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Spatial View Cells in the Primate Hippocampus and Memory Recall

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SYNOPSIS

Hippocampal spatial view neurons in primates provide allocentric representations of a view of space 'out there'. The responses depend on where the monkey is looking; and can be updated by idiothetic (self-motion) inputs provided by eye movements when the view is hidden. In a room-based object-place memory task, some hippocampal neurons respond to the objects shown, some to the places viewed, and some to combinations of the places viewed and the objects present in those locations. In an object-place recall task when the location in space at which an object has been seen is recalled by the presentation of the object, some primate hippocampal neurons maintain their responding to the object recall cue in a delay period without the object visible while the place is being recalled; and other neurons respond to the place being recalled. Other spatial view neurons form associations with the rewards present at particular locations in space. These findings, and computational models of the hippocampus, help to show how the primate including human hippocampus is involved in episodic memory.

KEY WORDS

hippocampus, spatial view cells, place cells, episodic memory, allocentric coordinate system, memory, recall, object-place memory, reward-place memory, computational models, attractor networks, auto-association networks

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INTRODUCTION

The aims of this paper are to consider how space is represented in the primate hippocampus, how this is related to the memory and spatial functions performed by the hippocampus, and how the hippocampus performs these functions. The neurophysiological studies described have been performed (unless stated otherwise) with macaque monkeys in order to provide information as relevant as possible to understanding memory and spatial systems in humans. Given the great development of vision in primates relative to rodents, and with it the temporal cortical visual areas concerned with vision (which provide many inputs to the hippocampus via, for example, the perirhinal cortex), it is important to investigate whether hippocampal processing of space is identical to that of rats, in which place cells are found /30,33,35,43/.

Because of the developments of the primate brain, some of the connections received by the primate hippocampus are reviewed, as they are relevant to understanding the types of neuron found in the primate hippocampus. The primate hippocampus receives inputs via the entorhinal cortex (area 28) and the highly developed parahippocampal gyrus (areas TF and TH) as well as the perirhinal cortex from the ends of many processing streams of the cerebral association cortex, including the visual and auditory temporal lobe association cortical areas, the prefrontal cortex, and the parietal cortex /2,3,91,99/ (see Fig. 1). The hippocampus is thus by its connections potentially able to associate together object and spatial representations. In addition, the entorhinal cortex receives inputs from the amygdala, and the orbitofrontal cortex, which could provide reward-related information to the hippocampus /10,49,85,90/. There are also direct subcortical inputs from, for example, the amygdala and septum /1/. The hippocampus in turn projects back via the subiculum, entorhinal cortex, and parahippocampal gyrus (area TF-TH), to the cere-

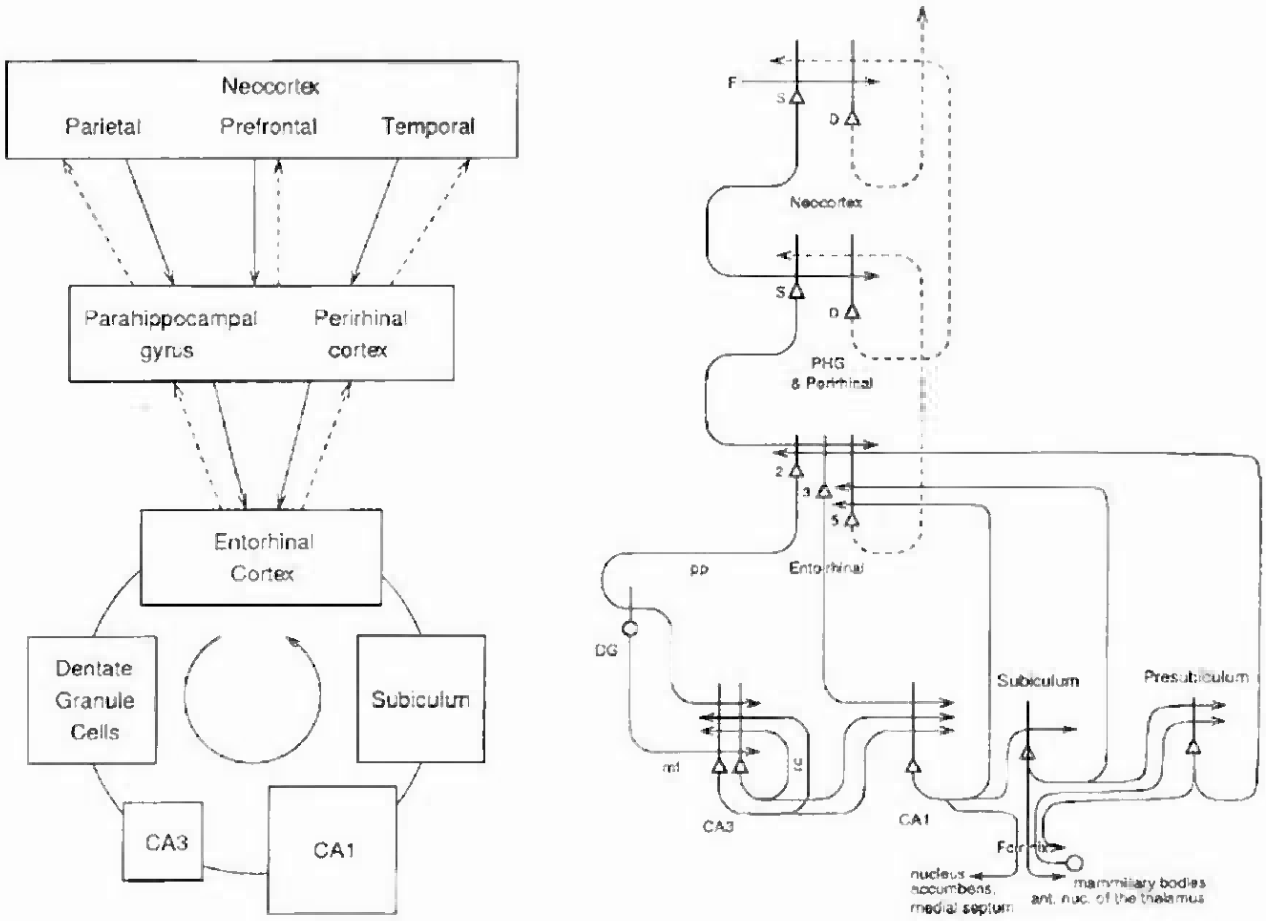

Fig. 1: Forward connections (solid lines) from areas of cerebral association neocortex via the parahippocampal gyrus and perirhinal cortex, and entorhinal cortex, to the hippocampus; and back-projections (dashed lines) via the hippocampal CA1 pyramidal cells, subiculum, and parahippocampal gyrus to the neocortex. There is great convergence in the forward connections down to the single network implemented in the CA3 pyramidal cells; and great divergence again in the back-projections. Left: block diagram. Right: more detailed representation of some of the principal excitatory neurons in the pathways. D = deep pyramidal cells; DG = dentate granule cells; F = forward inputs to areas of the association cortex from preceding cortical areas in the hierarchy; mf = mossy fibres; PHG = parahippocampal gyrus and perirhinal cortex; pp = perforant path; rc = recurrent collateral of the CA3 hippocampal pyramidal cells; S = superficial pyramidal cells; 2 = pyramidal cells in layer 2 of the entorhinal cortex; 3 = pyramidal cells in layer 3 of the entorhinal cortex; 4 = pyramidal cells in layer 4 of the entorhinal cortex. The thick lines above the cell bodies represent the dendrites.

bral cortical areas from which it receives inputs /99/, as well as to subcortical areas such as the mammillary bodies (see Fig. 1).

In the studies of neuronal responses in the primate hippocampus that are described, the recordings of neuronal activity have generally been made while the hippocampus is performing the functions for which lesion studies have shown it is needed. Lesion studies have shown that damage to the hippocampus or to some of its connections, such as the fornix, in monkeys produces deficits in learning about the places of objects and about the places where responses should be made. For example, macaques and humans with damage to the hippocampal system or fornix are impaired in object-place memory tasks in which not only the

objects seen, but where they were seen, must be remembered /20,23,47,84/. Posterior parahippocampal lesions in macaques impair even a simple type of object-place learning in which the memory load is just one pair of trial-unique stimuli /29/. Further, neurotoxic lesions that selectively damage the primate hippocampus impair spatial scene memory /37/. In addition, fornix lesions impair conditional left-right discrimination learning, in which the visual appearance of an object specifies whether a response is to be made to the left or the right /80/. A comparable deficit is found in humans /48/. Fornix sectioned monkeys are also impaired in learning on the basis of a spatial cue which object to choose (e.g. if two objects are on the left, choose object A, but if the two objects are on the right, choose object B) /21/. Monkeys with fornix damage are also impaired in using information about their place in an environment. For example, Gaffan and Harrison /22/ found learning impairments when which of two or more objects the monkey had to choose depended on the position of the monkey in the room.

In recordings made in the primate hippocampus under similar conditions to those in which place cells would be found in rats, we have not so far found neurons that respond in relation to the place where the monkey is. Instead, we have found spatial view cells, which may be thought of as responding to the place at which the monkey is looking. Because these neurons are in some sense concerned with place, their properties are described in this paper. The way in which these cells were discovered, and some of the tasks in which they respond, are as follows.

