HIPPOCAMPUS 5:409–424 (1995)

View-Responsive Neurons in the Primate Hippocampal Complex

Edmund T. Rolls and Shane M. O'Mara

Department of Experimental Psychology, University of Oxford, Oxford, UK

ABSTRACT: Recordings were made from single neurons in the hippocampus and parahippocampal gyrus while macaques were moved on a platform mounted on a free-moving robot or on wheels in a cue-controlled 2 m × 2 m × 2 m environment, in order to investigate the representation of space and of spatial memory in the primate hippocampus. The test conditions allowed factors that might account for spatial firing of the cells, including the spatial location where the monkey looked, the place were the monkey was, and the head direction of the monkey, to be identified. The responses of some ("view") neurons depended on where the monkey was looking in the environment, but not on the place of the monkey in the environment. The responses of one other neuron depended on a combination of where the monkey was facing and his place in the test chamber. The response of view-dependent neurons was affected by occlusion of the visual field. It was possible to show for one neuron that its "view" response rotated with rotation of the test chamber. Some neurons responded to a combination of whole-body motion and view or place, and one neuron responded in relation to whole-body movement to a particular place. One neuron responded depending on the place where the monkey was in the environment and relatively independently of view.

The representations of space provided by hippocampal view-responsive neurons may be useful in forming memories of spatial environments (for example, of where an object has been seen and of where the monkey is as defined by seen views) and, together with whole-body motion cells, in remembering trajectories through environments, which is of use, for example, in short range spatial navigation. © 1995 Wiley-Liss, Inc.

KEY WORDS: hippocampus, views, memory, navigation, space representation, place

INTRODUCTION

Bilateral damage to the temporal lobe in humans can cause anterograde amnesia (Scoville and Milner, 1957; Milner, 1972). A number of cortical and subcortical areas are affected in such patients, including structures of the hippocampal formation. Experimental investigations to determine the crucial structures in producing the amnesia are being developed in order to advance our understanding of the neural bases of the different types of amnesia and to develop possible therapeutic measures (Squire, 1992). In analyses of the way in which the hippocampus could contribute to a memory deficit in primates (for reviews see Rolls, 1990, 1991, 1994), it has been shown that tasks that are particularly affected by damage to the hippocampus or fornix in the primate include spatial tasks such as memory of where in space an object has been seen before (Smith and Milner, 1981; Gaffan and Saunders, 1985; Parkinson et al., 1988), use of spatial cues to determine which object to select for reward in spatial memory tasks (Gaffan and Harrison, 1988), and learning where to make a spatial response (for example, in a conditional spatial response task: Gaffan et al., 1984b; Rupniak and Gaffan, 1987; and in man, Petrides, 1985); and nonspatial tasks such as recognition memory (Gaffan, 1974, 1977; Gaffan and Weiskrantz, 1980; Owen and Butler, 1981; Gaffan et al., 1984a; Zola-Morgan and Squire, 1985). In analyses of the functions of the hippocampus in the rat, it has been suggested that rats with hippocampal damage have an impaired ability to create a map of space in that they are impaired in running correctly on an eight-arm maze, or in swimming correctly to a submerged platform, in situations in which extra-maze cues must be used to determine their position in space (O'Keefe and Nadel, 1978; Morris et al., 1982; Barnes, 1988). There is evidence in the rat that some hippocampal neurons fire when the rat is in a particular place in an environment (O'Keefe, 1979, 1983; McNaughton et al., 1983); such cells have been named *place* cells (O'Keefe and Nadel, 1978).

In order to analyze neurophysiologically how the primate hippocampus might be involved in spatial function, and in particular in memory of where in space objects had been seen before (see earlier and Rolls, 1990, 1991, 1995), Rolls et al. (1989) recorded the responses of hippocampal neurons in macaques using a serial multiple object-place memory task requiring a memory in which four or nine positions on a video monitor and a given object had appeared previously. (This task is known to be impaired by fornix section; Gaffan and Saunders, 1985.) It was found that 9.3% of neurons recorded in the hippocampus and parahippocampal gyrus had spatial fields in this and related tasks and that

Accepted for publication June 23, 1995.
Address correspondence and reprint requests to Dr. Edmund T. Rolls, Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford OX1 3UD, UK.
Shane O'Mara is now at Department of Psychology, University of Dublin, Trinity College, Dublin 2, Ireland.

2.4% of the neurons responded to a combination of spatial information and information about the object seen (i.e., they responded more the first time a particular object was seen in any position). This investigation showed that not only is spatial information processed by the primate hippocampus, but it can be combined with information about which stimuli have been seen previously (Rolls et al., 1989). These "space" neurons (see also Cahusac et al., 1989; Rolls et al., 1989; Rolls and O'Mara, 1993; Rolls, 1994, 1995) may be compared with place cells recorded in the rat hippocampus (see McNaughton et al., 1983; O'Keefe, 1983). Place cells respond when the rat is in a particular place in the environment as specified by extra-maze cues, whereas the cells described by Rolls et al. (1989) respond to particular positions in space, or at least when stimuli are shown in particular positions in space (see further Feigenbaum and Rolls, 1991).

These studies showed that some hippocampal neurons in primates have spatial fields. Feigenbaum and Rolls (1991) investigated whether the spatial fields of hippocampal neurons use egocentric or some form of allocentric coordinates. This was examined 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. They found that 10% of the spatial units represented space in egocentric coordinates, that is, relative to the monkey's body head axis. For 46% of the spatial neurons analyzed, 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, that is, independent of the monkey's own body axis.

Tamura et al. (1990, 1992a,b) examined the response of hippocampal neurons to various visual and auditory stimuli presented to an awake monkey from various directions. Some neurons were found to respond to the stimulus itself. Other neurons responded if the stimulus was presented from a particular direction. In further tests in which the monkey was rotated relative to the testing apparatus, it was shown that about 34% of the relevant neurons tested responded in egocentric coordinates, and about 30% responded in allocentric coordinates. Ono et al. (1993) have performed studies on the representation of space in the primate hippocampus by allowing a monkey in a cab to move to different places in a room while recording from hippocampal neurons. The experimenter turned on one of a set of five lights on a panel in front of the monkey. While the monkey pressed a bar under that light, the cab moved toward a location that the monkey could see within a 2.5 × 2.5 m area where he would obtain food. After the monkey had obtained food at that location, the next location in a sequence was chosen for a goal object. They found 13.4% of hippocampal formation neurons fired more when the monkey was at some particular place than when at other places in the area, independent of whether the monkey was performing the feeding-related task and of whether there was a stimulus (typically a human) placed at a certain direction in the environment. Little evidence was described about whether the responses of these neurons were independent of the direction in which the monkey was facing, and therefore it is not clear what accounted for the firing that occurred when the monkey was in some of the places.

