

Neurobiological bases of spatial learning in the natural environment: neurogenesis and growth in the avian and mammalian hippocampus

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Introduction

The amount of information amassed on the hippocampus is staggering. Certainly more than any other brain structure, the role of the hippocampus in learning has been explored at almost every level of analysis to include details about the gross anatomy, cytoarchitecture, physiology, biochemistry and possible mechanisms of plasticity primarily in humans, non-human primates and rodents. Much of the research addressing the relationship between spatial learning and the hippocampus has been performed in rodents, primarily rats. As noted by Nadel,¹ the vast majority of these studies have been 'nature-blind'; that is, they ignore behavior that is significant to the success of animals in the wild. It is unclear, therefore, how and indeed if theories derived from these experiments generalize to species in more naturalistic settings.

It has always been quite a puzzling observation that research involving the nocturnal laboratory rat, known for his notoriously poor visual acuity, requires that he perform tasks dependent upon visual processing of spatial information during the daylight. One can only speculate on their spatial prowess if trained and tested in a situation that would more accurately mimic highly probable conditions confronted in nature. Would tapping

into a naturally occurring behavioral repertoire not present the animal with a meaningful, ultimately more solvable problem? One need only ask simple questions such as 'does hippocampal involvement in learning and memory depend upon task difficulty or level of motivation?' to illustrate the strong likelihood that results obtained in laboratory settings using conventional learning tasks tell only a portion of the story. Laboratory studies of rats are extremely important to our understanding of the hippocampus and spatial memory, but these experiments must be complemented by research that investigates how spatial systems work in ecologically relevant contexts.

In their natural environment, both rodents and birds engage in behaviors that are believed to depend upon spatial learning ability such as home range navigation, migration, brood parasitism, foraging, and the storage and retrieval of food caches. We will review some of these biologically relevant models of the neurobiological bases of spatial learning in the natural environment. Towards this end we will provide an introduction to the evidence suggesting homology between the mammalian and avian hippocampal formations, a review of avian models, a review of mammalian models, a discussion of neural mechanisms of plasticity common to both and their possible involvement in learning and memory, and a summary and speculation that may provide insight into potentially fertile future directions.

Homology of the avian and mammalian hippocampal formation

In order to explore the respective roles of the avian and mammalian hippocampus, evidence on possible homology needs to be established. Although differences exist, extant research supports the proposition that the avian hippocampal formation (hippocampus plus parahippocampalis) is indeed homologous to the mammalian hippocampal formation (hippocampus plus dentate gyrus) on the basis of embryological, anatomical, physiological and neurochemical evidence. For purposes of the present discussion, the term 'hippocampus' will be used when referring to either the avian or mammalian complex. Since detailed treatment is beyond the scope of this paper, only a summary of general homology will be presented. Interested readers are urged to consult excellent reviews by Macphail² and Butler and Hodos.³

The mammalian and avian hippocampal formation were derived from the reptilian dorsomedial cortex; the mammalian hippocampus migrated laterally but the avian hippocampus remained in the original dorsomedial position² (Fig. 1). Given 300 million years in which birds and mammals evolved independently, it is not too surprising to find non-trivial differences between them. Striking differences are apparent in that the avian hippocampus lacks structures similar in appearance to the dentate gyrus and Ammon's horn, a distinct mossy fiber system⁴ and a well-defined trisynaptic pathway. Instead, the avian hippocampus consists of two structures: a V-shaped layer of densely packed neurons containing pyramidal cells and a dorsomedial zone found within and surrounding the 'V', containing more diffusely scattered neurons and granule cells (Fig. 2). On the basis of immunocytochemical evidence, Erichsen *et al.*⁵ suggested that the 'V' may be the avian equivalent of the mammalian hippocampus proper and the dorsomedial zone may correspond to the dentate gyrus.

Embryologically, the avian and mammalian hippocampus emerge from the same portion of telencephalon.⁶ Both share many of the same cell types including pyramidal and granule cells.^{7,8} The connectivity to other brain regions such as the septum, hypothalamus, brain stem nuclei and sensory processing areas are similar although some differences exist.^{8,9} For example, unlike the mammalian structure, the avian hippocampal formation does not project strongly to the septal region, there is no postcommissural fornix (that is, there is no direct projection to the hypothalamus), and there is no direct input from the medial septal nucleus which in mammals drives the theta rhythm.¹⁰ The neurochemistry is similar in the occurrence of various neuropeptides and neurotransmitters although the precise organization of the substances differs.^{5,11} Both structures also show long-term enhancement of synaptic responses,¹²⁻¹⁶ although NMDA-dependent long-term potentiation (LTP) may occur in some, but not all birds. That is, NMDA receptor antagonists fail to block LTP in non-homing pigeons.^{5,16} In contrast, LTP in homing pigeons is NMDA receptor-mediated.^{5,16} Similar discrepancies based on location of LTP induction have been noted within the rat hippocampus. LTP induced in the mossy fibers and lateral perforant path is opioid-dependent but NMDA-independent^{15,17,18} whereas Schaffer collateral and medial perforant path LTP is NMDA receptor-mediated.^{19,20} It remains possible that the difference in birds is one of location rather than absolute absence of this form of LTP.