MEMORY FOR THE POSITIONS OF RESPONSES AND FOR THE PLACES OF STIMULI IN MEMORY TASKS

Watanabe and Niki /100/ analysed hippocampal neuronal activity while monkeys performed a delayed spatial response task. In a delayed spatial response task, a stimulus is shown on, for example, the left, there is then a delay period, and after this the monkey can respond, by for example touching the left stimulus position. They reported that 6.4% of hippocampal neurons responded differently while the monkey was remembering left as compared to right. The responses of these neurons could reflect preparation for the spatial response to be made, or they could reflect memory of the spatial position in which the stimulus was shown. To provide evidence on which was important, Cahusac *et al.* /8/ analysed hippocampal activity in this task, and in an object-place memory task. In the object-place memory task, the monkey was shown a sample stimulus in one position on a video screen, there was a delay of 2 seconds, and then the same or a different stimulus was shown in the same or in a different position. The monkey remembered the sample and its position, and if both matched the delayed stimulus, he licked to obtain fruit juice. Of the 600 neurons analysed in this task, 3.8% responded differently for the different spatial positions, with some of these responding differentially during the sample presentation, some in the delay period, and some in the match period. Thus some hippocampal neurons (those differentially active in the sample or match periods) respond differently for stimuli shown in different positions in space, and some (those differentially active in the delay period) respond differently when the monkey is remembering different positions in space. In addition, some of the neurons responded to a combination of object and place information, in that they responded only to a novel object in a particular place. These neuronal responses were not due to any response being made or prepared by the monkey, because information about which behavioural response was required was not available until the match stimulus was shown. Cahusac *et al.* /8/ also found that the majority of the neurons which responded in the object-place memory task did not respond in the delayed spatial response task. Instead, a different population of neurons (5.7% of the total) responded in the delayed spatial response task, with differential left-right responses in the sample, delay, or match periods. Thus this latter population of hippocampal neurons had activity which was related to the preparation for or initiation of a spatial response, which in the delayed response task could be encoded as soon as the sample stimulus was seen.

These recordings showed that there are some neurons in the primate hippocampus with activity

which is related to the spatial position of stimuli or to the memory of the spatial position of stimuli (as shown in the object-place memory task). The recordings also showed that information about which visual stimulus was shown, and where it was shown, was combined onto some neurons in the primate hippocampus.

OBJECT-PLACE MEMORY TASKS.

The responses of hippocampal neurons in primates with activity related to the place in which a stimulus is shown was further investigated using a serial multiple object-place memory task. The task required a memory for the position on a video monitor in which a given object had appeared previously /66/. This task was designed to allow a wider area of space to be tested than in the previous study, and was chosen also because memory of where objects had been seen previously in space was known to be disrupted by hippocampal damage /19,20/. In the task a visual image appeared in one of four or nine positions on a screen. If the stimulus had been seen in that position before, the monkey could lick to obtain fruit juice, but if the image had not appeared in that position before, the monkey had not to lick in order to avoid the taste of saline. Each image appeared in each position on the screen only twice, once as novel, and once as familiar. The task thus required memory not only of which visual stimuli had been seen before, but of the positions in which they had been seen, and is an object-place memory task. It was found that 9% of neurons recorded in the hippocampus and parahippocampal gyrus had spatial fields in this and related tasks, in that they responded whenever there was a stimulus in some but not in other positions on the screen. 2.4% of the neurons responded to a combination of spatial information and information about the object seen, in that they responded more the first time a particular image was seen in any position. Six of these neurons were found which showed this combination even more clearly, in that they, for example, responded only to some positions, and only provided that it was the first time that a particular stimulus had appeared there. Thus not only is spatial information processed by the primate hippocampus, but it can be combined as shown by the responses of single neurons with information about which stimuli have been seen before /66/.

The ability of the hippocampus to form such arbitrary associations of information probably originating from the parietal cortex about position in space with information originating from the temporal lobe about objects may be important for its role in memory. Moreover these findings provide neurophysiological support for the computational theory according to which arbitrary associations are formed onto single neurons in the hippocampus between signals originating in different parts of the cerebral cortex, e.g. about objects and about position in space /58,74,97/.

AN ALLOCENTRIC REPRESENTATION OF SPACE IN THE PRIMATE HIPPOCAMPUS

These studies showed that some hippocampal neurons in primates have spatial fields. In order to investigate how space is represented in the hippocampus, Feigenbaum and Rolls /15/ investigated whether the spatial fields use egocentric or some form of allocentric coordinates. This was investigated by finding a neuron with a space field, and then moving the monitor screen and the monkey relative to each other, and to different positions in the laboratory. For 10% of the spatial neurons, the responses remained in the same position relative to the monkey's body axis when the screen was moved, or the monkey was rotated or moved to a different position in the laboratory. These neurons thus represented space in egocentric coordinates. For 46% of the spatial neurons analysed, the responses remained in the same position on the screen or in the room when the monkey was rotated or moved to a different position in the laboratory. These neurons thus represented space in allocentric coordinates. Evidence for two types of allocentric encoding was found. In the first type, the field was defined by its position on the monitor screen independently of the position of the monitor relative to the monkey's body axis and independently of the position of the monkey and the screen in the laboratory. These neurons were called 'frame of reference' allocentric, in that their fields were defined by the local frame provided by the monitor screen. The majority of the allocentric neurons

responded in this way. In the second type of allocentric encoding, the field was defined by its position in the room at which they monkey was looking, and was relatively independent of position relative to the monkey's body axis or to position on the monitor screen face. These neurons were called 'absolute' allocentric, in that their fields were defined by position in the room. They are what we have gone on to show subsequently are spatial view neurons. These results showed that in addition to neurons with egocentric spatial fields, which have also been found in other parts of the brain, such as the parietal cortex /5/, there are neurons in the primate hippocampal formation which encode space in allocentric coordinates.

SPATIAL VIEW NEURONS IN THE PRIMATE HIPPOCAMPUS

In rats, place cells are found which respond depending on the place where the rat is in a spatial environment (see /33,35,39/). In a first investigation to analyse whether such cells might be present in the primate hippocampus, Rolls and O'Mara /67,68/ recorded the responses of hippocampal cells when macaques were moved in a small chair or robot on wheels in a cue-controlled testing environment (2 m x 2 m x 2 m chamber with matt black internal walls and floors). Tests were performed to determine whether cells might be found which could be described as 'place-related', i.e. firing differently when macaques are moved to different places in this environment; or according to the position in space at which the monkey is looking; or according to his 'head direction'. The most common type of cell responded to the part of space at which the monkeys were looking, independently of the place where the monkey was. These neurons were called 'view' neurons, and are similar to the space neurons described by Rolls *et al.* /66/ and Feigenbaum and Rolls /15/. (The main difference was that in the study of Rolls *et al.* /66/ and Feigenbaum and Rolls /15/, the allocentric representation was defined by where on a video monitor a stimulus was shown; whereas spatial view cells respond when the monkey looks at a particular part of a spatial environment.) Some of these view neurons had responses which depended on the proximity of the monkey to what was being viewed. Thus in this study the neuronal representation of space found in the primate hippocampus was shown to be defined primarily by the view of the environment, and not by the place where the monkey was /67,68/. Ono *et al.* /45/ performed studies on the representation of space in the primate hippocampus while the monkey was moved in a cab to different places in a room. They found that 13.4% of hippocampal formation neurons fired more when the monkey was at some than when at other places in the test area, and although some neurons responded more when the monkey was at some places than at others, it was not clear whether the responses of these neurons responded to the place where the monkey was independently of spatial view, or whether the responses of place-like cells were view dependent. This critical issue is discussed after the properties of spatial view cells have been described further, when tests which can distinguish spatial view cells from place cells will become more clear.

In rats, place cells fire best during active locomotion by the rat /17/. To investigate whether place cells might be present in monkeys if active locomotion was being performed, we recorded from single hippocampal neurons /24,50,69,76/ while monkeys moved themselves round the test environment by walking (or running) on all fours. In addition, to bring out the responses of spatial cells in the primate hippocampus, we changed from the cue-controlled environment of Rolls and O'Mara /68/, which was matt black apart from four spatial cues, to the much richer environment of the open laboratory, within which the monkey has a 2.5 x 2.5 m area to walk. The position and head direction of the monkey are tracked continuously, and the eye position (i.e. the horizontal and vertical directions of the eyes with respect to the head) is recorded continuously with the scleral search coil technique so that we can measure exactly where the monkey is looking in the environment at all times. An example of a hippocampal pyramidal cell recorded during active locomotion in this environment is shown in Figure 2. Figure 2a shows in the outer set of rectangles all the firing that occurred during a period of 6 minutes when the monkey was walking around the laboratory. The icons of the cart position