In the experiments performed by Ono et al. (1993), the monkey was not tested in a cue-controlled environment, so that the room cues could not be manipulated in order to investigate how visual cues in the environment might be part of what accounted for the firing of the spatial cells they recorded. Nor was the monkey tested in each place with a set of different directions to which it faced from that place, so that the relative contributions of the place where the monkey was and the position where the monkey was looking were not fully defined for each cell. In order to analyze how visual cues in a spatial environment might influence the firing of hippocampal neurons with spatial responses, we performed the experiments described here. We designed a cue-controlled environment in which there were four major cues that defined where the monkey was in the environment. The cues could be moved to different walls of the environment, and the whole environment could also be rotated to allow investigation of the role of the cues on the walls of the environment in producing spatial responses. The cue-controlled environment was designed to be analogous to that used in experiments on the spatial representation in the hippocampus of rats (see, e.g., O'Keefe, 1983; O'Keefe and Speakman, 1987), in which place cells that are influenced by the cues in the cue-controlled environment are found. In such a standard cue-controlled environment we wished to investigate whether similar place cells are present in monkeys and to use the opportunities provided by the cue-controlled environment for investigating what does drive hippocampal cells. This type of cue-controlled environment has been very useful in rat studies (see, e.g., O'Keefe and Speakman, 1987). In our cue-controlled environment we have already described neurons that respond in relation to whole-body motion, for example, to linear motion or to angular rotation (O'Mara et al., 1994). Some of these cells were influenced by vestibular inputs produced by the whole-body motion, and others were activated by the optic flow induced by the whole-body motion in the cue-controlled environment.

In this paper we describe cells that respond to views of the environment, often relatively independently of where the monkey was in the environment. We suggest that the information represented in the firing of these hippocampal neurons in primates about a spatial view would be useful to store in an intermediate-term memory system such as the hippocampus may provide (Rolls, 1990, 1991, 1994, 1995; Rolls and O'Mara, 1993; Treves and Rolls, 1994). Storage of views together with other information about, for example, whole-body motion would be useful in short-range spatial navigation, in remembering the locations of objects in an environment, and in establishing where one is in an environment. It is important to understand the functions of this brain system, because impaired hippocampal function is likely to contribute to some of the amnesias associated with brain damage and with aging (Squire, 1992).

MATERIALS AND METHODS

Testing Environment

The cue-controlled rotatable test chamber used for these experiments measured 2 m × 2 m by 2 m high and is shown in Figure 1. The enclosure was high enough (2 m) so that the mon-

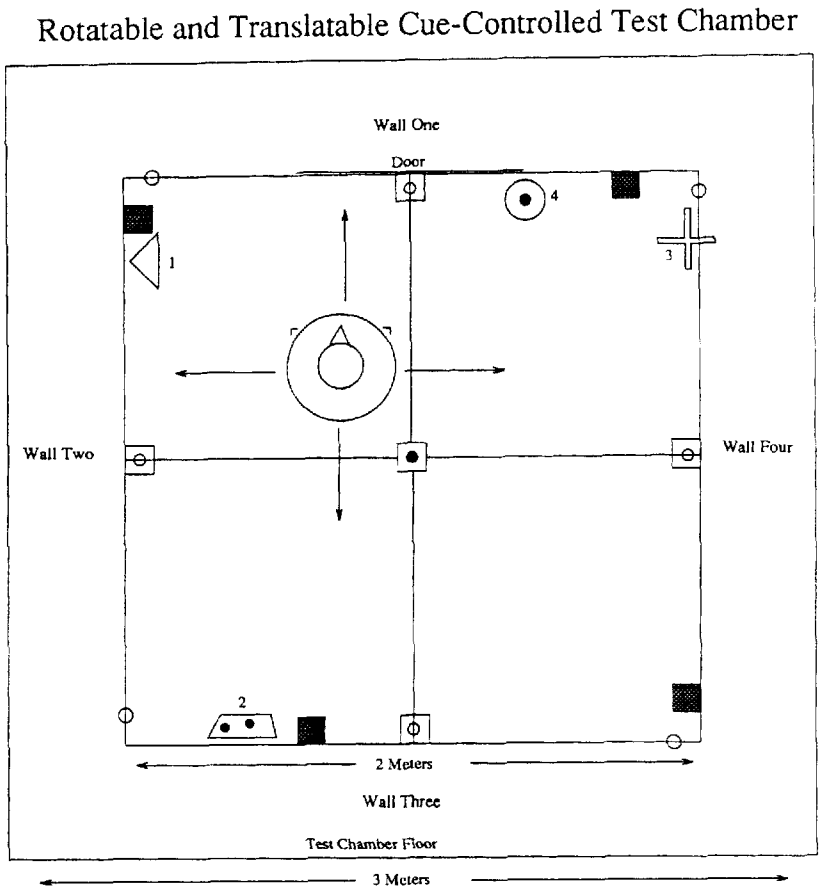


FIGURE 1. The 2 × 2 × 2 m cue-controlled rotatable and translatable test chamber, shown in plan view. Corner One is at the top left of the plan and Corner Two is at the bottom left, etc. The circle, square, etc., marked 1–4 are cue cards. The squares with the inlaid circle represent the touch pads mounted on each wall of the test chamber. The LEDs were mounted 10 cm above the touch pads. The shaded squares represent the food cups.

key could not see out, as described later. The chamber was matt black inside, and testing was normally performed with the matt black door closed. (The door was almost indistinguishable from the walls and was not a noticeable room cue.) The walls could be rotated, or translated 1 m, while the floor remained fixed. The chamber was evenly illuminated by artificial light to a level of 520 lux, a normal level for room illumination. The testing was generally conducted under normal light and sometimes in complete darkness, as described later. There was a set of four distinctive cues (a white cross, triangle, circle, and rectangle) placed on the walls of the chamber, as shown in Figure 1, to provide a spatial reference frame for the monkey. Each cue was approximately 30 cm in diameter. To encourage the monkey to use these cues to define the space in the test chamber, one grey plastic cup, 4 cm × 4 cm × 4 cm, was placed on each wall, as shown in Figure 1. Each of three cups contained a different food (peanut, banana, chip, apple chip), which was always in the same position in the test chamber, as defined by the four spatial reference cues. The cups were at eye height so that the monkey could not see inside but he could reach into a cup to obtain a piece of the food it contained. The cup on Wall Three of the test chamber never contained food. The monkey quickly became proficient at using the environmental cues to determine where he was, because he quickly learned to reach only into those cups that contained foods. The monkey used these four distinctive wall cues for orientation in the environment, as shown by the fact that if the walls were rotated in darkness, the monkey reached to obtain food only from the three cups in the correct spatial positions defined by the wall cues.