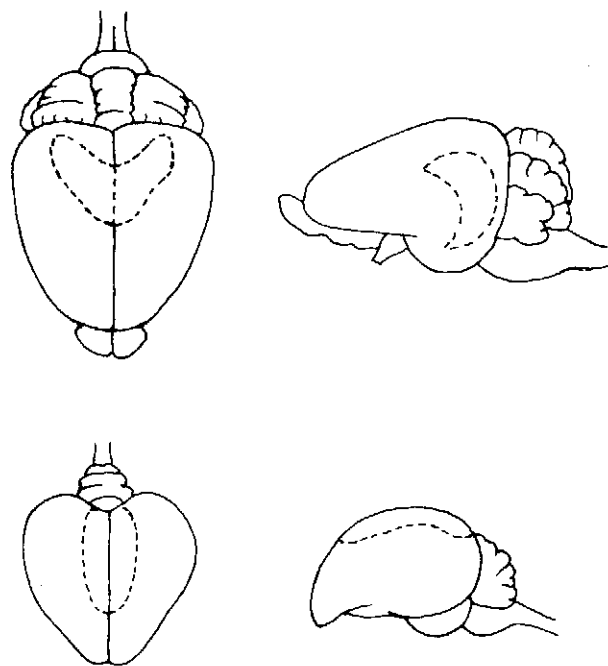


FIG. 1. Top: red squirrel brain, showing location of hippocampus (dashed line) in dorsal view (left) and lateral view (right). Bottom: black-capped chickadee brain, showing location of hippocampus (dashed line) in dorsal view (left) and lateral view (right). Note: chickadee and squirrel brains are not drawn to the same scale.

One last, but potentially the most significant similarity is that post-developmentally, both the avian and mammalian hippocampus demonstrate neurogenesis,²¹⁻²⁵ experience-dependent growth²⁶⁻²⁹ and experience-dependent neurogenesis.³⁰⁻³³ Furthermore, the growth of the hippocampus of both birds and mammals responds to seasonal/photoperiodic changes.³⁴⁻³⁷ This topic will be explored in greater detail later in this review. But first, evidence will be presented supporting the involvement of the hippocampal formation in spatial learning and memory in the natural environment of both birds and mammals. These functional similarities may be even more convincing than structural similarities when comparing the avian and mammalian hippocampus.

Avian models of spatial learning in the natural environment

Studies of the natural behavior of animals with highly specialized capabilities, such as food-storing birds, may add to our general understanding of the neurobiological bases of memory especially with regard to the role played by the hippocampus. Birds are particularly well suited for such studies because they show sophisticated and complex forms of memory-based spatial behavior including

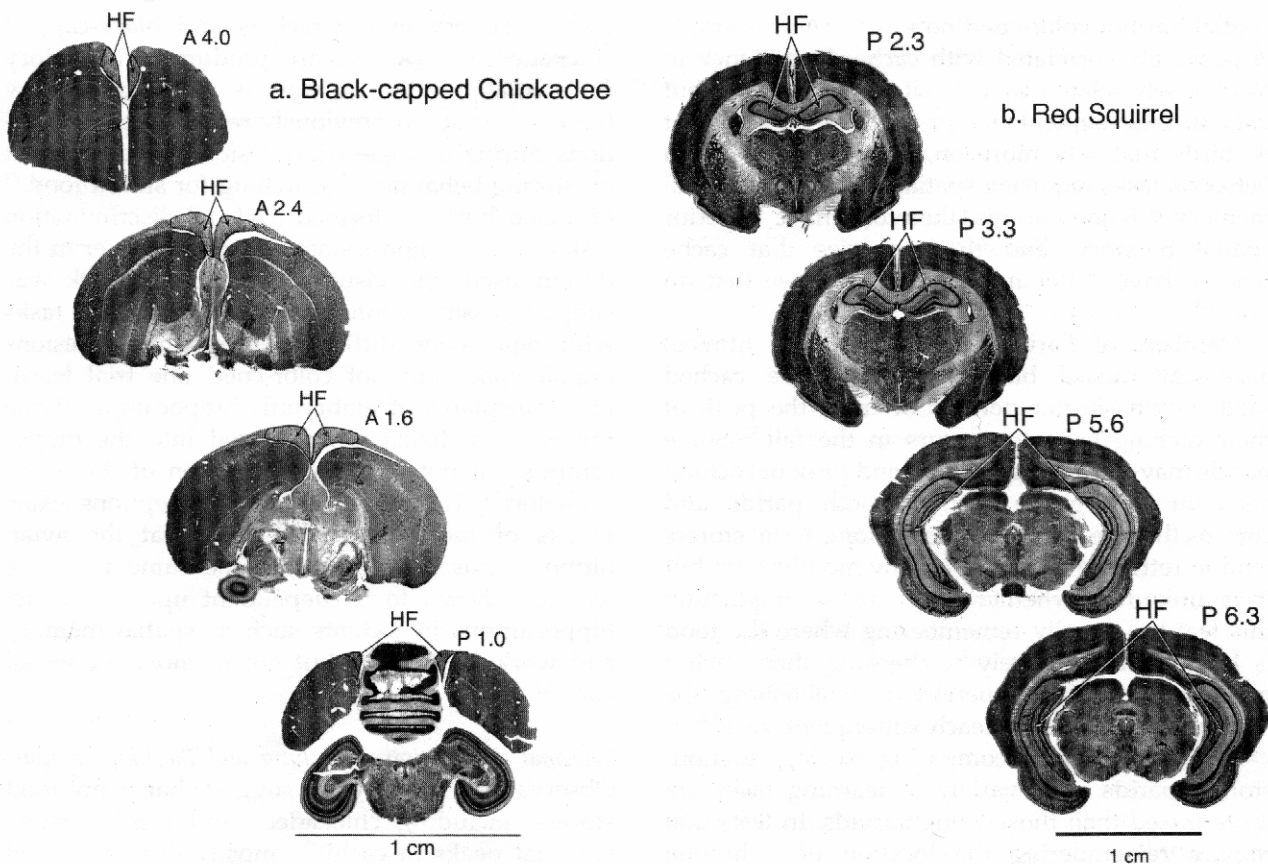


FIG. 2. (a) Coronal brain sections of a black-capped chickadee, with hippocampus (HF) demarcated by a black boundary. Sections stained with cresyl violet. Numbers to the upper right of the sections correspond to location (in mm) anterior to the anterior commissure of the canary brain following the standard nomenclature of Stokes *et al.*¹⁴¹ (b) Coronal brain sections of a red squirrel. Sections from two different individuals; stained with cresyl violet. Numbers to the upper right of the sections correspond to location (in mm) anterior (A) or posterior (P) to bregma of the rat brain following the standard nomenclature of Paxinos and Watson.¹⁴²

migration, homing and food-storing, as well as brood parasitism. There is increasing evidence that the avian hippocampus plays a critical role in these behavioral systems.