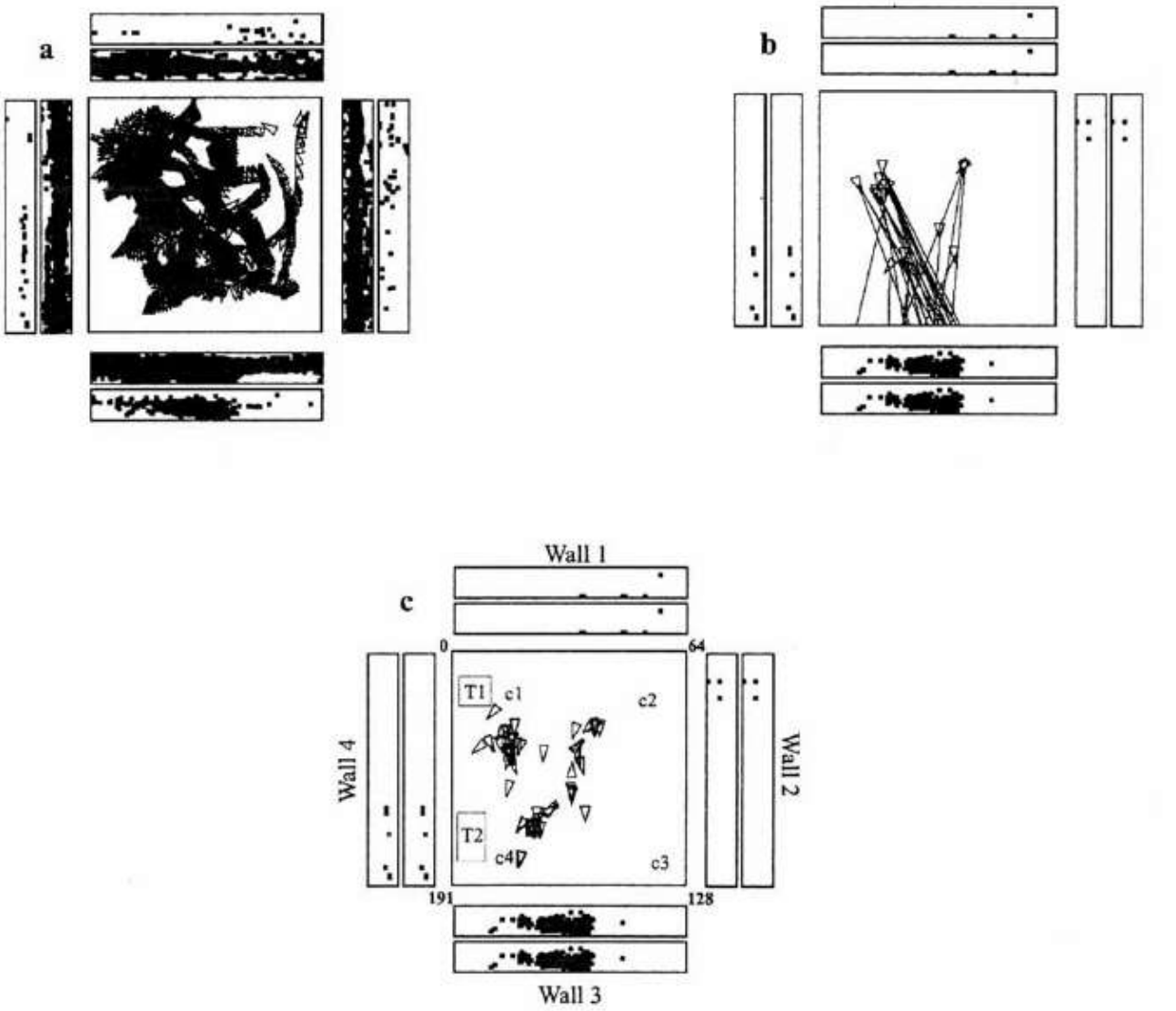

Fig. 2: Examples of the firing of a hippocampal cell (az033) when the monkey was walking around the laboratory. **a.** The firing of the cell is indicated by the spots in the outer set of four rectangles, each of which represents one of the walls of the room. There is one spot on the outer rectangle for each action potential. The base of the wall is towards the centre of each rectangle. The positions on the walls fixated during the recording sessions are indicated by points in the inner set of four rectangles, each of which also represents a wall of the room. The central square is a plan view of the room, with a triangle printed every 250 ms to indicate the position of the cart, thus showing that many different places were visited during the recording sessions. **b.** A similar representation of the same three recording sessions as in (a), but modified to indicate some of the range of cart positions and horizontal gaze directions when the cell fired. To enable individual cart/eye gaze direction icons to be distinguished, only every 10^{th} icon was plotted when the cell fired faster than 12 spikes/sec. A spot was placed in the rectangles whenever the cell fired at greater than 12 spikes/sec. **c.** A similar representation of the same three recording sessions as in (b), but modified to indicate more fully the range of cart positions when the cell fired. To enable individual cart/eye gaze direction icons to be distinguished only every 10^{th} icon was plotted when the cell fired faster than 12 spikes/sec. (12 spikes/sec was selected as it was half the peak firing rate of the cell, and thus helps to reveal the conditions when the cell was strongly activated.) The triangle indicates the current position of the monkey, and the line projected from it shows which part of the wall is being viewed at any one time while the monkey is walking. One spot is shown for each action potential. (Reprinted with permission from Georges-François *et al.* /24/; Fig. 1.)

printed every 250 ms show that a wide area of the laboratory was explored during the period. The cell fired mainly when the monkey was looking at a part of wall 3, and this is brought out in Figures 2b and 2c in which a spot is placed on the walls where the monkey was looking only when the firing rate was above 12 spikes/sec, the half-maximal firing rate. The fact that the cell responded when the monkey was looking at the spatial view field on wall 3 from a large number of different places in the room is brought out in Figure 2b, in which every tenth cart position and horizontal gaze direction when the cell fired at greater than 12 spikes/sec are shown. The range of different cart positions and head directions (which were aligned with the cart direction) over which the cell fired when the cell responded at more than 12 spikes/sec is brought out in Figure 2c, in which every cart position and head direction for this response rate are shown. Further analyses of the response properties of this cell, including evidence that it responded for a whole set of different head positions, head directions and eye positions, and that it had similar spatial view fields when the monkey was actively walking and when he was stationary but exploring the environment with eye movements, are provided by Georges-François *et al.* /24/.

The responses of another cell to show how the responses are related to spatial view, and not to place, head direction, or eye position *per se*, are shown in Figure 3. The firing of the cell as a function of horizontal and vertical eye position is shown in Figure 3a (left) with the monkey stationary at the place and with the head direction shown in Figure 3a (right). (The firing rate of the neuron was measured whenever the eyes were stationary to within 1 degree for more than 250 ms, and data for several minutes of recording are shown.) The highest firing rate of the cell was found when the monkey was looking approximately 10° left and level in the vertical plane. The response field of the cell is plotted against wall 1 in Figure 3a (right). The recording time for the data shown in Figure 3a was approximately 4 min. The monkey was then moved to the different place with a different head direction shown in Figure 3b. The highest firing rate was now when the monkey was looking approximately 30° right. The response field of the cell is again plotted against wall 1 in Figure 3b (right). Data with the monkey at a different place (but the same head direction as in b) are shown in Figure 3c. The cell now fired most when the monkey looked approximately 30° left. The response field was, however, at the same place on wall 1 as in Figure 3a and b. It is clear from this type of experiment that it was where the monkey was looking that determined whether the neuron responded, and not a particular head direction, eye position, or place where the monkey was located. This was confirmed in one-way analyses of variance, in which the several hundred firing rate and eye position data pairs used to construct Figure 3a-c were sorted according to different hypotheses. When the data for level eye position plus and minus 7° (the level of gaze where the cell fired if it was going to) were sorted according to where the monkey was looking on the wall (binned into six wall positions visible in Fig. 3a-c), one-way ANOVA was significant at $p < 0.001$, and the cell provided an average information (about spatial view) of 0.217 bits in a 500 ms epoch. When the same data were sorted according to eye position (binned into six bins), one-way ANOVA was not significant ($p \approx 0.8$), and the cell provided an average information (about eye position) of 0.006 bits in a 500 ms epoch. When the same data were sorted according to head direction (binned into two bins), one-way ANOVA was not significant ($p \approx 0.5$), and the cell provided an average information (about head direction) of 0.0 bits in a 500 ms epoch. When the same data were sorted according to the place where the monkey was located (binned into two bins), one-way ANOVA was not significant ($p \approx 0.9$), and the cell provided an average information (about place) of 0.001 bits in a 500 ms epoch. This analysis leads to the conclusion that the cell responded significantly differently for different allocentric spatial views and had information about spatial view in its firing rate, but did not respond differently just on the basis of eye position, head direction, or place. Across the population of cells analysed, it was possible to confirm that it was where the monkey was looking, and not the eye position, head direction, or head position in the room *per se*, which accounts for the firing of these neurons, and about which they convey most in-

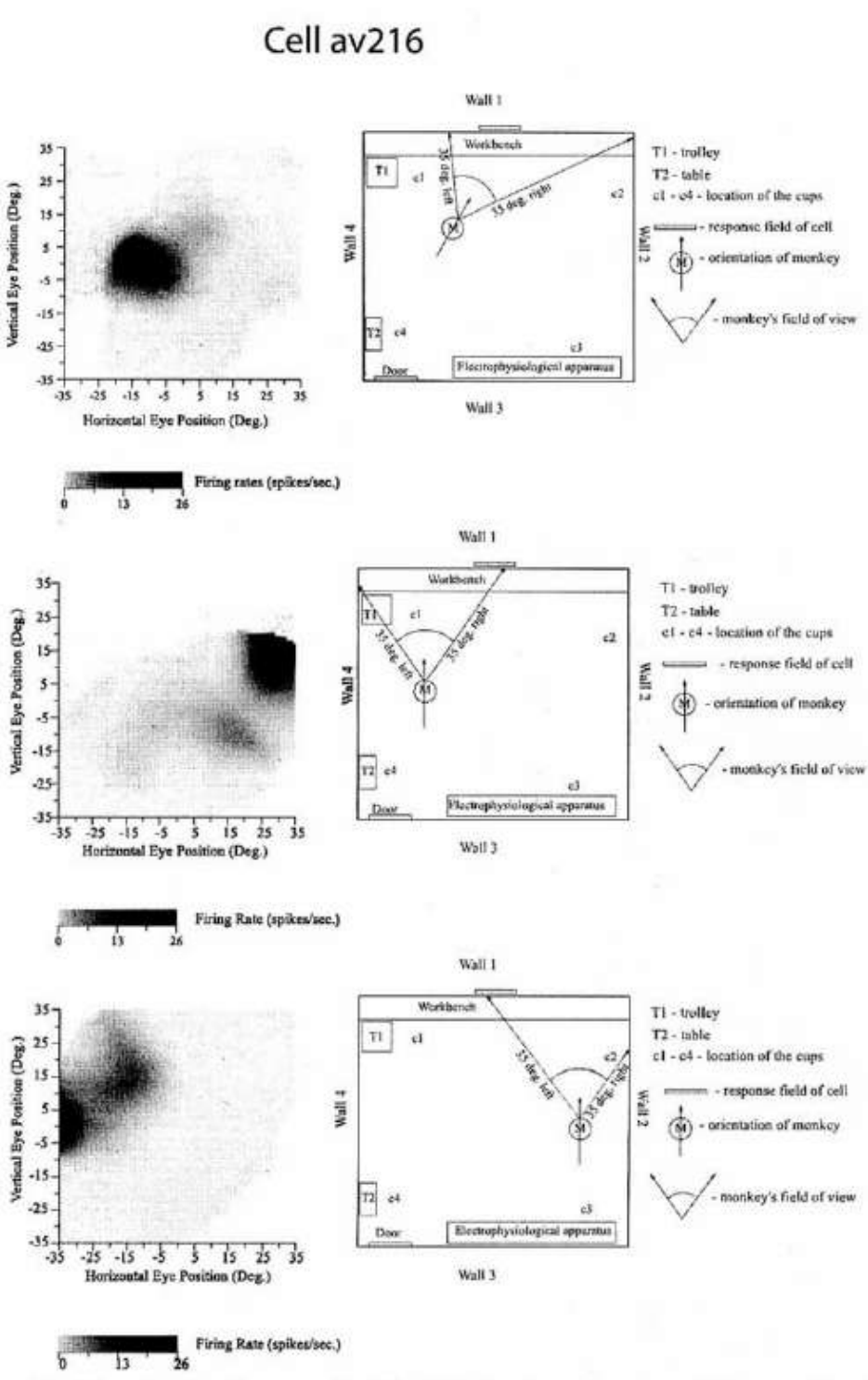

Fig. 3: Examples of the firing of another hippocampal cell (av216) when the monkey was at different positions in the room, with different head directions, looking at wall 1 of the room. The details of the spatial view field are shown by the different firing rates indicated as grey scale levels. The firing rate of the cell in spikes/sec as a function of horizontal and vertical eye position is indicated by the blackness of the diagram on the left (with the calibration bar in spikes/sec shown below). (Positive values of eye position represent right in the horizontal plane and up in the vertical plane.) The arrows in the diagrams on the right delineate the approximate position of the spatial view field. (Reprinted with permission from Georges-François *et al.* /24/; Fig. 5.)

formation /24/. This series of experiments proved that the representation was not in egocentric spatial coordinates (with respect to the head or body), but was instead allocentric, representing positions in space in world-based coordinates.

