to each other (such as hippocampus and parahippocampal cortex) may make it difficult to disentangle where the BOLD signal originates. Another possible explanation, if we assume the BOLD signal at least conveys unambiguous information in both the hippocampus and parahippocampal region, is that different testing conditions tap into different navigational memory systems and thus, different testing conditions result in different brain activations. As discussed earlier, Wang and Spelke found that when subjects make absolute judgments about the positions of objects in a room, egocentric representations predominate. In contrast, in situations in when subjects are required to reference to landmarks, allocentric representations predominate. Thus, when subjects view static environmental scenes, there may be no particular reason for subjects to form allocentric representations of space, thus providing an

explanation for why hippocampal activation may not have been observed when subjects view static spatial scenes. The presence of parahippocampal and not hippocampal activation during way findings, however, suggests a more involved role in allocentric-based spatial navigation.

How do we reconcile fMRI findings with those of the lesion literature? One possibility is that the parahippocampal region not only processes view information experienced during navigation but also does some (preliminary) allocentric processing. This theory would help explain why parahippocampal lesions would have such a profound effect on navigation, in general, as its absence would greatly impair visual-based input to the hippocampus. This proposal also explains the presence of parahippocampal activations simply when subjects view scenes and spatial layouts but are not required to form allocentric representations. Since the parahippocampal cortex also does some allocentric-based, view point extraction, this proposal can also explain why there is greater parahippocampal activation when subjects use objects as landmarks to remember spatial routes compared to when these same objects do not serve as landmarks.

This proposal, however, does not directly address what types of cellular responses might be present in the parahippocampal region and what types of visual stimuli might preferentially drive its neurons during navigation. Rodent studies emphasize the critical role for the hippocampus in forming place cells although the human lesion and fMRI literature suggest a more complex picture at least in the human. fMRI and lesion work, however, are limited to the resolution of whole brain structures and cannot report on single neuron activity. Thus, direct recordings of single neuron from the human hippocampal area are necessary in attempting to resolve this issue.

Neurophysiology of Human Spatial Navigation

As discussed, the rodent and nonhuman primate both support the presence of place cells in spatial coding. Human behavioral literature suggests both egocentric and allocentric coding systems are involved in human spatial learning. Lesion and fMRI work suggest roles for both the hippocampus and parahippocampal region in navigation. At University of California, Los Angeles (UCLA) Medical Center, in conjunction with neurosurgeon Itzhak Fried, we have the opportunity to record from single neurons in the human brain in patients undergoing monitoring for seizures. In a study that we have reported previously and elaborated here with more patients and data, we report on single neuron recordings from human patients undergoing seizure monitoring as they navigate a virtual environment.

Single Cell Recordings From Human Hippocampal Area during Navigation

The principle questions we wished to address were whether hippocampal area neurons responded at specific spatial locations, how they code landmarks, and whether these responses show allocentric coding properties. We additionally wanted to look at the view dependence and place dependence of neurons in these brain regions, given the previous literature. Would place representations show view dependence? Would representations for landmarks show place dependence? We recorded from hippocampal area neurons in 10 different patients as they navigated a virtual environment, binning firing rate according to behavioral epoch. We defined 'place responsive cells' to be cells that showed main effects of place with no main effects or interaction effects with view. We determined the number of cells responding to spatial positions (place) versus what was viewed during navigation (view) in an analysis of variance (ANOVA). We found cells in the hippocampus that responded robustly to place (see **Figures 1(a)–1(c)**); these neurons did not show changes in firing rate for viewing landmarks. We also found that cells showed effects of what landmarks a subject viewed (**Figures 2(a)** and **2(c)**). These neurons were active from a variety of spatial positions (see **Figures 2(b)** and **2(d)**) and thus, were place independent. We then tallied the total number of neurons responding to place and view across all the neurons we recorded. Place-responsive neurons were significantly clustered in the hippocampus compared to other brain regions, while view-responsive neurons were significantly clustered in the parahippocampal region compared to other regions (**Figures 3(a)** and **3(b)**). Only place-independent view responses were clustered in the parahippocampal region; we did not observe any anatomical clustering of cells showing place–view interactions.