Test Chair and Robot

The monkey sat in a test chair 65 cm high, which could either be placed on a trolley on wheels so that the experimenter could move the monkey, or could be placed on a robot so that the monkey could be moved with precisely defined accelerations and velocities. The robot was 55 cm in diameter and 45 cm high (Robosoft S.A., Neuilly-Plaisance, France). It was controlled by an IBM-PC computer, and we could make it rotate under program control with angular velocities in the range 0–100°/s, and translate forwards or backwards with velocities of 50–200 mm/s. The monkey's chair was on a turntable. The monkey's view of

the test environment was that allowed by eye movement; his head was recessed 25 cm inside the test chair, and his view was restricted laterally to an angle of 100° by the sides of the chair, and to 25° vertically by the top of the chair so that the monkey could not see above the walls of the test chamber. Eye gaze angle was not measured in the study described here, but during a firing rate measurement the chair was placed to face in one direction and the monkey was looking mainly at the view within ±20° of straight ahead during the firing rate measurements, as shown by subsequent studies with a search coil to measure eye gaze angle.

Recording Techniques

The activity of single neurons was recorded with glass-insulated tungsten microelectrodes (after Merrill and Ainsworth, 1972, but without the platinum plating) in four macaque monkeys (*Macaca mulatta*; weight, 2.5–3.5 kg; age, 1–2 years) seated in a primate chair using techniques that have been described previously (Rolls et al., 1976). The monkeys had been implanted under thiopentone sodium anesthesia with a stainless-steel holder that supported the head facing directly forward during experiments and that also supported the microdrive in the subsequent daily recording sessions. They were pretreated with ketamine (0.1 ml/kg) and post-treated with the analgesic buprenorphine (Temgesic; 0.2 ml/kg) and the antibiotic amoxicillin (Cynulox; 0.1 ml/kg per day for 5 days). The action potentials of single cells were amplified using techniques described previously (Rolls et al., 1979), were converted into digital pulses using the trigger circuit of an oscilloscope, and were analyzed on-line using a Microvax II computer or IBM PC. We ensured that recordings were from only a single cell by continuously monitoring the interspike interval to make sure that intervals of less than 2 ms were not seen and by continuously monitoring the waveform of the recorded action potentials. When testing was performed with the movements being performed by the robot, the computer collected perimovement rastergrams of neuronal activity for each trial and displayed, printed, and stored the data for each trial. The rastergrams started 1 s before the movement started and continued for 4 s after the start of the movement. When testing was performed by the experimenter moving the chair, the computer measured the firing rate of the neuron and its standard deviation based on 0.5 s samples during periods selected by the experimenter that corresponded to one of the movements (e.g., during a 4 s whole-body motion forward), or to a preceding or succeeding period in which the chair was stationary and the monkey was looking at the environment. The results described here were obtained with the monkey stationary, except where described in the results section, on the chair, looking at the environment, and not reaching for food during firing rate measurements. During testing the monkey was moved to a new place or orientation approximately every 20 s, and the firing rate counts for the majority of the cells described here were taken in a 4-s period starting 5 s after the monkey had reached the new testing position or orientation.

X radiographs taken in the coronal and parasaggital planes were used to locate the position of the microelectrode on each recording track relative to permanently implanted reference electrodes and bony landmarks, such as the posterior tip of the sphenoid bone (Aggleton and Passingham, 1981). At the time of histology, the animals were narcotized with ketamine, deeply anesthetized with intravenous pentobarbitone sodium, and perfused with normal saline followed by 10% formal saline. Sharpened hollow tubes (diameter = 1.5 mm) were passed stereotaxically through the brain parallel to the intra-aural/inferior orbital plane to provide a dorso-ventral reference point between sections. The position of cells was reconstructed from the X-ray coordinates taken together with serial 50 μ histological sections in the coronal plane stained with cresyl violet, which showed the reference electrodes and micro-lesions made at the end of some of the microelectrode tracks as follows. Drawings were made in coronal planes 0.5 mm apart from the X radiographs, showing the position of the electrode at the end of each track at a 10× scale. (The X radiographs were corrected for the 10% magnification that occurred.) The position of each unit recorded was marked on these drawings. Toward the end of each experiment (in the last 2–3 weeks), small electrolytic lesions (40–80 μA for 50–60 s) were made at the end of each recording session, usually at the site of a responsive neuron. X-rays were again taken. This allowed the relationship between positions as measured on radiographs and position in the brain when the microlesions were identified histologically to be calculated. A linear regression was then performed in each of the three dimensions between measurements in the brain and measurements on the radiographs (see Feigenbaum and Rolls, 1991). The accuracy of reconstruction according to this method was better than 0.5 mm.

Methods of Testing

The monkey sat in the test chair and was moved around the test chamber by the experimenter, or was moved around the test chamber while mounted on the robot. The test conditions allowed the separation of cells responsive to views of parts of the environment from cells responsive to where the monkey was in the environment. Figure 2 illustrates how this was achieved. The monkey could be placed in any of places A, B, and C in the test chamber, and in each place could be set to face in each of a set of directions. A typical test sequence involved, for example, bringing the monkey to place A (Corner One) of the test chamber and measuring the response of the cell to the view of Corner One (call this position 0°). The next step was to systematically rotate the monkey to the left or the right in, say, 90° steps, while he remained at Corner One. With a 180° rotation, the view the monkey had of the test chamber was completely different, so that he was now facing place B (the center of the test chamber) and place C (Corner Three of the test chamber), but his location remained constant throughout that test sequence. The monkey could then be brought to place B and tested in the same orientations toward particular portions of the environment as in place A. Differences in firing rate as a function of position, orientation (i.e., compass direction), and view may be dissociated in this way. This was the rationale for the testing method. The actual places tested usually included at least the four corners in two different orientations (looking into the corner and away from the corner), and a set of