In further experiments on these spatial view neurons, it was shown that the responses of some reflected quite an abstract representation of space, in that if the visual details of the view were completely obscured by floor-to-ceiling black curtains, then many of the neurons could still respond when the monkey looked towards where the view had been /50/. There was sometimes a slight drift of the spatial view field when the curtains were closed, consistent with the hypothesis that a remembered spatial view is not as accurately located as a seen one, and with the fact that the actual view of the scene was the normal determinant of the spatial response field of the cell. The slight drift of the spatial field of the cell is also consistent with the evidence from the study reported by Georges-François *et al.* /24/ that the coordinate system used by these cells is not in eye position coordinates, nor in a combination of eye position and head direction coordinates, but in allocentric, i.e. world coordinates. The experiment by Robertson *et al.* /50/ (see also Rolls *et al.* /76/) shows that primate hippocampal spatial view neurons can be updated for at least short periods by idiothetic cues, including eye position and head direction signals, and that the drift produced by the necessary temporal integration of these signals can then be corrected by showing the visual scene again.

The cells that responded with only a small diminution of their response when the view details were obscured (or the room was placed into darkness) were found in the CA1 region, the parahippocampal gyrus and the presubiculum. Other cells had a large diminution (to on average 23% of their normal response) when the monkey looked towards the normally effective location in the environment when the view details were obscured. These cells were in the CA3 region of the hippocampus. This finding provides additional evidence that visual inputs are important in defining the response properties of spatial view neurons /50/. This reduction in the firing of the CA3 cells reflects the reduction in the visual sensory drive or recall cue to a CA3 memory system. The results indicate that for CA3 cells the visual input is necessary for the normal spatial response of the neurons, and for other cells in the primate hippocampal formation, the response still depends on the monkey gazing towards that location in space, when the view details are obscured /50/. These latter cells could therefore reflect the operation of a memory system, in which the neuronal activity can be triggered by factors which probably include not only (idiothetic) eye position command/feedback signals, but also probably vestibular and/or proprioceptive inputs. The fact that the CA3 neurons continue to fire in the dark and with the view obscured is evidence that there is an attractor (auto-association) network implemented in the CA3 recurrent collateral system that can be triggered into an attractor state by the appropriate idiothetic signals /52,53,58,74,97/. The findings are consistent with partial recovery of information in the CA3 network, which may operate by auto-association, and further recovery of information in the CA3 to CA1 associatively modifiable synapses, as has been shown to be possible in simulations and analytically by Rolls /55/, who demonstrated this retrieval effect of the Schaffer collaterals in simulations of the hippocampus, and Schultz and Rolls /82/, who produced a quantitative analysis of this effect. Another factor that could contribute to the better responses of CA1 cells when the spatial view is obscured is the direct perforant path input to the CA1 cells, which may provide additional input to the CA1 cells (see also Rolls and Treves /74/).

The spatial view field of these cells typically occupies a part of space that is about as large as $^{1}/_{16}$ of all the four walls of the testing room. Each cell has a different view to which it responds. Thus over a population of many such neurons these partly overlapping view fields represent rather precise information about the part of space being viewed. This has been quantified using information theory, and indeed it has been shown that the amount of information about which part of space the monkey is viewing increases approximately linearly with the number of neurons in the sample. Thus an independent contribution is made by each of the cells in an ensemble to representing allocentric

space /76/. Because information is a logarithmic measure, this means that the number of spatial views (or the accuracy of the representation) increases exponentially with the number of neurons in the ensemble, a powerful result. Moreover, the indication is that most of this information is contained in the number of spikes that each neuron produces within a short time window, and not in the relative time of firing of the spikes of different neurons /46/.

Many spatial view (or 'space' or 'view') cells have been found in this series of experiments /24, 50,69,76/. (The number of spatial view cells in the initial sample of 352 cells recorded under these conditions is 40; see Rolls *et al.* /69/.) It is simply noted here that their average spontaneous rate is low, mean 0.5 spikes/sec, and that their average peak firing rate is 17 spikes/sec, interquartile range 11-20 spikes/sec. This low spontaneous rate and low peak response rate is similar to that of place cells in rats. No place cells have been found that responded based on where the monkey was, and not on where he was looking in the environment. Although Ono *et al.* /45/ (see also /31/) have described cells in the macaque whose firing rate depended on the location of the macaque, we note that very extensive testing with formal contrasts of different hypotheses performed along the lines described by Georges-François *et al.* /24/ is in general needed to show whether a cell in the primate hippocampus responds to the place where the monkey is rather than spatial view. For example, given that a region of allocentric space in a room which defines the spatial view field of a spatial view cell will not be visible from all places in a room, it is not sufficient to show that the firing rate depends on the place where the monkey is, because the spatial view does as well. Another example is shown in Figure 2 of a cell (av057) which might have been interpreted as a place cell if testing with different head directions of the monkey allowing different spatial views had not been performed /56,57/. It is essential to measure the firing rate of a primate hippocampal cell with different head directions so that different spatial views can be compared, as testing with just one head direction /31/ cannot provide evidence that will distinguish a place cell from a spatial view cell. These points will need to be borne in mind in future studies of hippocampal neuronal activity in primates including humans (*cf.* /13,18,26/), and simultaneous recording of head position, head direction, and eye position, as described in this paper, will be needed. To distinguish spatial view from place cells it will be important to test neurons while the primate or human is in one place with all the different spatial views visible from that place; and also to test the same neuron when the organism is in a different place, but at least some of the same spatial views are visible, as has been done in our primate recording. It is also necessary to test primate hippocampal cells during active locomotion, in case this is an important factor as in the rat. Having said this, we have found that spatial view cells in the primate hippocampus have similar responses during active locomotion as when the monkey is stationary, but is allowed to look around and actively explore the environment with eye movements. Indeed, it is possible that this active exploration of an environment by eye movements is somewhat analogous to the active exploration which a rat does by running around. The actual recording system we use does allow the monkey very active locomotion when he is moving on all four legs, in that the chair on wheels is attached only to his head, and allows head angular velocities as large as 100 degrees/sec and linear motion of 0.6 m/sec, so it is unlikely that this has resulted in our not finding place cells in the primate hippocampus. However, we do not have a strong position on this issue. We simply note that we have not so far observed place cells in the primate hippocampus, we note that great care would be needed to show that they are place cells if found, and we draw attention to a remarkable new type of cell, spatial view cells, which in primates respond to places 'out there', and which are well suited to participating in the memory for where objects have been seen in an environment. We also note that hippocampal spatial view cells are very different from inferior temporal cortex neurons which respond to objects or faces wherever they are moved to in an environment /63,64/. In contrast, although spatial view cells must respond to features in an environment, it appears that it is normally the combination of a set of features in a fixed position in the world that is

what activates spatial view neurons. In a sense, an object can be defined as a set of co-occurring features that can easily be moved to different locations in an environment, whereas a place is defined by a set of co-occurring features that remain together in the same location in the world and are not normally seen to move independently of the rest of the world.

It is also useful to emphasise that spatial view cells are very different from head direction cells, which are found in the primate presubiculum and parahippocampal gyrus /51/. For example, for a given head direction, if the monkey is moved to different places in the environment where the spatial view is different, spatial view cells give different responses. In contrast, the response of head direction cells remains constant for a given head direction, even when the spatial view is very different /51/. To provide a simple concept to emphasize the difference, one can think of head direction cells as responding like a compass attached to the top of the head, which will signal head direction even when the compass is in different locations, including in a totally different, and even novel, spatial environment.

OBJECT-PLACE NEURONS IN THE PRIMATE HIPPOCAMPUS

A fundamental question about the function of the primate including human hippocampus is whether object as well as allocentric spatial information is represented. To investigate this, Rolls *et al.* /79/ made recordings from single hippocampal formation neurons while macaques performed an object-place memory task which required the monkeys to learn associations between objects, and where they were shown in a room. Some neurons (10%) responded differently to different objects independently of location; other neurons (13%) responded to the spatial view independently of which object was present at the location; and some neurons (12%) responded to a combination of a particular object and the place where it was shown in the room. These results show that there are separate as well as combined representations of objects and their locations in space in the primate hippocampus. This is a property required in an episodic memory system, for which associations between objects and the places where they are seen is prototypical. The results thus show that a requirement for a human episodic memory system, separate and combined neuronal representations of objects and where they are seen 'out there' in the environment, are present in the primate hippocampus /79/.

RECALL-RELATED NEURONS IN THE PRIMATE HIPPOCAMPUS

Having described the discovery of spatial view neurons in the primate hippocampus, and neurons involved in associations between spatial view and the objects present at the places viewed /79/, or the rewards present at the places viewed /78/, we now describe a new investigation of how hippocampal neuronal activity is related to the recall of memories. We have a full and quantitative theory of how the hippocampus, and its backprojection pathways to the neocortex, are involved in the recall of previously stored episodic memories from just a fragment of the original memory /52,58,74, 97/, but we believe this is the first neurophysiological investigation of the hippocampal recall process in primates.