Our data both support previous ideas on human spatial navigation developed from the imaging and lesion literature as well as expand on it in important ways. Hippocampal neurons showed increased firing at specific spatial locations and not others – regardless of the patient's trajectory – supporting the idea that these representations are both spatially specific and allocentric. These same neurons, however, did not respond to viewing landmarks. Interestingly, in many cases, these place-specific responses remapped depending on a subject's navigational goals, demonstrating the context dependence of these responses. Thus, our data have several implications for theories of the human hippocampus. First, our data confirm the importance of the

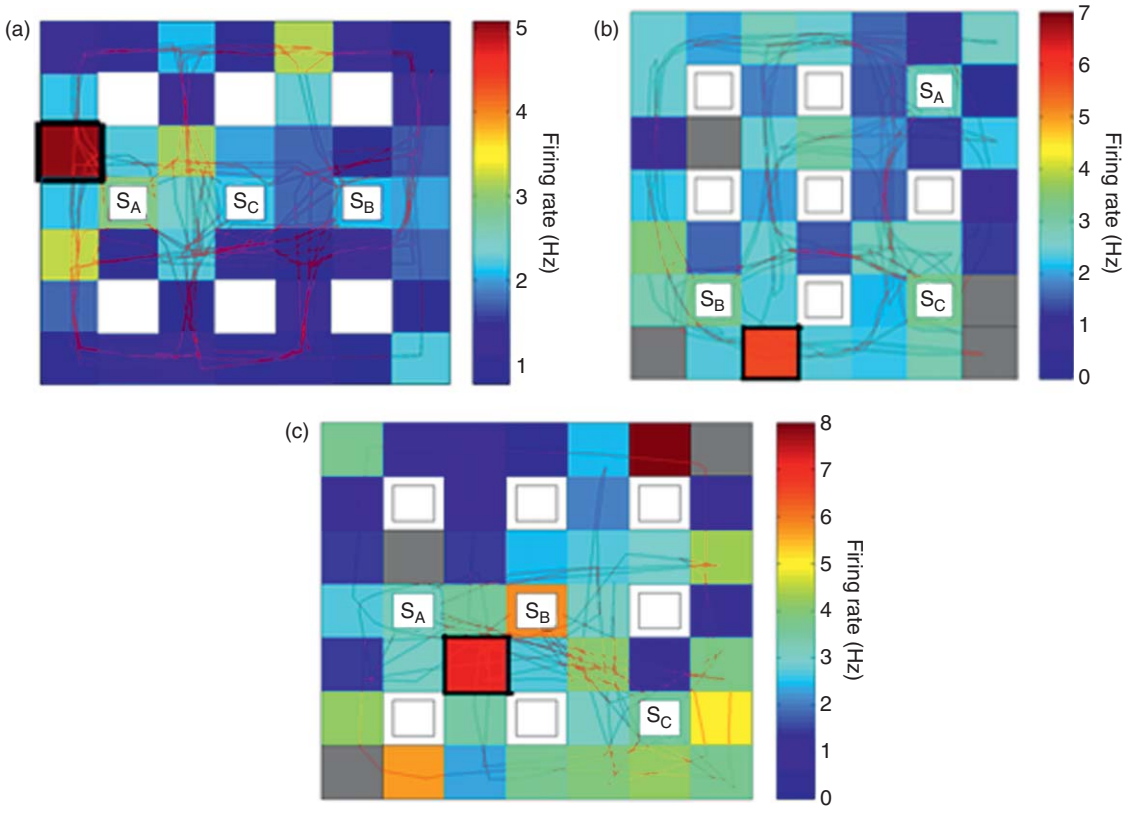

Figure 1 Place responsive cells. (a)–(c) Firing rate maps of hippocampal cells show significant place selectivity. Letters (S_A,S_B,S_C) indicate store locations, white boxes indicate nontarget buildings, gray boxes indicate unoccupied areas, red lines indicate the subject's trajectory, and black squares indicate regions of significantly high firing rate (determined using a resampling procedure at $p < 0.01$). From Ekstrom AD, Kahana MJ, Caplan JB, *et al*. (2003) Cellular networks underlying human spatial navigation. *Nature* 425: 184–188.

hippocampus in allocentric coding and extend previous work to demonstrate the conservation of place-selective firing from rodents to humans. Second, our data indicate that these place responses are context dependent, confirming a role for the hippocampus in representing information updated by the current experimental context.

Our data also confirm a role for the parahippocampal region in allocentric-based view coding. In our study, parahippocampal neurons showed increased firing when subjects viewed specific landmarks and did not show significant changes in firing rate for place (over the population of neurons recorded). While we found neurons that responded to viewing landmarks both independent and dependent on spatial position, only place-independent view responses were significantly clustered in the parahippocampal region. These data expand on previous ideas developed in the imaging literature and support a role for the parahippocampal region in both egocentric- and allocentric-view coding. These data support the parahippocampal region as an important source of input of visual information and also highlight its role in both egocentric and allocentric processing of spatial information.