Homing behavior in pigeons: Homing behavior of pigeons is believed to rely on a spatial navigation system. A well-trained homing pigeon will fly off in an approximate homeward direction when released from a distant, unfamiliar location. This ability is hypothesized to be based on a navigational map that permits a bird to identify its location relative to home.³⁸ Hippocampal ablation has no effect on the established map of experienced adult homing pigeons; however, the performance of hippocampus-lesioned experienced adults and young pigeons required to learn a new map is impaired.^{38–40} Furthermore, when measured without the neighboring area parahippocampalis, the hippocampus of homing pigeons is larger than other non-homing breeds⁴¹ and shows NMDA-dependent LTP.¹⁶ These findings suggest that the hippocampal complex is not necessary for

the operation of a navigational map but is critical for navigational map learning. In other words, similar to evidence obtained in mammals,⁴² the avian hippocampal formation appears to be involved in the consolidation of new memories as opposed to the storage or recall of old ones.

Food storage and retrieval in birds that cache: A second model used in investigating spatial memory in naturalistic settings involves the storage and retrieval of food caches. Evidence from both field and laboratory studies indicates that some species of animals store food and rely on spatial memory to retrieve their caches.^{43–45} Although the details vary between species, individuals can store anywhere from thousands to tens of thousands of food items, each one in a different site.⁴⁶ Stored items can then be retrieved from hours to months after storage. Members of Corvidae (nutcrackers, crows and jays) tend to cache in many distributed locations during the fall and then retrieve their food during the winter and early spring.^{43–47} Furthermore, performance on operant tests of

spatial but not color-cued non-matching-to-sample is positively correlated with cache dependency in four closely related corvids all of which cache but vary in their dependency upon cached food. That is, birds that rely more on their caches perform better on tasks requiring spatial but not non-spatial memory.⁴⁸ Some corvids, therefore, have superior spatial memory, and those species that cache tend to have better memories than those that do not.⁴⁹⁻⁵¹

Members of Paridae (chickadees and titmice) also scatterhoard but tend to retrieve cached food within shorter periods of time; the peak of their caching behavior occurs in the fall.⁵² Some parids may also engage in a second peak of caching behavior during the spring.⁵³ Both parids and corvids that are considered to be 'long-term' storers tend to retrieve their caches many months later but it is unknown whether they are accomplishing this feat by actually remembering where the food is hidden or by merely re-checking their caches over short intervals thereby re-establishing the memory for location at each subsequent visit.⁵⁴⁻⁵⁵

Results of studies comparing storing- to non-storing parids on a variety of learning tasks are more mixed than those using corvids. In tests that require remembering the location of a hidden peanut given a number of spatial locations and visual/color cues, birds that store perform better than those that do not.⁵⁶⁻⁵⁸ There is some evidence that food-storers are superior to non-storers in tests of spatial but not color-cued non-matching-to-sample⁵⁹⁻⁶¹ and hippocampal lesions reverse this difference⁶² (but see also Ref. 63). Furthermore, black-capped chickadees, when given a choice, appear to prefer solving tasks using spatial information rather than color cues.⁵⁹⁻⁶⁴ Similarly, storing marsh tits and jays prefer to use positional cues whereas non-storing blue tits and jackdaws rely equally upon positional and feeder-specific cues.⁶⁵ Although beyond the scope of the present article, an excellent review of comparative studies of memory in food-storing birds is presented by Shettleworth.⁶⁶

Recent work has made it possible to link spatial memory for caching with its neural basis. Two studies of 35 European and 23 North American species or subspecies of passerine birds, have shown that the volume of the hippocampal complex relative to brain and body size is significantly larger in birds that store food than in those that do not.^{67,68} Neuroanatomical studies have determined that the amount and duration of food storage positively correlates with hippocampal volume.⁶⁹⁻⁷¹ Furthermore, studies have shown that lesions of the hippocampus disrupt

cache recovery in nutcrackers and black-capped chickadees.^{72,73} Deficits are produced in memory for spatial location as well as working memory (repeated visits to previously retrieved cache locations during a single trial); lesions have no effect on storing behavior or searching for stored food.⁷³ Lesioned birds performed a visual discrimination task as well as non-lesioned birds; however in the design used, the visual discrimination task was simpler possibly confounding the results. On tasks with equivalent difficulty, hippocampal lesions impair space but not color-cued one trial learning; transplants of embryonic hippocampal tissue reverse this deficit when placed into the hippocampus but not into another region of the telencephalon.⁷⁴ Therefore, although exceptions exist, results of most studies indicate that the avian hippocampus is involved in the same forms of learning shown to be dependent upon an intact hippocampus in rodents such as spatial memory and working memory but not memory for visual cues.^{2,10,75}

Seasonal modulation of caching and the hippocampus: Observations in the wild suggest that many food storers, including chickadees and titmice, show seasonal peaks in caching, mostly during the fall and early winter months.^{76,77} Seasonal caching occurs in captive willow tits housed in an outdoor aviary.⁷⁸ European jays also observed in outdoor aviaries spend more time caching, cache more items, and leave their caches for longer periods of time during the fall than in the spring.⁷⁹ However, in the wild or in an outdoor aviary, many seasonal factors are allowed to vary potentially influencing food storage. For example, in the wild, food supply and energetic demands influence caching.⁸⁰⁻⁸² Changes in temperature, photoperiod, and the amount of wild food entering an outdoor aviary could also influence storing. When food supply and energetic demands are held constant, captive black-capped chickadees persist in seasonal caching; when housed in identical conditions, birds caught during autumn store significantly more than those caught during spring.⁸³⁻⁸⁵

Directly manipulating temperature and photoperiod to mimic those experienced in the natural environment induces changes in storing behavior in black-capped chickadees.⁸⁵ Switching photoperiod (and temperature) from long to short days also induces storing behavior in chickadees; however, this is not accompanied by differences in hippocampal volume.⁸³ Others have reported that hippocampal volume is larger during fall when food storing is at its peak.³⁶ Furthermore, a seasonal increase in hippocampal neurogenesis is observed

in wild-caught black-capped chickadees in late summer slightly preceding the seasonal peak in storing.²⁴ Since neither of the later two studies included a non-caching species, it is not known whether these changes are specific to birds that cache or the result of a more general seasonal mechanism.