We used an object-place memory task because this is prototypical of episodic memory, and there is evidence that the primate hippocampal system is required for this type of memory. (Posterior parahippocampal lesions in macaques impair even a simple type of object-place learning in which the memory load is just one pair of trial-unique stimuli /29/; further, it has been shown that a one-trial odour-place recall memory task is hippocampal-dependent in rodents /11/.) We designed a one-trial object-place recall task, in which the whole memory was recalled from a part of it. The task is illustrated in Figure 4. Images of new objects were used each day, and within a day the same objects were used, so that with non-trial unique objects within a day, the recall task is quite difficult.

Recordings were made from 347 neurons in the hippocampus of a macaque performing the object-place recall task. The following types of neurons were found in the task.

One type of neuron had responses that occurred to one of the objects used in the task. A number of

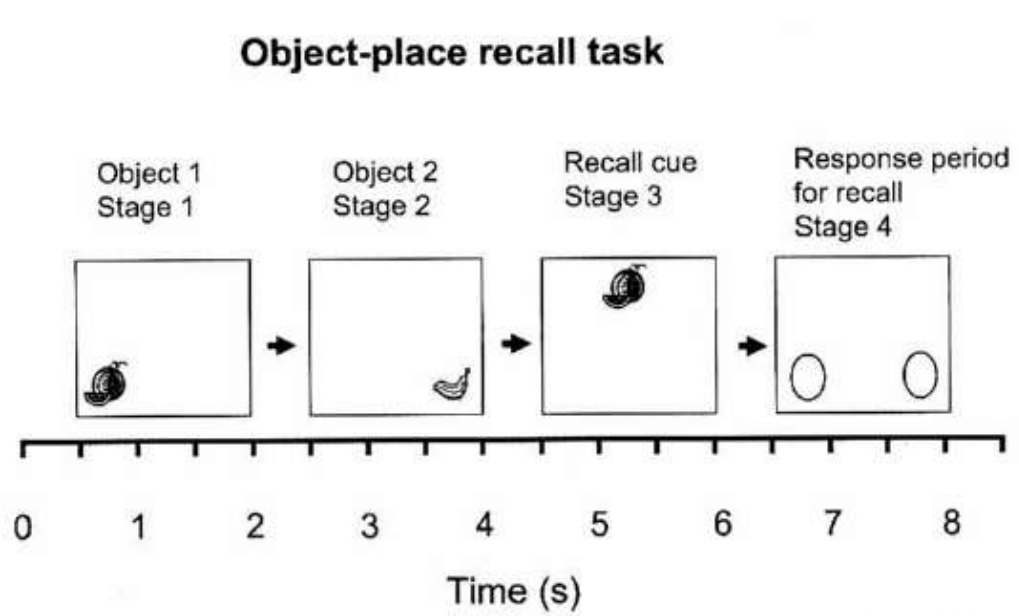

Fig. 4: The object-place recall task. One trial is shown. After a 0.5 sec tone to indicate the start of a trial, in Stage 1 one of two objects (O1) is shown at one of the places (P1). (The object and the place are chosen randomly on each trial.) To ensure that the monkey sees the stimulus, the monkey can touch the screen at the place to obtain one drop of juice reward by licking. After a 0.5 sec delay, in Stage 2, the other of the two objects (O2) is shown at the other place (P2). (One drop of fruit juice was available as in Stage 1.) After a 0.5 sec delay, in Stage 3, the recall cue, one of the objects chosen at random, is shown at the top of the screen in the middle. (One drop of fruit juice was available as in stage 1.) After a 0.5 sec delay, in Stage 4, the macaque must then recall the place in which the object shown as the recall cue in stage 3 was presented, and must then touch that place on the screen to obtain four licks of fruit juice, thus indicating that he has recalled the location correctly. In stage 4 of the trials, the left and right positions (P1 and P2) have no image present, with the two possible locations for a response indicated by identical circles. The task requires the monkey to perform recall of the place from the object, within the period beginning at the presentation of the recall cue at the start of stage 3 and ending when the response is made in stage 4.

these neurons had activity that was related to the recall process. An example of one of these neurons is shown in Figure 5. The neuron had activity that was greater to object 1 not only when it was shown in stages 1, 2 and 3 of the task, but also in the delay period following stage 3 when the object was no longer visible, and in stage 4, when the object was also no longer visible and the macaque was touching the remembered location of that object. Thus while the location was being recalled from the object, this type of neuron continued to respond as if the object were present; that is it kept the representation of the object active after the object was no longer visible, and the place to touch was being recalled. Sixteen of the neurons responded in this way, and an additional six had object-related firing that did not continue following stage 3 of the task in the recall period. The difference of the firing rates of these 22 neurons to the different objects was in many cases highly statistically significant (e.g. $p < 10^{-6}$). We performed a Fisher exact probability test to confirm that the set of statistically significant results in the 22 neurons could not have arise by chance within the 347 tests performed, and were able to reject this with $p < 5.4 \times 10^{-8}$. Thus the population of 22 neurons had statistically very highly significance in its object-related responses. (The Fisher /16/ probability combination [or generalized significance or exact probability] test is well established and asymptotically Bahadur optimal /28,103/.) None of these neurons had differential responses for the different places used in the object-

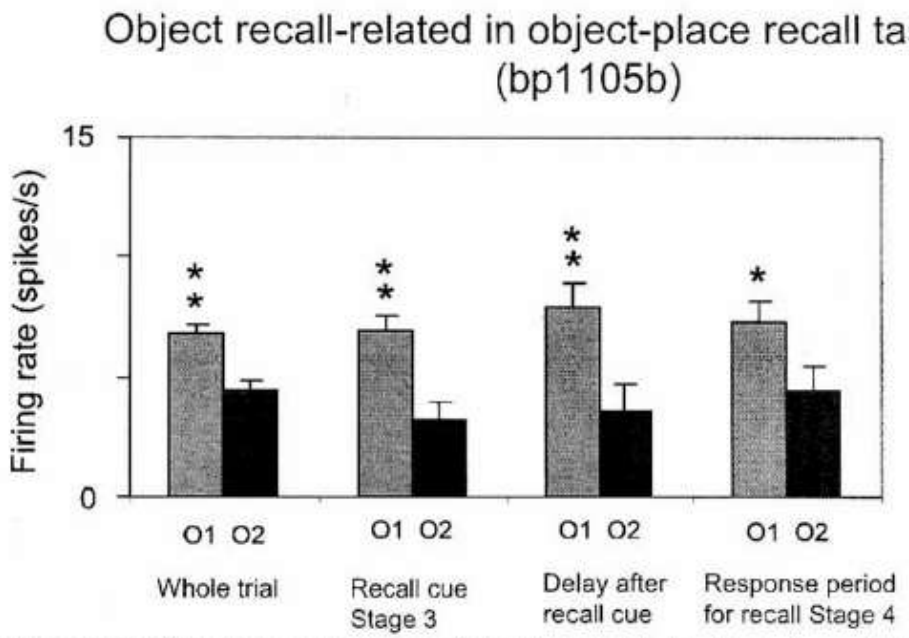

Fig. 5: Activity of a neuron with responses related to one of the objects used in the object-place recall task. The firing rate to object 1 (O1) and object 2 (O2) are shown (mean firing rate in spikes/sec across trials ± SEM). The first histogram pair (on the left) shows the responses to the two objects measured throughout the trial whenever object 1 or object 2 was on the screen. The second histogram pair shows the neuronal responses when the objects were being shown in stage 3 as the recall cue. The third histogram pair shows the neuronal responses in the 0.5 sec delay period after one of the objects had been shown in stage 3 as the recall cue. The neuron continued to respond more after object 1 than after object 2 had been seen, in this recall period in which the place was being recalled from the object. The fourth histogram pair shows the neuronal responses in stage 4 when the macaque was recalling and touching the place at which the cue recall object had been shown. The responses of the neuron were object-related even when the object was not being seen, but was being used as the recall cue, in the delay after stage 3 of the task, and in stage 4. ** $p < 0.01$; * $p < 0.05$.

place recall task.

A second type of neuron had responses related to the place (left or right) in which an object was shown in stages 1 or 2 of each trial. An example of one of these neurons is shown in Figure 6. The neuron responded more when an object was shown in the left position (P1) than in the right position (P2) on the screen. Interestingly, when the recall object was shown in stage 3 of the trial in the top centre of the screen, the neuron also responded as if the left position (P1) were being processed on trials on which the left position had to be recalled. This firing continued in the delay period after the recall cue had been removed at the end of stage 3, and into stage 4. Thus this type of neuron appeared to reflect the recall of the position on the screen at which the object had been represented. Analysis of trials on which errors were made indicated that the responses were not just motor response related, for if due to some response bias the monkey touched the incorrect side, the neuron could still respond according to the correct recalled location. Thirteen neurons had differential responses to the different places, P1 and P2, and continued to show place-related activity in the recall part of the task, stage 3. Five other neurons had left-right place-related responses without a memory recall component, in that they did not respond in stage 3 of the task, when a non-spatial recall stimulus was being shown, and a place should be being recalled (see Table 1). We performed a Fisher exact probability test to confirm that the set of statistically significant results in the 18 neurons could not have arise by chance within the 347 tests performed, and were able to reject this with $p < 0.05$. Thus these 18 neurons as a population had statistically significant