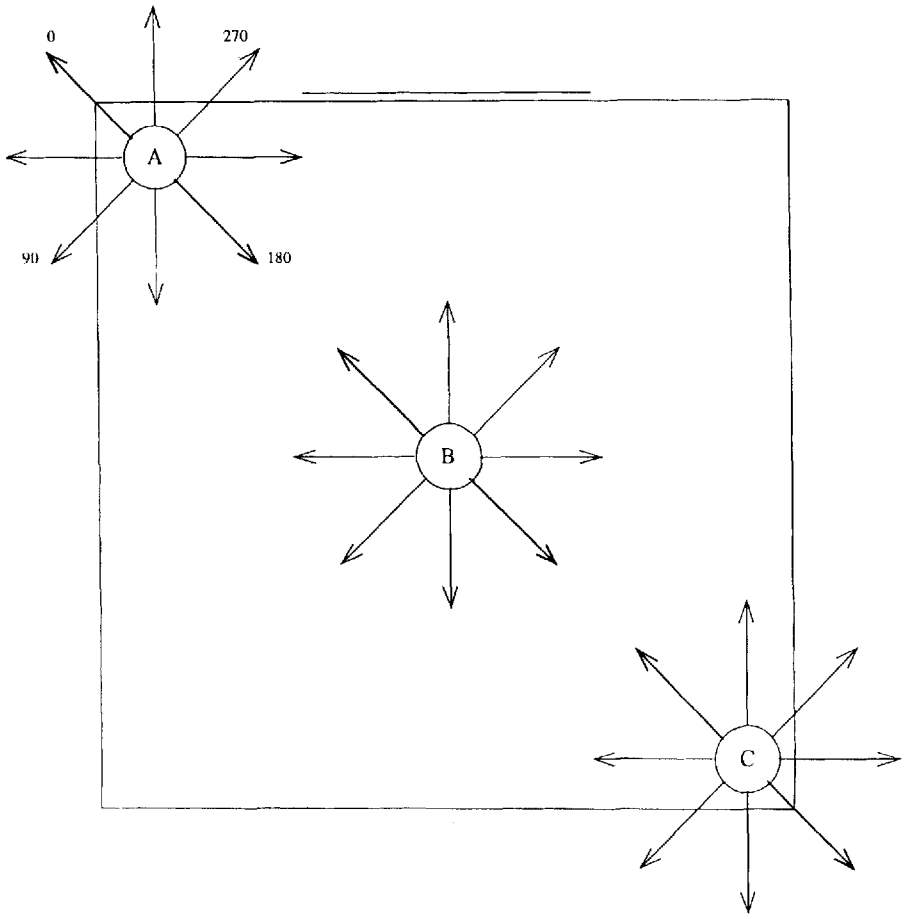


FIGURE 2. Schematic of experimental design. The responses of a neuron were analyzed when the monkey was located at different places (e.g., A, B, and C), and when he was facing in different directions (e.g., 0° and 180°) at each of those places.

views from the center of the test chamber, as shown, for example, in Figure 3. Additional tests involving whole-body motion (see O'Mara et al., 1994) were used to determine if a view-responsive neuron was also sensitive to motion.

In all cases the monkey was brought to all the positions being tested in a sequence determined by a table of pseudorandom numbers to select which of the four corners, and centers of the four walls of the test chamber, should be tested next with each orientation, itself varied pseudorandomly. An informal pretesting phase preceded the formal testing of isolated neurons, in which the monkey was moved to various places and orientations in the test chamber, and any variations in firing rate were determined by firing rate counts. This pretesting phase also revealed if the cell responded to whole-body motion as well as views of the test chamber.

Statistical Analysis

Between 4 and 10 measurements of the firing rate in each condition (taken over a 4–6 s period) were obtained. A one-way analysis of variance was then performed to determine whether there were significant differences between conditions. Provided that the ANOVA was significant (at the 0.05 level at least, though for the majority of the cells this was <0.001), the conditions that were significantly different from each other were then determined with post hoc Newman-Keuls' test analysis, and two further statistical analyses were performed. First, the data were recast according to what view the monkey had of the environment without taking into account where the monkey was, and another ANOVA was performed to determine whether there was a significant effect of where in the environment the monkey was facing. Second, the data were recast according to the place where the monkey was, independent of the view that the monkey had of the environment, and another ANOVA was performed to determine whether there was a significant effect of place. This general procedure follows that described by Feigenbaum and Rolls (1991) and was adopted rather than a two-way ANOVA (with, e.g., position in the environment as one factor and view of the environment as the other) because with this type of mobile recording experiment it was usually not possible to obtain a set of data with every cell in the position by view data matrix filled sufficiently.

In the data plots to follow, the monkey is represented as a circle and the direction he is facing is represented by a spike firing-rate histogram. Any difference in firing rate that is statistically sig-