Given the results of other researchers, why then was a photoperiod-induced change in caching behavior not accompanied by volumetric hippocampal changes in the report by Krebs *et al.*?⁸³ Some possible answers were posited in their report. First, some seasonal factor could cause the brain to change in preparation for changes in cognitive demand (just as photoperiod induces gonadal growth prior to breeding opportunities). If this were the case, then one would expect to find seasonal volumetric changes. If, on the other hand, the brain changes in response to the increased cognitive demands of the season, then one would not expect to see seasonal volumetric changes until after storing and retrieval behaviors had been established. March tits show an increase in hippocampal cell number and volume after experience with storing and retrieving food during development. In contrast, lack of this type of experience results in a decrease in hippocampal cell number and volume suggesting that experience may trigger recruitment of neurons while lack of experience may promote cell loss.²⁷ It is possible that the photoperiodically induced change in caching behavior was not accompanied by volumetric hippocampal changes because the conditions of the experiment did not allow for adequate caching and retrieving experience. Work currently conducted in this lab is providing captive chickadees with varying amounts of caching experience and addressing the question of how much activity is really necessary to see volumetric changes.

In summary, black-capped chickadees show seasonal peaks in storing behavior induced by changes in photoperiod, possible seasonal changes in hippocampal volume, and seasonal hippocampal neurogenesis.^{24,36,52,83,86} These morphological changes may slightly precede the behavioral changes. However, neither study reporting positive morphological change used a non-caching control species making it impossible to determine whether these changes are specific to birds that cache. Thus, the picture remains unclear. We are conducting further studies that link season-induced and photoperiod-induced morphological changes in the hippocampus and food-storing behavior to learning in birds that cache as well as those that do not. Furthermore, in birds that cache, it has not yet been demonstrated unequivocally

that season (presumably photoperiod) influences learning at all, and if it does, whether this influence is limited to the hippocampus and hippocampus-dependent learning tasks.

Photoperiod and gender differences in spatial learning tasks: If food-storing birds store more, have a larger hippocampus and show increased levels of hippocampal neurogenesis during the fall and winter, then a number of predictions can be made when directly manipulating photoperiod in the laboratory. When put on a short day, fall-like photoperiod storers should increase their storing activity, have a larger hippocampus than non-storers or storers maintained on long-days, perform better on hippocampus-dependent tasks than do non-storers, and perform better on hippocampus-dependent tasks when compared with their own performance when tested on long-day, spring-like photoperiods. Although the first two predictions have been explored by a number of studies, attempting to address the latter two predictions has proven to be quite difficult and has produced mixed results. For example, food-storing marsh tits were originally maintained on long day photoperiods. As predicted, birds having experienced a shift from the long day to a short day photoperiod performed better on a spatial- but not a color-cued test than those maintained on long-days. However, when conditions were switched, that is when the short-day group was put back on long-days and the long-day group was switched to short-days, instead of reversing directions, the difference disappeared.⁸⁶

Food-storing Alaskan black-capped chickadees were compared to non-storing white-crowned sparrows on a spatial learning task in which birds learned to remove string knots placed over a baited hole positioned on wood feeding stations.⁵⁸ To determine where the food was hidden, birds could rely on spatial but not color or feeder-specific cues. When kept on short days, chickadees were superior to sparrows especially when tested at long retention intervals. However, when half were changed to long days and the other half to an even shorter photoperiod, short-day chickadees performed much better than sparrows but not their long-day cohorts. An interesting finding was that female chickadees performed considerably better than males, but it is currently unknown whether this gender difference in behaviour is accompanied by hippocampal differences. No gender differences were found in food-storing, memory for food caches, or hippocampal volume in black-capped chickadees caught in London, Ontario, Canada.⁸⁷

Although there is little to indicate that there are gender differences in the food storing behavior of chickadees, and therefore by extrapolation differences in spatial learning ability, geographical considerations may play a role. For example, there were no gender differences in the performance of chickadees caught in Colorado (personal observation) but a striking difference favouring females in the Alaskan strain trained on a spatial learning task.⁵⁸ As suggested by Petersen and Sherry,⁸⁷ a gender difference could still occur if the dominance hierarchy in winter flocks make one gender more dependent upon stored food or if differences in energy expenditure or body weight make one gender more reliant upon their caches. One could argue that harshness of winter conditions could easily exacerbate the situation and produce a gender difference unseen in more moderate climates. Within-species comparisons on equivalent learning tasks would be a logical and desirable next step.

Sherry *et al.*⁸⁸ predicted that gender differences in the hippocampus would indeed occur but only in species in which males and females differ on their reliance on spatial cues. Although gender differences are known to exist in spatial learning tasks, they quite often favor males; that is, males of a variety of species including humans usually perform better than females on tasks that call for the use of spatial memory.⁸⁹ Many rodent species that show gender differences in home range size, and therefore reliance upon space in the natural environment, also show gender differences in spatial learning ability and hippocampal size. Polygynous male voles and deer mice increase their home range size during breeding season, perform better on spatial learning tasks and have a larger hippocampus than their female counterparts (see review below). In birds, males have a larger hippocampus than females in two food-storing species, magpies and jackdaws,⁶¹ although it is unclear why there should be a difference based upon their similar ecology. A second example of gender-based differences in behavior and hippocampus occurs in bird species that engage in brood parasitism.