Brain Activity in a Virtual Environment: Is it Comparable to Real Navigation?

One of the limitations with fMRI and clinical single cell recording is that subjects cannot navigate in an unrestrained manner, so all testing must be done with a computer laptop. The vast majority of research on the neural basis of spatial coding in the rodent, in contrast, has been conducted during real, locomotion-based, spatial navigation. In the literature, we reviewed previously regarding spatial navigation in patients with hippocampal area lesions, testing was performed during both real and virtual spatial navigation. As the reader will recall, both types of navigation depended on parahippocampal cortex. Similarly, monkeys tested both during real and virtual navigation showed formation of place representations in both conditions. One could still argue, however, that conclusions about spatial coding mechanisms derived in VR studies may not be the same as those observed during real navigation. Indeed, additional information is available during real navigation that is not available during virtual navigation. For example, real movement involves the additional input of head-direction and proprioceptive information into brain systems. Movement of the head

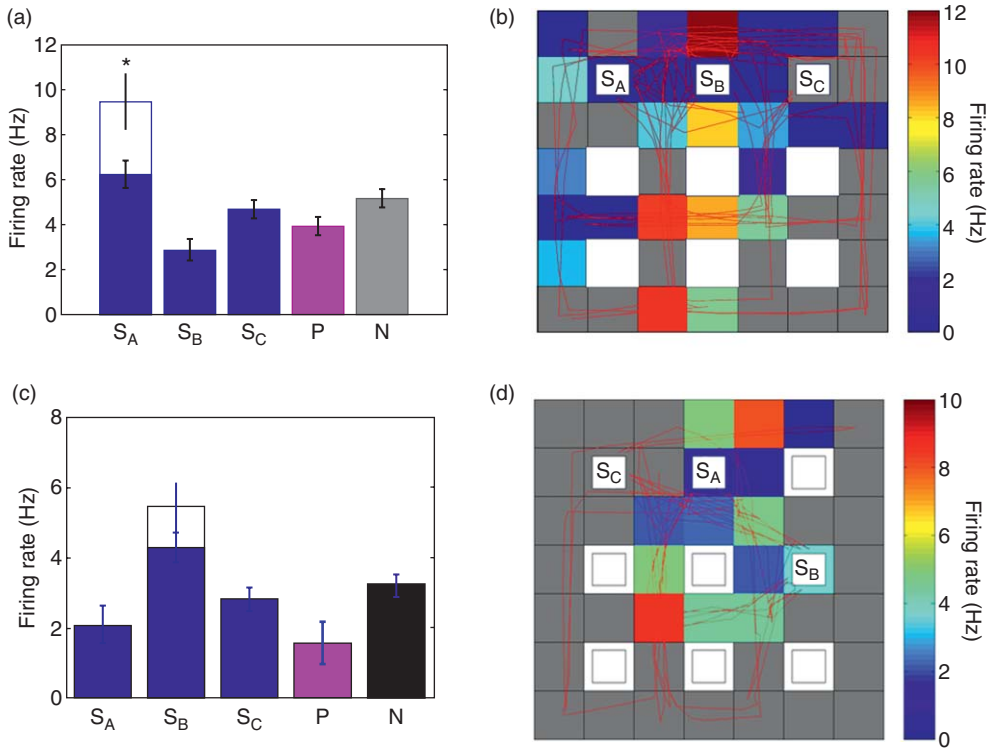

Figure 2 View responsive cells. (a) Mean firing rate for a parahippocampal cell that responded to viewing S_A (as compared with other stores, passengers (P) and control views (N)). The firing rate to viewing S_A (but not other targets) increased significantly when S_A was the goal (white bar). (b) Firing rate map shows that this cell responded to viewing S_A from disparate regions; gray regions indicate that S_A was not viewed from these locations. (c, d) Another parahippocampal neuron that responded significantly to viewing a store (in this case, S_B).