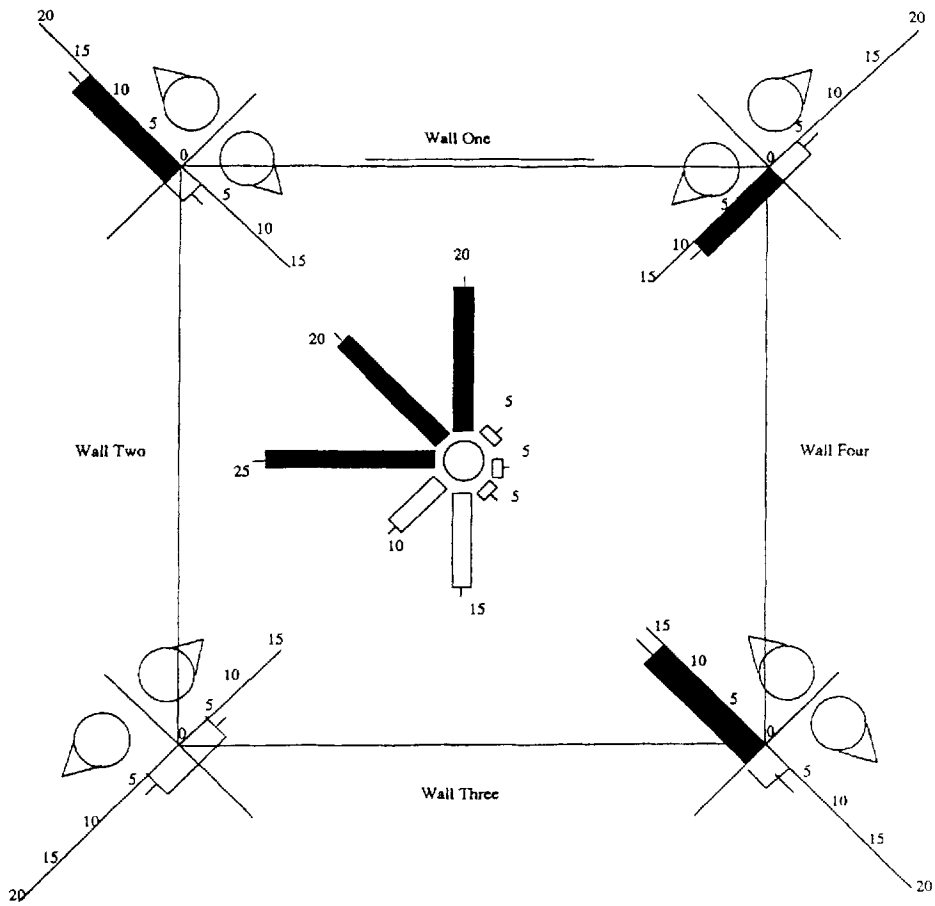


FIGURE 3. The responses of a hippocampal neuron that were primarily related to the view of the environment rather than the place where the monkey was. The response of the neuron was measured when the monkey was close to each of the four corners of the test chamber and when the monkey was in the center. At each of these positions, the mean and the SEM neuronal firing rate is shown for the different directions in which the monkey was facing. (The circles with triangles indicate which way the monkey faced.) The firing rate histograms are shaded when the firing rate in that direction was significantly different from the firing rate in the opposite direction, based on the ANOVA and post-hoc tests (see text). The numbers against the histograms show the scale in spikes/s.

nificant from the rate of the neuron when the monkey was facing in the opposite direction is indicated by a filled black bar in the histogram. This convention for illustrating the data will be used unless otherwise stated. In the figures bars are drawn wherever sufficient firing rate counts were available for the statistical analysis, to indicate the completeness of the data.

RESULTS

Four hundred and sixty-one neurons were recorded, of which 26 (5.6%) responded in the ways described next to views of the testing environment. Each figure illustrates data for a different neuron, except where stated (Figs. 6 and 7).

View Cells

One set of cells responded to particular views of the environment, relatively independently of the place where the monkey was located. An example is shown in Figure 3. The cell was tested by bringing the monkey to each of the corners of the test chamber in a pseudorandom sequence and taking a firing count while he was facing into and out of each corner. The monkey was also tested in the center by varying his orientation pseudorandomly, allowing him to face in eight different directions (0°, 45°, 90°, . . .) while seated in the center. The cell had significant increases in firing rate (indicated by black in Fig. 3, as shown by the one-way ANOVA and post-hoc Newman-Keuls' tests) when the monkey was facing toward and looking at Wall One (left part) and Wall Two (upper two-thirds). (The ANOVA performed across all positions and orientations showed $F_{7,32} = 4.03$; $P < 0.003$.) The firing rate of the cell for any pair of opposite directions was consistently higher for all cases when the monkey faced Corner One and Walls One and Two. When the data were recast irrespective of the place where the monkey was to test for an effect of view, the ANOVA showed a very significant effect ($F_{7,72} = 10.9$; $P < 0.0001$). When the data were recast irrespective of view to test for an effect of the place where the monkey was, the ANOVA was not significant ($F_{4,75} = 1.8$; ns). The firing of the

neuron was thus independent of the position of the monkey: The cell responded irrespective of whether the monkey was in Corner One, the center, or Corner Four, provided that he was facing toward Corner One. When the monkey was rotated 180° in all three places, the firing rate in each case decreased to a low level (which was less than one-sixth of its previous evoked firing rate, that is, from about 12–15 spikes/s to about 1–2 spikes/s).

The responses of another example of a view cell are illustrated in Figure 4. This cell responded primarily when the monkey had a view of the left part of Wall One, irrespective of the position where the monkey was. (With the data sorted according to the view the monkey had, comparing, in particular, responses to views of the left half of Wall One, the right half of Wall One, and Wall Two: $F_{3,59} = 13.7$, $P << 0.0001$.) The cell did not respond according to the place where the monkey was (with the data sorted according to place, the one-way ANOVA was just significant: $F_{3,59} = 3.1$, $P > 0.03$); nor did the cell respond according to head direction, as shown by the fact that the cell did not respond when he was facing "north" in the lower right of Figure 4; but did respond when the monkey was facing "north" in the upper left and center of Figure 4. (In addition to the detailed testing shown in Fig. 4 and the ANOVAs just described, many additional single tests of the firing rate of the cell showed that the only condition under which it responded was when the monkey faced toward the left part of Wall One from any place in the chamber.)

Three cells had such view-related responses, in which the response of the cell depended on which part of the environment the monkey could see. The responses of this group of cells were relatively independent of the place where the monkey was in the test chamber, and of the head direction of the monkey, as illustrated in Figures 3 and 4. The cells continued to fire while the monkey looked at a particular view of the environment.

Effect of test chamber rotation on view neurons

To test whether the view cells were responding to the four cues on the walls of the test chamber, the test chamber was rotated by, for example, 90° while recordings were made from view cells (or view cells with modulation by place, see later). The room was in darkness when the chamber was rotated. It was possible to test the effects of rotation of the environment on two view-responsive neurons, as described next.

Figure 5 (left panel) shows the responses of a cell that responded best to a view of Wall Two of the test chamber ($F_{3,16} = 4.87$; $P < 0.001$). The chamber was then rotated 90° anticlockwise and the cell was then tested again (Fig. 5, right panel). The cell continued to respond best to a view of Wall Two of the test chamber after 90° anticlockwise rotation ($F_{3,12} = 3.52$; $P < 0.05$). Although the differences in the firing rates to the different views were not very great, the differences were as great as 25%, and were significantly different. In Figure 4 right, the chamber is shown in the same orientation as it was before rotation, in order to facilitate comparison of the responses of the cell before and after chamber rotation. The overall activity of the cell was decreased a little after the chamber rotation. The chamber rotation was disorienting to the experimenter, and probably also to the monkey. The small general reduction of the neuronal activity after the chamber rotation could be related to slight disorientation. Thus