Brood parasitism: Cowbirds typically hide their eggs in the nests of other, unsuspecting birds and the 'host' birds raise their offspring for them. Birds that engage in brood parasitism must remember where these other potential nests are located and when the hosts' eggs are about to hatch so they can time their egg-laying accordingly. Similar to caching, this behavior occurs seasonally, but during the spring breeding season not the fall. Also similar to caching, brood

parasitism in cowbirds is accompanied by a large hippocampus when compared to other non-parasitic cowbirds.^{34,90,91}

Female brown-headed cowbirds search for host nests then return later to lay their eggs; males of this species do not. Hippocampal volume is larger in the females than in males, but no gender difference is found in two non-parasitic species, the red-winged blackbird or the common grackle.⁹¹ Further testing the hypothesis that hippocampal size varies with the demands placed upon the individual for spatial learning ability, three phylogenetically closed related species of cowbirds were compared, each differing in their level of investment in brood parasitism.⁹⁰ Female shiny cowbirds search for host nests unassisted by their male cohorts; both female and male screaming cowbirds search together, while in bay-winged cowbirds, neither gender searches since they are not brood parasites. As predicted, the two parasitic species had a larger hippocampus relative to telencephalon than the non-parasitic species. There were no gender differences except in the shiny cowbirds, the species in which females search for host nests without males; these females have a larger hippocampus than their male counterparts. In addition, for the two parasitic species, the hippocampus is larger during the breeding than the non-breeding season; the gender difference in the shiny cowbirds appears only during breeding and is not present in non-breeding season when neither females nor males engage in nest searching activities.³⁴

Thus far, observed gender differences in spatial learning ability and/or the size of the hippocampus in birds have been limited to the findings in magpies and jackdaws as well as in cowbirds engaging in brood parasitism. This is certainly not the case with naturalistic studies of spatial learning in mammals. Most of these studies repeatedly report gender-based differences in reliance upon spatial cues in the environment, spatial learning ability, and hippocampal size.

Mammalian models of spatial learning in the natural environment

It has been long established that the mammalian hippocampus is especially important for the formation of memories about spatial aspects of the environment.^{92,93} However, recent work has investigated the significance of the hippocampus in behaviors occurring in nature believed to rely on spatial learning ability such as home range navigation and foraging.^{92,93}

Home range navigation in voles: Much of our knowledge of how mammals rely on spatial memory in the wild is based on examination of differential space use in voles. During the breeding season, male meadow voles mate with multiple females and have home ranges four times larger than those of females; no such sex difference in space usage is seen in juveniles, or in monogamous pine and prairie voles. Moreover, in a series of laboratory maze-learning tasks, meadow vole males captured during the breeding season made fewer errors than conspecific females, whereas pine and prairie vole males and females did not differ in spatial performance.⁹⁴⁻⁹⁶ Similar sex differences in spatial learning were reported for polygynous adult deer mice: long-day photoperiod males (breeding season) outperformed females in a Morris water maze task; no gender differences were seen on a short-day photoperiod.⁹⁷ Hippocampal volume relative to total brain volume during the breeding season was also significantly greater in meadow vole males than in conspecific females; this sex difference was not seen in pine voles.³⁵ These data imply that adult animals with larger home ranges require better navigational abilities than immature or adult individuals with small home ranges; hence, these wide-ranging individuals (i.e. polygynous males) have evolved a larger hippocampus than their more range-restricted counterparts. This relationship between ranging behavior and hippocampus could be examined further by correlating individual home range sizes with hippocampal volumes or by experimentally manipulating the distance over which animals must travel. In terms of hippocampal anatomy, the volumetric measurements may detect only gross morphological differences between animals; more detailed measurements could be made at a finer level to determine the cellular, molecular, biochemical and physiological bases for these differences. Neurogenesis, apoptosis, spine density and morphology, synaptic plasticity, modifications to particular areas of the hippocampus (e.g. CA1, CA3, dentate gyrus), and synaptic efficacy (e.g. demonstration of long-term potentiation) are some of the variables that may differ among animals with divergent space use habits.

Foraging behavior in kangaroo rats: Another naturalistic system involving spatial learning focuses on species differences in food-storing and hippocampal volume in kangaroo rats. Merriam's kangaroo rats scatterhoard seeds distributing them in small quantities at multiple sites, unlike bannertail kangaroo rats which store seeds in a centralized location. Merriam's kangaroo rats also

have greater relative hippocampal volumes than bannertail kangaroo rats.⁹⁸ Thus, it appears that the greater spatial memory needs of the scatterhoarding species is reflected in increased hippocampal size. Further studies could clarify whether species differences in kangaroo rat hippocampal volumes are due to Merriam's kangaroo rats' need to remember cache locations, or because they have larger home ranges in general (comparable to the voles described previously), or still other factors.

Comparison among the results of the aforementioned studies on small mammals reveals two clear trends in hippocampal measurements and spatial performance: sex differences and seasonal changes that correspond to differential usage of space. We will now focus more closely on the latter phenomenon.

Seasonal modulation of spatial learning and the hippocampus: Seasonal changes in whole brain weight and weight of specific brain regions occur in several species of small rodents and shrews.³⁷ Average brain weight reaches a maximum during the summer then declines during the fall and winter months; during spring, brain weights begin to increase again. However, similar to changes seen after environmental enrichment, these seasonal changes are not uniformly distributed throughout the brain. The most significant decreases in brain mass occur in the neocortex and corpus striatum. The largest increase in brain mass during the spring occurs in the hippocampus (+22.9%). These seasonal changes in the brain weight of voles are dependent upon changes in photoperiod as opposed to other seasonal variables such as temperature fluctuation, or the availability of food and water resources.⁹⁹

Since one of the main functions of caching is to ensure a reliable source of energy in a variable environment, as might be expected to occur during a harsh winter, additional studies on seasonal effects on brain size could specifically compare food-caching and non-caching mammals.¹⁰⁰ Moreover, future studies could determine whether seasonal changes in hippocampal morphology occur. For example, hippocampal volume, neurogenesis, or spine density might increase during the breeding season in conjunction with the increased spatial demands of male meadow voles or other polygynous mammals; one might test this via manipulations of photoperiod, temperature, or other seasonally varying factors. Additionally, it would be interesting to ascertain whether species that rely on spatial memory primarily during the autumn when food caching is at its peak show

seasonal changes in hippocampal morphology and/or spatial learning abilities opposite to that which may occur in species whose spatial performance is maximal during the spring when home range size expands.