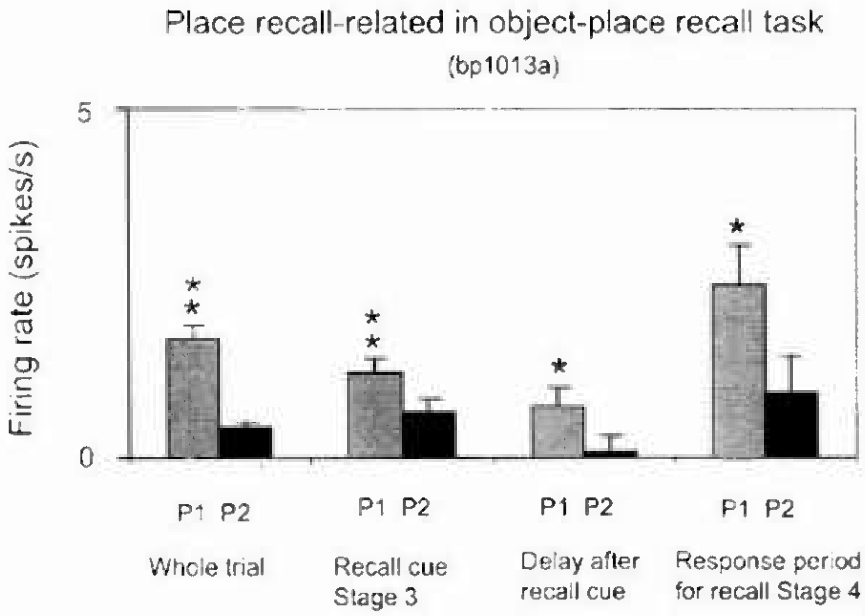

Fig. 6: Activity of a neuron with responses related to the left place (P1) in the task. The firing rate to place 1 (P1) and place 2 (P2) are shown (mean firing rate in spikes/sec across trials ± SEM). The first histogram pair (on the left) shows the responses to the two places measured when a stimulus was on the screen in stage 1 or stage 2. The second histogram pair shows the neuronal responses when the objects were being shown in stage 3 as the recall cue, and depending on whether the place to be recalled was place 1 or place 2. The third histogram pair shows the neuronal responses in the 0.5 sec delay period after one of the objects had been shown in stage 3 as the recall cue. The neuron responded more when place 1 was the correct place to be recalled on a trial. The fourth histogram pair shows the neuronal responses in stage 4 when the macaque was recalling and touching the place at which the cue recall object had been shown. The responses of the neuron were place-related even in stage 3 when the object being shown as a place recall cue was at the top of the screen, in the delay after stage 3 of the task, and in stage 4. ** $p < 0.01$; * $p < 0.05$.

TABLE 1

Numbers of neurons in the hippocampus with different types of response during the object-place recall task

Type of response	n
Object with activity continuing after the recall cue	16
Object with activity not continuing after the recall cue	6
Place with activity during and after the recall cue	13
Place with activity during the recall cue	5
Object × Place	3
Total	347

place-related responses. The new finding is that 13 of the neurons had place-related responses when a place was being recalled by an object cue.

The responses of the population of neurons recorded in one macaque are shown in Table 1. In addition to the neurons described above, three further neurons responded to particular combinations of objects and places, e.g. to object 1 when it was shown in place 1, but not to other combinations.

The recording sites of the object and of the place neurons are shown in Figure 7. All the neurons were within the hippocampus proper. The mean (± SEM) firing rate of the population of responsive neurons (see Table 1) to the most effective object or place was 7.2 ± 0.6 spikes/sec, and their mean spontaneous rate was 3.2 ± 0.6 spikes/sec.

These findings are the first we know in the primate hippocampus of neuronal activity that is related to recall. It is particularly interesting that the neurons with continuing activity to the object after it had disappeared in the recall phase of the task could reflect the operation of the object-place recall process that is hypothesized to take place in the CA3 cells. By continuing to respond to the object while the place is being recalled in the task, the object-related neurons could be part of the completion of the whole object-place combination memory from an auto-association or attractor process in CA3 /65/.

The neurons with recall-related activity in the object-place recall task also provide neurophysiological evidence on the speed of association learning in the hippocampal formation. Given that this is a one-trial object-place recall task, with the association between the object and its place being

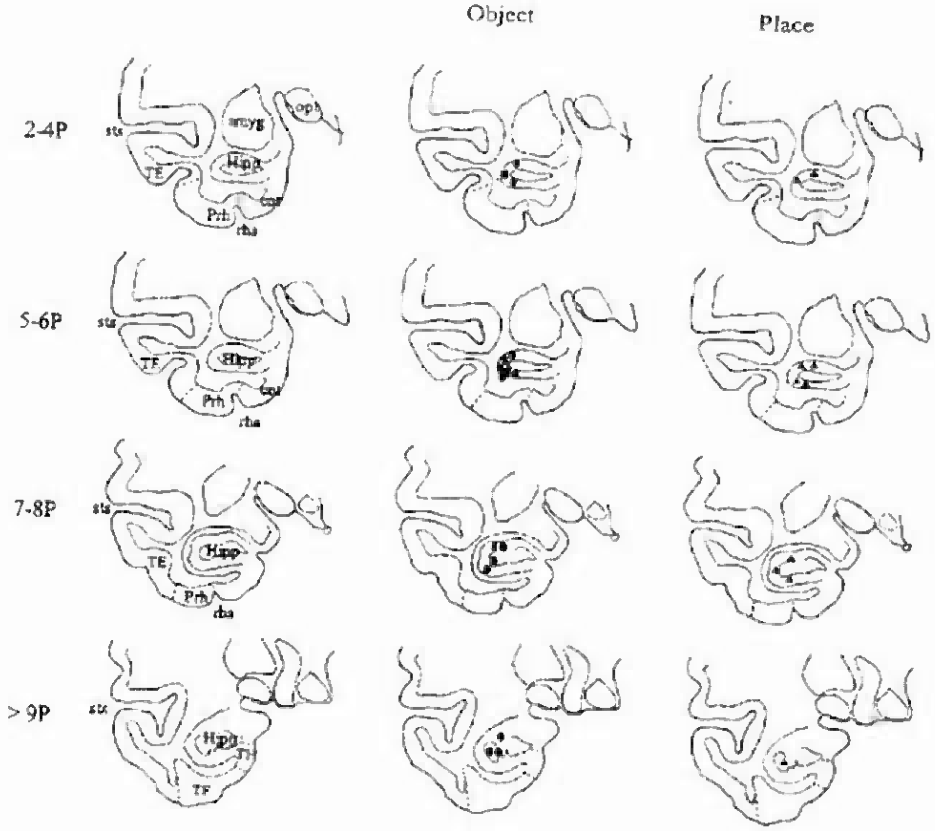

Fig. 7: The recording sites of the different neuron types in the object-place recall task are shown. Amyg = amygdala; Hipp = hippocampus; opt = optic tract; Prh = perirhinal cortex; rhs = rhinal sulcus; sts =superior temporal sulcus; TE = inferior temporal visual cortex; TF, TH = parahippocampal gyrus.

made in stages 1 and 2 of each trial (see Fig. 4), it is clear that it takes just one trial for the object-place associations to be formed that are relevant to the later recall on that trial. This is the speed of learning that is required for episodic memory, and this neurophysiological evidence shows that this type of rapid, one-trial, object-place learning is represented in the primate hippocampus.

REWARD-PLACE NEURONS IN THE PRIMATE HIPPOCAMPUS

It is suggested that whenever memories are stored, part of the context is stored with the memory. This is very likely to happen in associative neuronal networks such as those in the hippocampus /52,54, 58,60,61,72,74,97/. The CA3 part of the hippocampus may operate as a single auto-associative memory capable of linking together almost arbitrary co-occurrences of inputs, including inputs about emotional state that reach the entorhinal cortex from, for example, the amygdala and orbitofrontal cortex /62/. Recall of a memory occurs best in such networks when the input key to the memory is nearest to the original input pattern of activity which was stored /64,73-75,95-97/. It thus follows that a memory of, for example, a happy episode is recalled best when in a happy mood state. This is a special case of a general theory of how context is stored with a memory, and of how context influences recall /58,70,97/. The recall itself from the hippocampus is likely to use the highly developed backprojections from the hippocampus to the neocortex (shown in Fig. 1 of Treves and Rolls /97/). The effect of emotional state on cognitive processing and memory is thus suggested to be a particular case of a more general way in which context can affect the storage and retrieval of memories, or can affect cognitive processing /62/.

There is now direct evidence that the hippocampus, which is implicated in the memory for past episodes /59,72,74/, contains neurons in primates that respond to combinations of spatial information and reward information /78,79/, as described next. The ability to form associations between events, including where they occur and what is present, is a fundamental property of episodic memory /58,97/, and this new neurophysiological evidence shows that reward-related information, relevant to affect and mood, is associated with other events in the representations in the primate hippocampus. The primate anterior hippocampus (which corresponds to the rodent ventral hippocampus) receives inputs from brain regions involved in reward processing, such as the amygdala and orbitofrontal cortex /10, 49,85,90/.

To investigate how this affective input may be incorporated into primate hippocampal function, Rolls and Xiang /77,78/ recorded neuronal activity while macaques performed a reward-place association task in which each spatial scene shown on a video monitor had one location which if touched yielded a preferred fruit juice reward, and a second location which yielded a less preferred juice reward. Each scene had different locations for the different rewards. Of 312 hippocampal neurons analysed, 18% responded more to the location of the preferred reward in different scenes, and 5% to the location of the less preferred reward /78/. When the locations of the preferred rewards in the scenes were reversed, 60% of 44 neurons tested reversed the location to which they responded, showing that the reward-place associations could be altered by new learning in a few trials. The majority (82%) of these 44 hippocampal reward-place neurons tested did not respond to object-reward associations in a visual discrimination object-reward association task. Thus the primate hippocampus contains a representation of the reward associations of places 'out there' being viewed, and this is a way in which affective information can be stored as part of an episodic memory, and how the current mood state may influence the retrieval of episodic memories. There is consistent recent evidence that rewards available in a spatial environment can influence the responsiveness of rodent place neurons /25,92/ which respond to the place where the animal is located, not to the view of a place 'out there' /12, 59/.

Thus the primate hippocampus can combine by associative learning a representation of places 'out there' not only with which object is present at the viewed location /79/, but also with which reward is present at the viewed location /78/. The general principle here then is that the hippocampus may store information about where emotion-related (e.g.

rewarding) events happened; may take part in the recall of emotions when particular places are seen again; and may provide a system in which the current mood can influence which memories are recalled.