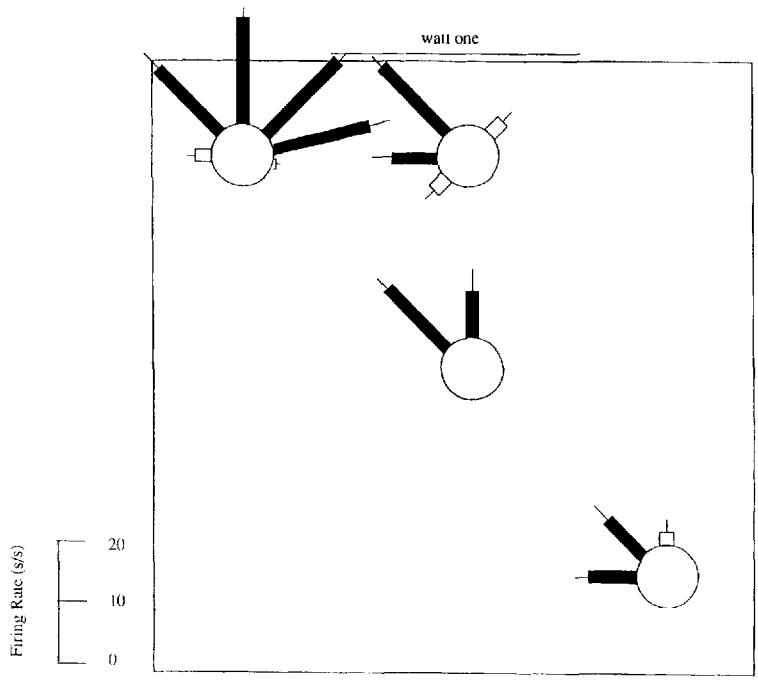
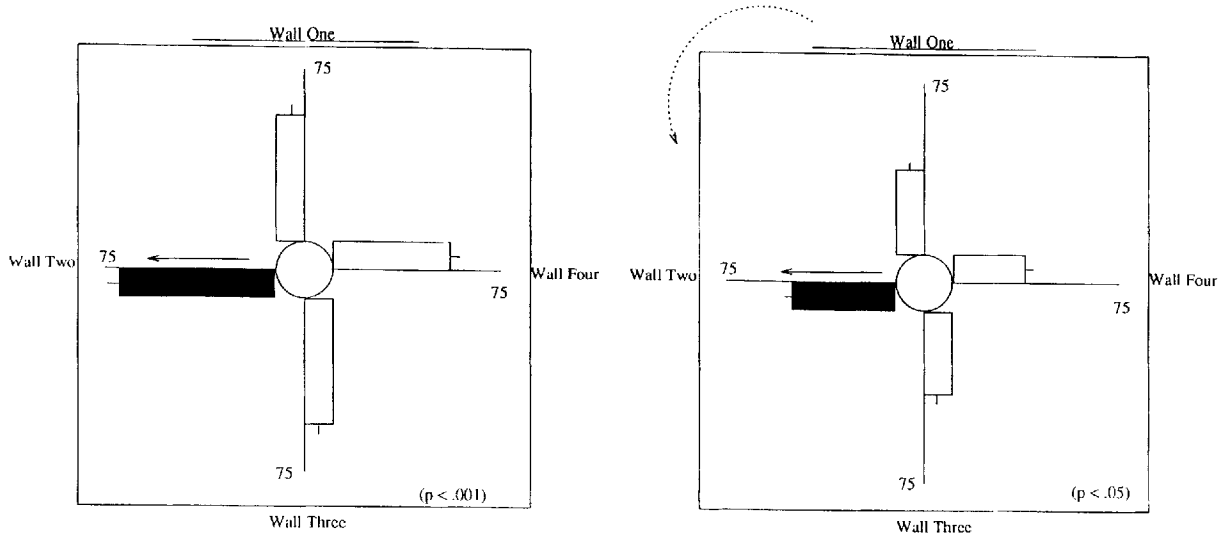


FIGURE 4. The responses of another hippocampal neuron with activity that was primarily related to the view of the environment rather than the place where the monkey was. Conventions as in Figure 3. Additional data for further locations for the neuron are described in the text.



(i) The cell was tested in the above four orientations; the maximum response was found to be while the monkey was facing toward Wall Two of the test chamber (direction indicated by ←).

(ii) The test chamber was rotated by 90 degrees anticlockwise as indicated above and the cell was retested. The chamber is re-oriented above to facilitate comparison between the test conditions. It can be seen that the strongest response is still elicited by Wall Two.

FIGURE 5. Effects of chamber rotation on the responses of a cell with view-related activity. The neuron responded best (and significantly differently than when facing in the opposite direction, as shown by the filled histogram bars) when the monkey was facing Wall Two, even after rotation of the test chamber. (The chamber is drawn non-rotated on the right to facilitate comparison of the two conditions.)

for this cell the responsiveness remained locked to the view of the environment as defined by the wall cues after chamber rotation.

The responses of another cell are shown in Figure 6 before (left) and after (right) chamber rotation. (The cell was classified as view responsive modulated by place, see later.) Before rotation, the cell responded best to a view of Wall Two and Wall Three. (Four independent trials were performed for every histogram bar and statistical analysis shown in Figure 4.) After rotation of the test chamber 90° anticlockwise, the cell did not respond differentially to views of Wall Two and Wall Three of the test chamber. (The cell again showed a general shift in its average firing rate after this rather disorienting procedure). Although in this experiment the responses of this cell did not rotate with the environment, the experiment did show that before the rotation the view the monkey had (and not some other factor) did influence the responses of the cell, in that the cell selectivity was disrupted by the rotation. The failure of the cell to respond after room rotation to the cues was presumably because of the disorientation caused by the room rotation, which brought the external cues in the room into conflict with internal (e.g., vestibular) cues.

Effects of visual field occlusion on view neurons

Further evidence that the view the monkey had of the room cues determined the responses of these neurons came from experiments in which the monkey's view of the room cues was occluded. The effects of occlusion are illustrated in Figure 7. The cell illustrated (the same as that in Figure 6) responded best to a view of Wall Two and Wall Three, and least when the monkey was facing toward Wall One and Wall Four of the test chamber (Fig. 7, left; $F_{3,16} = 13.2$, $P < 0.001$). After occluding the view of the environment by placing a masking screen on the test chair and by switching off the room lights, the cell ceased to respond differentially when the monkey's chair was facing in different directions (Fig. 7, right; $F_{3,16} = 1.0$, ns). (The firing rate of the cell rose for all directions the monkey was facing as a result of this manipulation.) Similar tests conducted on 8 of the other 26 cells shown in Table 1 as having view-related responses indicated that all the cells tested with occlusion ceased to have clear differential responses after visual field occlusion.