Other areas of interest: While the aforementioned mammalian systems provide much-needed details about spatial learning in an ecologically relevant context, they offer only a glimpse into areas that remain largely unexplored. For example, studies of spatial memory generally show a human-centered bias: visual cues are examined in detail, despite the possibility that animals may rely more heavily on other senses or may vary their dependence on particular modalities. Yellow pine chipmunks use spatial memory to locate hidden seeds that are dry but rely on olfactory cues when seeds are wet.¹⁰¹ Various other rodent species show decreased ability to locate seeds buried in dry as opposed to moist substrates.^{102,103} This finding may have important implications for food caching rodents living in arid habitats: spatial memory may be relied upon more heavily to locate buried food items during times of drought than during periods of higher water availability. Since the dentate gyrus is important in spatial processing,^{104,105} and since neurogenesis in adult mammals is thought to be restricted to the dentate gyrus and olfactory bulbs, might chipmunks show differential reliance on the two structures between the dry and rainy season? If so, is it also possible that chipmunks show seasonal differences in neurogenesis or other measures of plasticity in these two regions?

It also would be worthwhile examining species or population differences in spatial abilities with respect to differences in habitat. Tantalizing results along these lines have been provided by Galea *et al.*,⁹⁷ who demonstrated that deer mice from an island population performed better on a Morris water maze task than deer mice from a population living in an arid mainland habitat. Although this difference was believed to be due to the superior swimming ability of the island mice rather than any spatial learning deficiencies on the part of the land-locked animals, it illustrates the potential for discovery of behavioral differences linked to local habitat variations within a species. Differential spatial performance is also nicely illustrated by two primate species, golden lion tamarins and Wied's marmosets, which have similar diets but show very different feeding ecologies: tamarins, which forage over much larger areas than marmosets, outperformed marmosets on a radial arm maze-analog.¹⁰⁶ It remains to be seen

whether these species also show differences in hippocampal size.

Ontogenetic studies of the relationship between brain and naturalistic behaviors are fairly uncommon; nonetheless, spatial experience during early developmental stages can have profound effects on spatial performance during later life. Suckling rat pups can increase their milk uptake by exhibiting nipple-shifting behavior as each nipple becomes depleted of its contents. The number of maternal nipples available to suckling rats and at 25 days of age were experimentally altered; rats were then tested on an 8-arm radial maze. Pups that had been reared with only four nipples available took much longer to acquire this task than those that had 12 nipples available. Moreover, rats allowed to nipple-shift among 12 nipples had significantly larger hippocampal mass than animals exposed to only four nipples.¹⁰⁸

Another gap in our understanding of spatial systems comes from the fact that, although a wealth of knowledge is available regarding the fine structure and connectivity of the mammalian hippocampus (particularly in rodents), very little has been done to relate this information to spatial learning in naturalistic settings. The studies mentioned above determine only gross changes in hippocampal morphology such as relative volumes, whereas synaptic plasticity, changes in dendritic arborization, and other such variables have been largely ignored. An intriguing step in this direction is exemplified by studying relationships between the extent of infrapyramidal mossy fiber (IIP-MF) projections (which project to hippocampal pyramidal cells) and various hippocampus-dependent behaviors in genetically defined rodent (generally mouse) strains.^{109,110} For example, mouse strains with more extensive IIP-MF projections showed better spatial working memory in a radial maze task than did other strains.¹¹¹ Moreover, these mouse strains could be artificially selected for better or worse performance on spatial tasks.^{92,112}

An exciting new approach to grasping the mechanisms underlying spatial learning is illustrated by work on the development of a line of genetically engineered 'knockout' mice in which the gene encoding the NMDA₁-receptor is deleted only in the pyramidal cells of the CA1 region of the hippocampus.¹¹³ These animals show severe deficiencies in acquiring the Morris water maze task, lack of normal synaptic plasticity at the Shaffer collateral-CA1 junction, and abnormalities in firing behavior of CA1 place cells. Use of this new technology could be applied to examine the cellular and subcellular basis of spatial learning in

naturalistic behavioral assays. However, it would be wise to heed warnings not to jump blindly onto the gene-targeting bandwagon; the cause(s) of phenotypic (including behavioral) changes that occur may not be immediately discernible.¹¹⁴⁻¹¹⁸ For example, disruption of a single gene might lead to compensatory effects of other genes, the presence or absence of which may vary depending on the strain of mouse used. Gerlai^{114,115} and Lathe¹¹⁷ provide suggestions for how such problems may be avoided. Another noteworthy observation is that although the Morris water maze is typically used to test spatial learning in rodents, the house mouse is ill-adapted to watery environments and thus would not be expected to perform optimally in such a situation.¹¹⁹ Despite these caveats, recent innovations in recombinant DNA techniques such as the ability to target gene knockouts to particular regions or cell types^{113,120} and the ability to induce such effects as desired time-points^{121,122} show great promise for future comprehension of the interplay between genes and neural systems.

Hippocampal growth and neurogenesis

How do experiences in nature affect the structure of the nervous system, and how does the nervous system in turn translate these experiences into "the stuff that memories are made of?" One of the most popular held beliefs in neuroscience is that the neurobiological bases of learning and memory reside in changes in synaptic efficacy. Synaptic efficacy can be altered in a number of ways including changes in amount of presynaptic neurotransmitter release, number of postsynaptic neurotransmitter receptors, extent of dendritic arborization, dendritic spine numbers and size, number of synapses, etc. One additional candidate postulated for the hippocampus, occurs concomitant with spatial learning in the natural environment: the birth of new neurons.