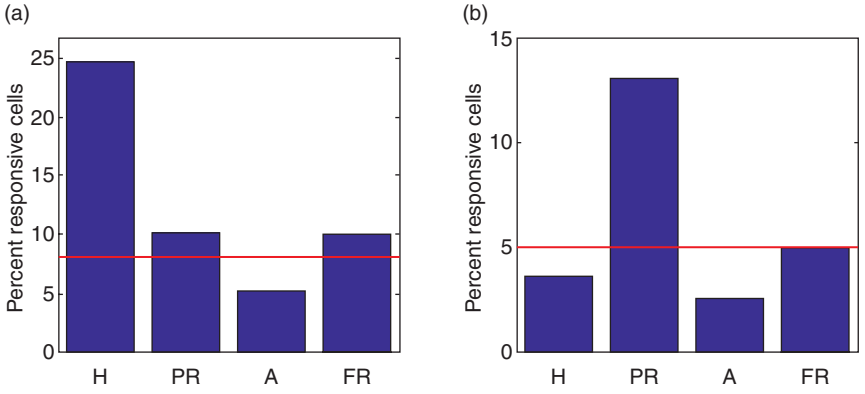

Figure 3 Anatomical clustering of responses. (a) Place-responsive cells were clustered in the H, hippocampus compared to A, amygdala; PR, parahippocampal region; and FR, frontal lobes. (b) View-responsive (location-independent) cells were clustered in the PR compared to other brain regions. Red line indicates bootstrapped type-I error rate.

invokes the head-direction system via the vestibular system, which provides important information about the subject's bearing not available in VR. Proprioceptive information, obtained through changes in muscle position, can provide information about speed. How does this additional information available during real navigation affect one's internal representation for space?

In several studies, the combination of proprioceptive information with head-direction information was shown to provide the needed information for a rat to compute the optimal path to find a location, referred to as 'path integration.' A classic illustration of path integration comes from mother rats separated from their pups. When their pup is placed at a new location, rats can readily find the shortest path back to their nest. In support of the critical role of path integration in place coding, lesions of the vestibular system greatly impair path integration as well as the specificity and stability of place fields. Thus, vestibular and proprioceptive

input clearly provide important additional information to the navigator that are not present during virtual navigation.

Despite the lack of vestibular and proprioceptive input, human subjects can still path integrate in a virtual environment. Previous research suggests that humans can use optic flow and egocentric bearing in VR to guide themselves to visual targets. Human subjects can also readily find optimal paths to store locations in virtual space, similar to real-world path integration. But given that the inputs differ between real and virtual navigation, despite some of the similarities in how people navigate in both situations, how comparable is the utilization of information obtained during VR to that obtained during actual navigation? In one study, subjects trained in a virtual environment were more accurate at navigating a real-world version of the environment than subjects who received verbal instructions on how to navigate the environment. These data suggest that at least some aspects of what is learned during virtual navigation also apply to real-world navigation. Further studies that directly compare neural responses during virtual and real-world navigation, however, are needed to fully address how comparable VR and real-world navigation are.

Summary

How do we know where we are going when we navigate? What brain systems and neural representations are involved in this task? Are these systems conserved from lower mammals to humans and how can we test these questions in humans? In this article, we have attempted to address some of these questions. We first discussed the distinction between egocentric and allocentric representations as a way of distinguishing between navigation that is dependent on the original viewpoint learned (egocentric learning) and navigation that is independent of static view point (allocentric learning). Rodent electrophysiological studies demonstrated the presence of place cells, neurons in the hippocampus that increase firing for specific spatial locations in an allocentric manner. Nonhuman primate studies also support the presence of place cells as the basis for allocentric spatial coding. In humans, allocentric coding mechanisms have been more difficult to demonstrate, in part because certain coding systems may predominate under certain testing conditions. Under the correct testing conditions, such as making relative judgments about objects positioned in a room, subjects do indeed use allocentric coding schemes to solve a task. Human lesion work suggests the importance of the hippocampus and surrounding parahippocampal cortex in spatial representation, with a greater emphasis on the parahippocampal cortex in visual representation of an environment and the hippocampus in representing multiple spatial environments. fMRI research not only supports the role of the hippocampus in allocentric-based navigation but also indicates the involvement of the parahippocampal cortex, particularly in extracting view information from spatial scenes. Both fMRI and lesion work are limited to broader statements about brain regions and brain circuits and cannot directly demonstrate whether place cells exist. Direct recordings from the human are rare and limited to clinical situations, yet offer promise for revealing the neural representations underlying spatial navigation. Recording from the human brain while subjects navigate a virtual environment, we report on both place responsive cells (clustered in the hippocampus) and view-responsive neurons (clustered in the parahippocampal region). These data support the idea that place cells are conserved from rats to humans. These data also show that our spatial coding mechanisms involve additional mechanisms, including a greater reliance on view than rodents.

See also: Animal Models of Learning and Memory; Brain Mapping of Language and Memory in Epilepsy; Cognitive Decline in Laboratory Animals: Models, Measures, and Validity; Cognition: Learning and Memory: Spatial; Knock-Outs: Learning and Memory; Role of Gene Transcription in Long-Term Memory Storage.

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