Wide View and Restricted View Cells

Sixteen neurons responded significantly differently (at least at the $P < 0.05$ level, though for the majority at the $P < 0.001$ level) depending on whether the monkey was facing into the test chamber with a wide view of the test chamber, or instead was close to and was facing any wall or corner with, therefore, a restricted view of the test chamber. The responses of one of these cells are shown in Figure 8. The cell responded with an increase in firing rate whenever the monkey was rotated so that his back was adjacent to a wall or corner. The firing rate of the cell fell to about one-third of this value whenever the monkey was rotated so that he was facing any wall or corner. The responses of all these cells were

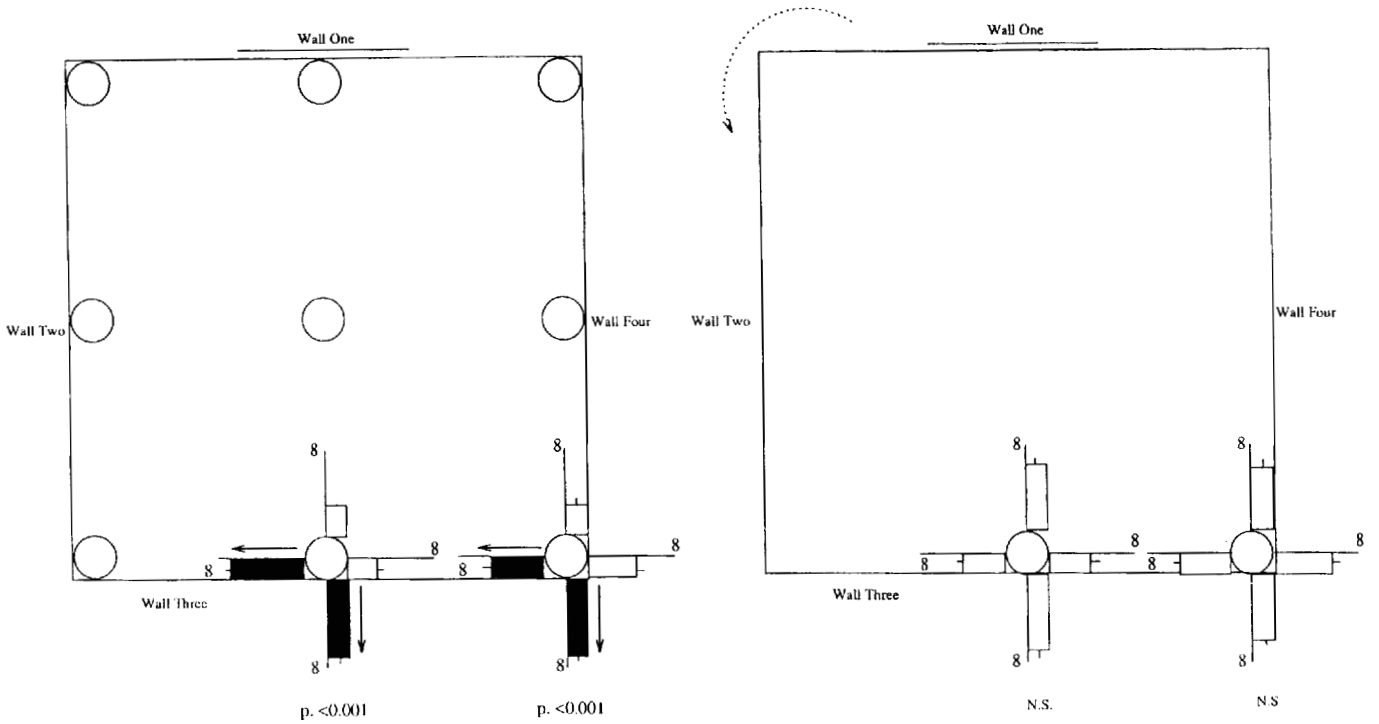


FIGURE 6. The responses of another cell are shown before (left) and after (right) chamber rotation. Before rotation, the cell responded best to a view of Wall Two and Wall Three in the positions illustrated. The cell did not respond in any other position sampled in the test chamber—along the other walls or in the center of the test chamber. After rotation of the test chamber 90° anticlockwise (as indicated by the curved arrow and dotted door), the cell did not respond differentially to views of Wall Two and Wall Three of the test chamber (see text). The right chamber is illustrated in the standard position to facilitate comparison with the panel to the left. Conventions as in Figure 3.

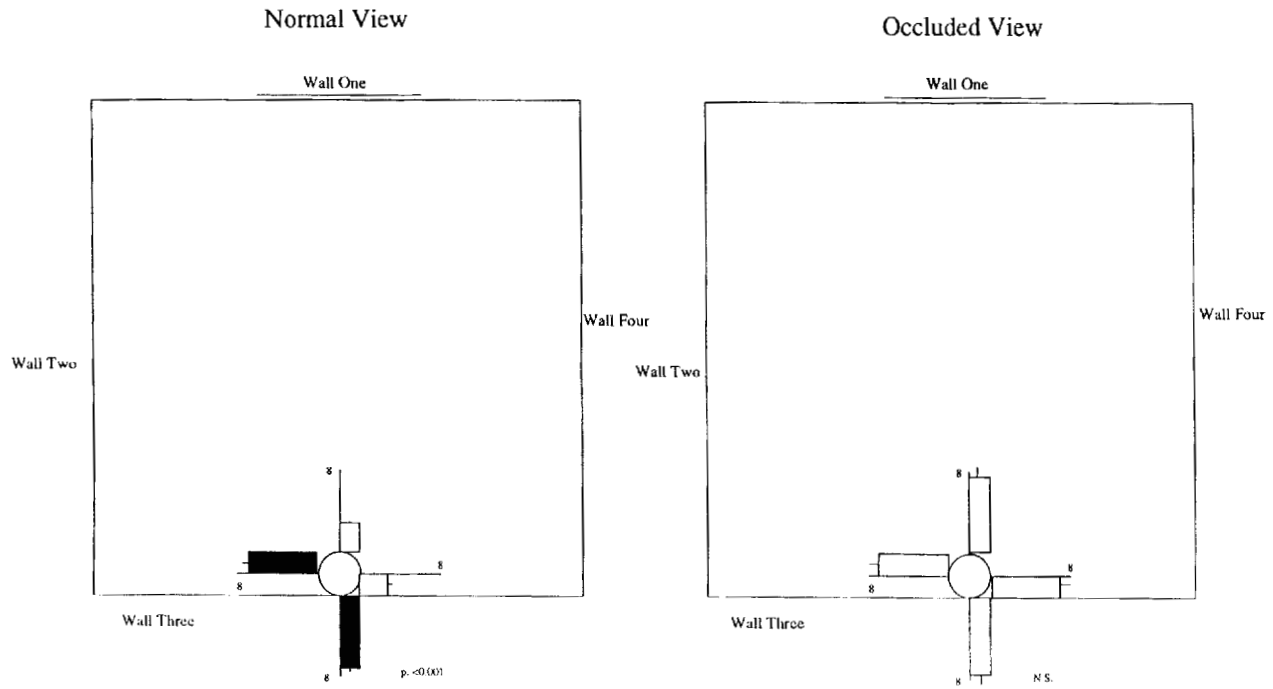


FIGURE 7. The effects of occlusion of the view of the environment on the activity of a cell with view-related activity. The cell responded best to a view of Wall Two and Wall Three when the monkey had a view of the environment (left), and after occluding the view of the environment by placing a masking screen on the test chair and by switching off the room lights, the cell ceased to respond differentially when the monkey was facing in different directions (right).