Perhaps the single most striking similarity between the avian and mammalian hippocampus is that post-developmentally, both the avian and mammalian hippocampus demonstrate neurogenesis,²¹⁻²⁵ experience-dependent growth²⁶⁻²⁹ and experience-dependent neurogenesis.³⁰⁻³³ Furthermore, the growth of the hippocampus of both birds and mammals responds to seasonal/photoperiodic changes.³⁴⁻³⁷ Although post-developmental neurogenesis in the hippocampus of mammals was first observed over 3 decades ago, the possible connection to learning and memory has been relatively unexplored until recently.

Experience-dependent growth and neurogenesis in mammals: The landmark publication by Rosenzweig *et al.*²⁸ provided the first evidence for brain plasticity and our notions of how experiences could mold the brain were radically changed. Young rats raised in enriched environments since weaning had substantially larger brains than their impoverished cohorts, implying that the experiences gained by the enriched rats somehow resulted in significant morphological brain changes. Typically, these studies involved the addition of toys, manipulanda and activity wheels into the animals' home cages and was considered to be enrichment relative only to the lack of these objects in standard laboratory housing conditions. Furthermore, rats which learned to traverse mazes in their home cages also showed increased in brain weight when compared to those maintained in impoverished conditions; however these differences were not as large as those seen in the rats given the standard enrichment toys.¹²³ In additional studies, Rosenzweig and his colleagues introduced the animals at successively older ages and continued to find brain chemistry (primarily in acetylcholinesterase activity) and size differences even when rats were placed in the enriched or impoverished environments after the age of 280 days. These changes included increased brain weight mainly due to changes in cerebral cortex, especially the occipital area. Brains of animals maintained in an enriched environment showed greater branching of dendrites, increased number of dendritic spines, increased hippocampal thickness and more glia.^{124,125}

At the time, synaptogenesis and growth of dendritic arborization was hypothesized to be the probable causes of volumetric changes, although others hypothesized that production of new neurons may also account for the increase.³⁰ Recent evidence indicates that neurogenesis does indeed occur in young³¹ and old mice³² and that enriched environments serve to prevent subsequent apoptosis of the new cells in the mammalian dentate gyrus. Specifically, mice housed in enriched environments did not differ from their impoverished cohorts in initial levels of neurogenesis but did differ on total numbers of newly-born cells one month later. This is, environmental enrichment had no effect on the proliferative activity of the progenitor cells but instead acted to promote survival in newly formed cells. Furthermore, enriched housing resulted in behavioral improvement on a Morris water maze task in both young and old mice.

Neurogenesis in the mammalian hippocampus is found almost exclusively in the granule cell layer of the dentate gyrus.¹²⁶ Neural precursor cells

found at the border between the hilus and the granule cell layer divide, migrate into the granule cell layer as early as 24 h following DNA synthesis,¹²⁷ and extend neuronal processes. New-born granule cells are capable of extending their axonal projections along the mossy fibers to the hippocampal CA3 region. The mechanisms underlying adult neurogenesis are unknown, however, it seems likely that since neurogenesis is a common developmental process, factors mediating the birth of new cells in the developing brain may also do so in the aging brain. For example, in the developing brain, radial glia are presumed to guide migrating neurons to their final destinations,¹²⁸ after serving this function, they are believed to differentiate into astrocytes. Probably not by coincidence, radial glia can also be found in the adult rat brain in the dentate gyrus¹²⁹ and may serve the same function. Additionally, both developmental and adult neurogenesis is mediated by adrenal steroids possibly through the activation of NMDA receptors.^{130,131}

Although it is not known what role hippocampal neurogenesis plays in learning and memory, models of hippocampal function and LTP predict that the performance of a distributed associative memory system may be greatly enhanced with increases in size (and presumably number) especially those neural networks hypothesized to involve the dentate gyrus.¹³² One fascinating study determined that *in vivo* stimulation of mossy fibers in rats results in an increase in dentate gyrus neurogenesis.¹³³ LTP induction was not necessary which implies that an increase in cell birth is the result of general neural activity but not specific neural activity hypothesized to mediate learning and memory.

The effects of enriched environments or LTP stimulation on hippocampal neurogenesis has yet to be explored in birds. However much has been done to explore the conditions under which hippocampal growth and neurogenesis occurs in the brains of birds that store food.

Experience-dependent growth and neurogenesis in birds: Studies in both corvid and parid bird species have shown that food-storers and non-storers differ in their relative hippocampal volume with no measurable difference in cell density.^{67,68} These volumetric differences are accompanied by more cells as well as qualitatively different cells.^{134,135} Furthermore, this difference is seen only in adult birds not in nestlings^{136,137} and, in black-capped chickadees, it is accompanied by a peak in neurogenesis during the same seasonal period as the peak in storing behavior.²⁴ This indicates that

changes in volume may occur in response to changes in the environment itself as the bird ages (e.g. season) and/or changes in behavior called into play post-developmentally that are reliant upon the hippocampus such as food storing and retrieval.

These possibilities were investigated by studying the development of food storing in hand-reared marsh tits.^{27,138,139} Birds were hand-reared until nutritional independence, then housed individually and released individually into a room provided with seeds and places in which to store food. Birds in the control condition were treated identically but were given powdered seed instead of whole seeds so that they could eat but not store. Trials were conducted either daily or once every 3 days starting at day 35. In the experimental room, storing began on trial one of day 35 posthatching and showed a sharp increase in the number of seeds stored at day 44. This sharp increase was not dependent upon amount of experience; that is, birds given daily exposure to *ad lib* seeds did not differ from birds exposed once every 3 days nor birds given only one seed to store every day.¹³⁹ Memory-based retrieval increased gradually after the initial onset of storing. If birds were deprived of storing and retrieving experience until different ages (day 59, 83 or 115), all still stored and retrieved within the first three trials; thus, within the range of ages tested, birds did not show a sensitive period beyond which storing and retrieving could not occur.¹³⁹

Marsh tits deprived of storing experience until different ages then given various amounts of experience storing and retrieving seeds show an increase in the number of neurons and relative volume of the hippocampus regardless of age; there were no differences in neuron size or density.²⁷ Amount of experience tended to result in asymptotic hippocampal growth such that after a point, no additional 'gain' was observed. Storing one seed per day did not trigger growth; but storing and retrieving *ad libitum* seeds daily did not result in any additional growth than that obtained by storing and retrieving once every third day. Quite the contrary, absence of experience resulted in a cumulative loss of cells and decrease in hippocampal volume; the longer they went without storing experience, the smaller the hippocampus became. No such effects were found in a control area of the brain, the ectostriatum.