Before discussing the possible functions of primate spatial view cells, and their relation to rat place cells, it is useful to summarise the properties of other cells in the primate hippocampus which are relevant to understanding the representation of space by the primate hippocampus.

NEURONS RELATED TO LEARNING ASSOCIATIONS BETWEEN VISUAL STIMULI AND SPATIAL RESPONSES

In another type of task for which the primate hippocampus is needed, conditional spatial response learning, in which the monkeys had to learn which spatial response to make to different stimuli, that is, to acquire associations between visual stimuli and spatial responses, 14% of hippocampal neurons responded to particular combinations of visual stimuli and spatial responses /34/. The firing of these neurons could not be accounted for by the motor requirements of the task, nor wholly by the stimulus aspects of the task, as demonstrated by testing their firing in related visual discrimination tasks. These results showed that single hippocampal neurons respond to combinations of the visual stimuli and the spatial responses with which they must become associated in conditional response tasks, and are consistent with the computational theory described above according to which part of the mechanism of this learning involves associations between visual stimuli and spatial responses learned by single hippocampal neurons.

In a following study by Cahusac *et al.* /9/, it was found that during such conditional spatial response learning, 22% of this type of neuron analysed in the hippocampus and parahippocampal gyrus altered their responses so that their activity, which was initially equal to the two new stimuli, became progressively differential to the two stimuli when the monkey learned to make different responses to the two stimuli. These changes occurred for different neurons just before, at, or just after the time when the monkey learned the correct response to make to the stimuli, and are consistent with the hypothesis that when new associations between objects and places (in this case the places for responses) are learned, some hippocampal neurons learn to respond to the new associations that are required to solve the task. Similar findings have been described by Wirth *et al.* /102/.

RESPONSES OF NEURONS IN THE PRIMATE HIPPOCAMPUS TO WHOLE BODY MOTION

Another type of cell found in the primate hippocampus responds to whole body motion /44/, an idiothetic cue. For example, such cells respond when the monkey is rotated about the vertical axis, with a much larger response for clockwise than for anti-clockwise rotation. By occluding the visual field, it was possible to show that in some cases the response of these cells required visual input. For other cells, visual input was not required, and it is likely that such cells responded on the basis of vestibular inputs. Some cells were found that responded to a combination of body motion and view or place. In some cases these neurons respond to linear motion, in others to axial rotation (n = 43). In some cases these neurons require visual input for their responses; in other cases the neurons appear to be driven by vestibular inputs. Some cells responded to a combination of movement together with either a particular local view seen by the monkey (n = 2) or a particular place towards which the monkey is moving (n = 1). These (idiothetic) whole-body motion cells may be useful in a memory system for remembering trajectories through environments, of use for example in short range spatial navigation and path integration /44/.

PRIMATE PRESUBICULAR HEAD DIRECTION CELLS

Rat head direction cells have a firing rate which is a simple function of head direction in the horizontal plane (see /36,93/). The firing does not depend on the place where the rat is located. The cells in the rat are found in the dorsal presubiculum (also referred to as the postsubiculum), and also in some other brain structures including the anterior thalamic nuclei /93/. We have analysed a similar

population of head direction cells in primates /51/, and shown that they are place independent, can be idiothetically updated in the dark, and encode information about head direction which is independent for different neurons (up to several neurons).

CONTINUOUS AND DISCRETE ATTRACTOR NETWORKS AND EPISODIC MEMORY

Space is continuous, and object representations are discrete. If these representations are to be combined in, for example, an object-place memory, then we need to understand the operation of networks that combine these representations. A class of network that can maintain the firing of its neurons to represent any location along a continuous physical dimension, such as spatial position, head direction, etc., is a 'continuous attractor' neural network (CANN) (see references provided below and Chapter 19 in Rolls and Deco /64/). It uses excitatory recurrent collateral connections with associative modifiability between the neurons to reflect the distance between the neurons in the state space of the animal (e.g. head direction space). These networks can maintain the packet or bubble of neural activity constant for long periods wherever it is started to represent the current state (head direction, position, etc.) of the animal, and are likely to be involved in many aspects of spatial processing and memory, including spatial vision. Global inhibition (implemented by feedback inhibitory interneurons) is used to keep the number of neurons in a bubble or packet of actively firing neurons relatively constant, and to help to ensure that there is only one activity packet.

Continuous attractor networks can be thought of as very similar to auto-association or discrete attractor networks /64,74/ and have the same architecture, as illustrated in Figure 8. The main difference is that the patterns stored in a CANN are continuous patterns, with each neuron having broadly tuned firing which decreases with, for example, a Gaussian function as the distance from the optimal firing location of the cell is varied, and with different neurons having tuning that overlaps throughout the space. Such tuning is illustrated in Figure 9, together with the examples of discrete (separate) patterns (each pattern implemented by the firing of a particular subset of the neurons), with no continuous distribution of the patterns throughout the space, that are useful for storing arbitrary events or objects. A consequent difference is that the CANN can maintain its firing at any location in the trained continuous space, whereas a discrete attractor or auto-association network moves its population of active neurons towards one of the previously learned attractor states, and thus implements the recall of a particular previously learned pattern from an incomplete or noisy (distorted) version of one of the previously learned patterns.

It has now been shown that attractor networks can store both continuous patterns and discrete patterns, and can thus be used to store, for example, the location in (continuous, physical) space (e.g. the place 'out there' in a room represented by spatial view cells) where an object (a discrete item) is present /72/ (*cf.* /52,58/). Such associations between an object and the place where it is located are prototypical of episodic or event memory, and may be implemented in the primate hippocampus /79/. In this network, when events are stored that have both discrete (object) and continuous (spatial) aspects, then the whole place can be retrieved later by the object, and the object can be retrieved by using the place as a retrieval cue. Such networks are likely to be present in parts of the brain such as the hippocampus which receive and combine inputs both from systems that contain representations of continuous (physical) space, and from brain systems that contain representations of discrete objects, such as the inferior temporal visual cortex. The combined continuous and discrete attractor network described by Rolls *et al.* /72/ shows that in brain regions where the spatial and object processing streams are brought together, then a single network can represent and learn associations between both types of input. Indeed, in brain regions such as the hippocampal system, it is essential that the spatial and object processing streams are brought together in a single network, for it is only when both types of information are in the same network that spatial information can be retrieved from object information, and vice versa, which is a fundamental property of episodic memory /64,74/.

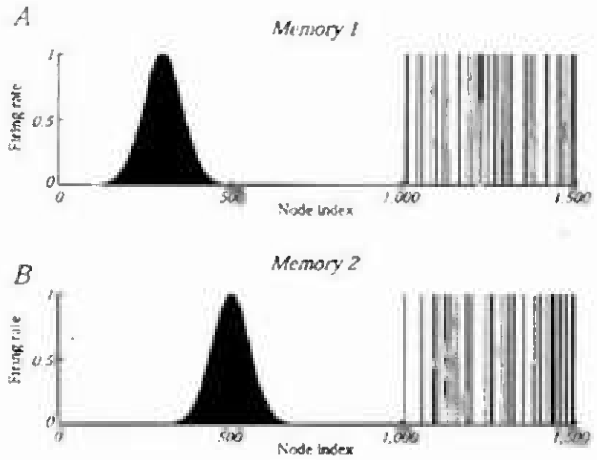

Fig. 8: The architecture of a continuous attractor neural network (CANN). Recurrent collateral axons with associatively modifiable synaptic connections make contact with the excitatory pyramidal cells in the network. The vertical lines are the dendrites, the cell bodies are triangles, and the axons extend out of the bottom of each cell body. The synaptic weight or strength for axon j to the dendrite of neuron i is w_{ij}. The external firing rate input to the network is conveyed by axons e_i. Feedback inhibitory interneurons are not shown. (For details see Rolls *et al.*, /72/ and Rolls and Deco /64/.)

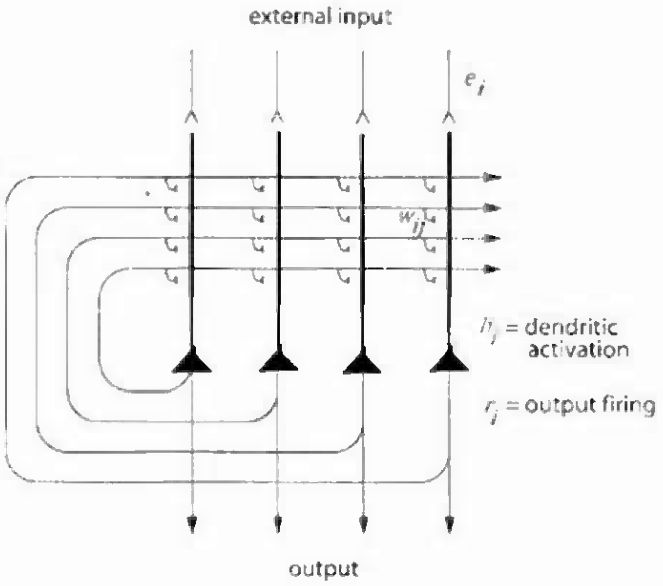

Fig. 9: The types of firing patterns stored in continuous attractor networks are illustrated for the patterns present on neurons 1-1,000 for Memory 1 (when the firing is that produced when the spatial state represented is that for location 300), and for Memory 2 (when the firing is that produced when the spatial state represented is that for location 500). The continuous nature of the spatial representation results from the fact that each neuron has a Gaussian firing rate that peaks at its optimal location. This particular mixed network also contains discrete representations that consist of discrete subsets of active binary firing rate neurons in the range 1,001-1,500. The firing of these latter neurons can be thought of as representing the discrete events that occur at the location. Continuous attractor networks by definition contain only continuous representations, but this particular network can store mixed continuous and discrete representations, and is illustrated to show the difference of the firing patterns normally stored in separate continuous attractor and discrete attractor networks. For this particular mixed network, during learning, Memory 1 is stored in the synaptic weights, then Memory 2, etc., and each memory contains part that is continuously distributed to represent physical space, and part that represents a discrete event or object. (Adapted from Rolls *et al.* /72/.)

CONTINUOUS ATTRACTOR NETWORKS AND PATH INTEGRATION

We have considered how spatial representations could be stored in continuous attractor networks, and how the activity can be maintained at any location in the state space in a form of short term memory when the external (e.g. visual) input is removed /64/. However, many networks with spatial representations in the brain can be updated by internal, self-motion (i.e. idiothetic), cues even when there is no external (e.g. visual) input. Examples are head direction cells in the presubiculum of rats and macaques, place cells in the rat hippocampus, and spatial view cells in the primate hippocampus. The major question arises about how such idiothetic inputs could drive the activity packet in a continuous attractor network, and in particular, how such a system could be set up biologically by self-organising learning.

One approach to simulating the movement of an activity packet produced by idiothetic cues (which is a form of path integration whereby the current location is calculated from recent movements) is to

employ a look-up table that stores (taking head direction cells as an example), for every possible head direction and head rotational velocity input generated by the vestibular system, the corresponding new head direction /81/. Another approach involves modulating the strengths of the recurrent synaptic weights in the continuous attractor on one but not the other side of a currently represented position, so that the stable position of the packet of activity, which requires symmetric connections in different directions from each node, is lost, and the packet moves in the direction of the temporarily increased weights, although no possible biological implementation was proposed of how the appropriate dynamic synaptic weight changes might be achieved /104/. Another mechanism (for head direction cells) /83/ relies on a set of cells, termed (head) rotation cells, which are co-activated by head direction cells and vestibular cells and drive the activity of the attractor network by anatomically distinct connections for clockwise and counterclockwise rotation cells, in what is effectively a look-up table. However, no proposal was made about how this could be achieved by a biologically plausible learning process, and this has been the case until recently for most approaches to path integration in continuous attractor networks, which rely heavily on rather artificial pre-set synaptic connectivities.

Stringer *et al.* /89/ introduced a proposal with more biological plausibility about how the synaptic connections from idiothetic inputs to a continuous attractor network can be learned by a self-organising learning process. The mechanism associates a short-term memory trace of the firing of the neurons in the attractor network reflecting recent movements in the state space (e.g. of places) with an idiothetic velocity of movement input. This has been applied to head direction cells /89/, rat place cells /88,89/, and primate spatial view cells /71,86, 87/. These attractor networks provide a basis for understanding cognitive maps, and how they are updated by learning and by self-motion.

SPATIAL VIEW NEURONS IN PRIMATES COMPARED TO PLACE CELLS IN RODENTS

Primate spatial view cells are unlike place cells found in the rat /27,38,40,41,101/. Primates, with their highly developed visual and eye movement control systems, can explore and remember information about what is present at places in the environment without having to visit those places. Such spatial view cells in primates would thus be useful as part of a memory system, in that they would provide a representation of a part of space that would not depend on exactly where the monkey or human was, and that could be associated with items that might be present in those spatial locations. An example of the utility of such a representation in humans would be remembering where a particular person had been seen. The primate spatial representations would also be useful in remembering trajectories through environments, of use for example in short-range spatial navigation /44,64/.

The representation of space in the rat hippocampus, which is of the place where the rat is, may be related to the fact that with a much less developed visual system than the primate, the rat's representation of space may be defined more by the olfactory and tactile as well as distant visual cues present, and may thus tend to reflect the place where the rat is. A hypothesis on how this difference could arise from essentially the same computational process in rats and monkeys is as follows /12,59/.

The starting assumption is that in both the rat and the primate, the dentate granule cells and the CA3 and CA1 pyramidal cells respond to combinations of the inputs received. In the case of the primate, a combination of visual features in the environment will, because of the fovea providing high spatial resolution over a typical viewing angle of perhaps 10-20 degrees, result in the formation of a spatial view cell, the effective trigger for which will thus be a combination of visual features within a relatively small part of space. In contrast, in the rat, given the very extensive visual field subtended by the rodent retina, which may extend over 180-270 degrees, a combination of visual features formed over such a wide visual angle would effectively define a position in space that is a place.

The actual processes by which the hippocampal formation cells would come to respond to feature combinations could be similar in rats and monkeys, involving, for example, competitive learning in the dentate granule cells, auto-association learning in CA3 pyramidal cells, and competitive learning in CA1 pyramidal cells /74,97/. Thus the selective properties of spatial view cells in primates and place cells in rats might arise by the same computational process but be different by virtue of the fact that primates are foveate and view a small part of the visual field at any one time, whereas the rat has a very wide visual field (for details see /12/). Although the representation of space in rats may therefore be in some ways analogous to the representation of space in the primate hippocampus, the difference does have implications for theories, and modelling, of hippocampal function.

In rats, the presence of place cells has led to theories that the rat hippocampus is a spatial cognitive map, and can perform spatial computations to implement navigation through spatial environments /6,7,41,43/. The details of such navigational theories could not apply in any direct way to what is found in the primate hippocampus. Instead, what is applicable to both the primate and rat hippocampal recordings is that hippocampal neurons contain a representation of space (for the rat, primarily where the rat is, and for the primate primarily of positions 'out there' in space) which is a suitable representation for an episodic memory system. In primates, this would enable one to remember, for example, where an object was seen. In rats, it might enable memories to be formed of where particular objects (for example those defined by olfactory, tactile, and taste inputs) were found. Thus at least in primates, and possibly also in rats, the neuronal representation of space in the hippocampus may be appropriate for forming memories of events (which usually in these animals have a spatial component). Such memories would be useful for spatial navigation. Evidence that what neuronal recordings have shown is represented in the non-human primate hippocampal system may also be present in humans is that regions of the hippocampal formation can be activated when humans look at spatial views /14,42/.

DISCUSSION

The spatial view cells we have described in this and related papers in the primate hippocampus, and in some parts of the parahippocampal cortex which send afferents to and receive efferents from the hippocampus /24,50,59,76,78,79/, are in the ways described above unlike place cells found in the rat /35,38/. Primates, with their highly developed visual and eye movement control systems, can explore and remember information about what is present at places in the environment without having to visit those places. Such spatial view cells in primates would thus be useful as part of a memory system, in that they would provide a representation of a part of space which would not depend on exactly where the monkey was, and which could be associated with items that might be present in those spatial locations. An example of the utility of such a representation in monkeys might be in enabling a monkey to remember where it had seen ripe fruit, or in humans of remembering where they had seen a person, or where they had left keys. The representation of space provided by primate hippocampal spatial view-responsive neurons may thus be useful in forming memories of what has been seen where, an example of an episodic memory. Such memories would be useful for spatial navigation, for which according to the present hypothesis the hippocampus would implement the memory component but not the spatial computation component. A detailed and quantitative model of how the hippocampus could operate as a memory system, and of how information stored in the hippocampus could be recalled, has been developed elsewhere /52,53,55,58,74,75,82,97,98/.

Some of the cells with spatial responses in the primate hippocampus and presubiculum described here could be involved in functions other than purely episodic memory. For example, head direction and whole body motion neurons could be useful as part of a system for remembering the compass bearing (head direction) and distance travelled, to enable one, for example, to find one's way back to the origin, even with a number of sectors of travel, and over a number of minutes. This is referred to as path integration. Spatial memory and navigation can also benefit from visual information about places being looked at,

which can be used as landmarks, and spatial view cells added to the head direction cells and whole body motion cells would provide the basis for a memory system useful in navigation. Another possibility is that primate head direction cells are part of a system for computing during navigation which direction to head towards next. For this, not only would a memory system be needed of the type elaborated elsewhere /52,53,58,74,97/, that can store spatial information of the type found in the hippocampus, but also an ability to use this information in spatial computation of the appropriate next bearing would be needed. Such a system might be implemented using a hippocampal memory system which associated together spatial views, whole body motion and head direction information. The findings described here certainly implicate the hippocampus in the update of spatial view cells' firing produced in the dark by idiothetic cues including eye position and head direction signals. The system would be different from that in the rat /7,32/, in that spatial view is represented in the primate hippocampus.

Evidence that the primate hippocampal spatial view cells could be involved in arbitrary associations with the objects and rewards present at particular viewed locations has been described above. These studies provide direct evidence that the primate hippocampus contains the necessary representations for forming such associations, such as representations of objects as well as of spatial view. Moreover, the new investigation described here of object-place recall memory shows some of the representations that become active within the hippocampus when places are recalled from objects. This recall operation, and the learning of the associated events that precede it, are described in a model of how the hippocampus is involved in episodic memory, and the subsequent retrieval of a whole episodic memory from one part of it in recall. The model describes quantitatively not only the storage and recall operations within the hippocampus, but also their recall to the neocortex /4,94,95/. In the theory, the CA3 network forms an auto-associative or attractor memory /4/ which operates with sparse representations and incomplete connectivity /52,55,75,82,94,95,97/. Modifiable back-projection synapses to the neocortex implement the recall /52,55,58,74,97/.

The studies described here provide fundamental evidence about the information represented in the primate hippocampus, and are of considerable interest in relation to understanding what the primate (including human) hippocampus does, and how it works as a memory system /74/. Indeed, the relevance to humans of this work in primates is attested to by the fact that neuroimaging studies in humans are showing that the sight of simple spatial views can activate hippocampus-related areas (for example, /14,42/). However, it is only at the neuronal level that one can address issues such as the spatial coordinate frame used /24/, how the information is represented (which has important implications for how it is stored) (see /76/), and how similar the recall state is to the stored memory state when retrieval occurs to a partial cue /50/. It would be difficult with neuroimaging studies to show, for example, that there is an allocentric representation of space 'out there' that is accessed either by looking at the particular location in space, or by rotating the head and moving the eyes to another head direction/eye position (and even head position) combination that will result in looking towards that location in space when the view details are made invisible. Nor can such neuroimaging studies show that, for example, other neurons in the hippocampus respond to whole body motion, which for some neurons is based on vestibular signals, for other neurons on optic flow signals, and for other neurons on either. Analyses at the neuronal level are thus essential because they provide clear evidence about what is being represented in a brain structure, and are also especially relevant to understanding how a part of the brain operates, because they show what information is being exchanged between the computing elements of the brain /64,74/.

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