In a further analysis, hippocampal volumes were obtained from birds allowed to store every 3 days having received 3, 5 or 8 trials (days 41, 47 and 56 respectively).²⁶ A significant increase in hippocampal volume was evident by day 41 after only three trials and prior to the sharp increase in storing

seen on day 44. These results suggest that only three trials are necessary to trigger hippocampal growth and this trigger occurs prior to rather than after, or simultaneous with, the sudden increase in storing. Later studies showed that experiences on a one-trial learning task can also trigger hippocampal growth in food storing birds but not in non-storers,²⁶ indicating that hippocampal growth is not triggered only by food caching experience and that the brains of food-storing birds may respond to hippocampus-dependent activities in a different way to non-storers. Furthermore, there may be differences in the way storers and non-storers solve tasks; for example, storers preferentially used spatial cues whereas non-storers preferentially used feeder-specific color and pattern cues.

Since new neurons are added to the avian brain throughout adulthood, these results may reflect the possibility that specific experiences may induce neural proliferation above and beyond baseline levels, suppress baseline levels of apoptosis (this is, promote survival of pre-existing cells), promote survival of new cells, or any combination of the above. Unlike mammalian hippocampus neurogenesis which occurs in the granule cell layer of the dentate gyrus directly, neural proliferation in the avian brain occurs in the ventricular zone (VZ) forming the ventral border of the hippocampus and dorso-medial aspect of the hyperstriatum ventrale. New cells then migrate into the brain and differentiate into neurons; gliogenesis is thought to also occur within the parenchyma but only neurons are believed to originate with the VZ.¹⁴⁰

To determine whether caching experience induces neural proliferation, a comparison was made between juvenile marsh tits that were given either 0, 3, 5 or 8 trials of food storing and retrieving experience every 3 days between the ages of 35 and 56 days posthatch; control birds were given the same number of trials in the experimental room, but powdered food was provided so that storing and retrieving was impossible.³³ Autoradiographic data indicated that after 3 trials of storing and retrieval, experienced birds showed a significantly higher rate of cell proliferation in the VZ than controls. After 8 trials, experienced birds showed a significantly higher total cell count and neuron count in the hippocampus. Since birds were sacrificed before new neurons could migrate, it is impossible to show definitively whether the higher total cell count was the result of neural proliferation. However, since there was no significant differences between groups in the rate of cell death, it is unlikely that the high cell counts were the result of the sparing of older cells from apoptosis.

It is of interest to note that in adult black-capped chickadees when new neurons are allowed to migrate for 6 weeks, they move a mean distance from the nearest ventricular wall of 165 μ and show a marked distribution from rostral (highest number) to caudal (lowest) hippocampus.²⁴ Closer analysis and further work will be directed at determining whether these new neurons migrate into the putative hippocampus proper or rather into the avian homolog of the dentate gyrus, area parahippocampalis.

Ontogenetic studies have shed much light on processes that occur as a result of caching experience in juveniles, but do the same processes occur in adults? Although at lower levels, neurogenesis occurs in adults and it shows seasonal peaks that correspond to seasonal peaks in storing behavior. The key question here seems to be 'does season recapitulate development?'

Summary and speculation

A compelling argument can be made that the avian and mammalian hippocampus plays an important role in natural behaviors that are reliant upon spatial learning ability. Furthermore, seasonal constraints on the occurrence of these behaviors provide a potentially illuminating framework within which to explore neurobiological mechanisms and brain plasticity. A summary of the evidence is as follows. First, the avian and mammalian hippocampal formation are homologous structures. Second, both the mammalian and avian hippocampus retain the ability for neurogenesis. Third, behaviors occurring in nature that are dependent upon spatial learning ability such as homing and caching in birds and home range navigation in mammals involve the hippocampus. Fourth, of these hippocampus-mediated natural behaviors, those that vary seasonally are accompanied by seasonal morphological changes in the hippocampus. Specifically, the hippocampus increases in volume in mammals, and both volume and neurogenesis in birds during those seasons in which the demand for spatial learning ability is at its greatest. It is currently unknown whether the mammalian hippocampus undergoes seasonal neurogenesis however work to that effect is being done in our laboratory comparing Alaskan red squirrels trapped at various times of year.

Changes in absolute or relative weights of whole brains or of various brain structures do not necessarily result in changes of functions important to memory formation. It is also possible that the waxing and waning of selective brain regions may be concomitant to changes in the forms of learning

dependent upon those structures; such seems to be the case with the hippocampus. One must remain cautious however, in continuing with the logic to hypothesize a role of such volumetric changes, specifically those due to neurogenesis, in memory formation per se. To date, no study, mammalian or avian, has indicated that neurogenesis actually mediates learning and memory. Certainly neurogenesis alone does not account for the total growth of the hippocampus due to experience but might not neurogenesis then be a mechanism through which the hippocampus can respond to an influx of environmental stimuli in order to become a more efficient and effective processor of information?

Using an approach based on the problems confronted by animals in their own environments and designing tasks that exploit these behaviors, we can begin to provide the link between information derived solely in the laboratory with that derived from the field. A synthesis of this information would yield theories grounded by ecological relevancy and supported by naturalistic, semi-naturalistic, and laboratory research.

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