TABLE 1.

Summary of Cell Types

View, independent of place	3	
View, modulation by place	2	
View and whole-body motion	2	
Place and whole-body motion	1	
Wide view	11	
Restricted view	7	
Total cells with view-related responses	26	5.6%
Place cells with no view dependence	0	
Total cells recorded	461	100%

independent of the particular place (wall or corner) where the monkey was located. Of these 16 cells, 7 responded with an increase in firing rate when the monkey was looking into the corner and 11 responded with an increase in firing rate when the monkey was looking into the test chamber.

Responses to a Combination of View and Place in the Test Chamber

The responses of a cell with this type of response is illustrated in Figure 9. The activity of the cell is shown when the monkey was in each of four orientations in Corner One and Corner Two of the test chamber. The cell responded maximally in Corner One when the monkey was facing toward Wall One of the test chamber. The next largest response was to a view of Wall Two, although the response in this case was about half the response to a view of Wall One ($F_{3,16} = 3.39$; $P < 0.04$). When the monkey was tested at Corner Two of the test chamber, the response of the cell increased by about one third to a view of Wall One and by approximately twofold when the monkey viewed Wall Two of the test chamber ($F_{3,16} = 16.49$; $P < 0.001$). The response of the cell when the monkey was facing toward Wall Three and Wall Four of the test chamber was approximately the same regardless of whether the monkey was in Corner One or Corner Two of the test chamber.

The cell illustrated in Figure 9 responded primarily to the place where the monkey was in the test chamber, but, as shown later, view was also a significant factor. The one-way ANOVA across all testing conditions was significant ($F_{19,100} = 8.7$; $P < 0.0001$). With the data cast into conditions according to place but combined irrespective of view, the ANOVA was highly significant ($F_{4,115} = 15.5$; $P < 0.0001$). With the data cast into conditions according to view but combined irrespective of place, the ANOVA was not significant ($F_{3,116} = 1.4$; ns).

Further analyses were performed to determine whether there was any view dependency of this cell. To assess this separate analyses of variance were performed for each place where the monkey was to test whether the responses when the monkey was facing in different directions were significantly different. For three places (corners 1, 3, and 4) there were significant effects of view (all $P < 0.001$). Thus two cells were found in which the view-related responding of the cell depended on the place where the monkey was in the test chamber. No cells were found that responded to the place where the monkey was independent of view.

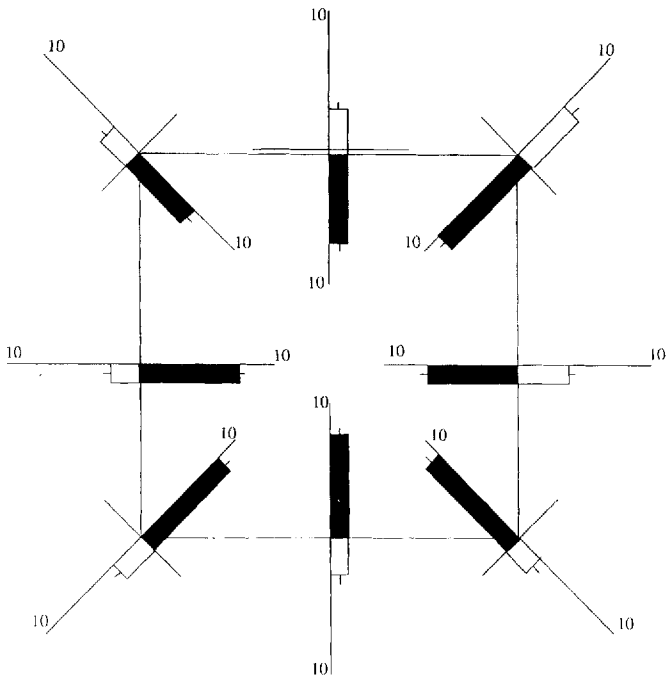


FIGURE 8. The responses of a neuron with activity related to a wide as compared with a restricted view of the environment. The cell responded with an increase in firing rate whenever the monkey was rotated so that his back was adjacent to a wall or corner. The firing rate of the cell fell to about one-third of this value whenever the monkey was rotated so that he was facing a wall or corner. Conventions as in Figure 3. A two-way ANOVA on the data showed a significant effect of whether the monkey was facing the wall or the center of the room ($F_{1,71} = 10.8$, $P = 0.002$), with no significant effect of where the monkey was, or the interaction term.

Cells Responding to a Combination of Whole-Body Motion and Environmental View or Place

Some cells were found that responded when the monkey was moving, but only when he was moving when he had a particular view, or was in a particular place. For example, one cell responded only when the monkey was moving along Wall Two of the test chamber, but not when he was moving along other walls. The cell did not respond at any time when the monkey was stationary, for example, when he was in the corners, or when he was looking at Wall Two. Another cell responded during forward and backward motion when the monkey was facing away from the door of the test chamber, but only when moving backward when facing the door of the test chamber. These two cells, described in more detail elsewhere (O'Mara et al., 1994), thus had activity that occurred to a combination of whole-body motion with some but not other views of the environment. A third cell responded best when the monkey was moved toward the door of the test chamber, regardless of the orientation of the monkey in the chamber

when moving toward that place. In this experiment the monkey was moved forward, backward, to the left side, and to the right side toward the door of the test chamber. The neuron did not respond during similar movements toward other places in the environment. Thus this cell responded to whole-body motion toward a particular place.

Cells that responded to views and whole-body motion *independent* of each other were not found at all in the present sample. An example of such a cell would be one that responds to a view of a particular portion of the test chamber and also responds to, say, linear translation, but not linear translation to that particular portion of the chamber for which a view activates the cell. Motion cells and view cells were very largely two non-overlapping populations of cells. Cells responsive to view accounted for 5.6% of the sample tested, and cells responding to whole-body motion comprised 9.8% of the sample tested (O'Mara et al., 1994). Cells responding to whole-body motion *and* view or place comprised 3 of 461 cells tested or 0.65% of the sample.

Proportions and Characteristics of the Different Cell Types Recorded

Four hundred and sixty-one cells were recorded, of which 26 (5.6%) responded to views of the environment in the ways shown in Table 1. The mean spontaneous firing rate of cells that responded by increasing their rate of firing was 12.1 spikes/s (SEM ± 1.7), and their responses increased to a mean of 18.9 spikes/s (SEM ± 2.2). The mean firing rate of cells that responded by decreasing their rate of firing was 11.7 (SEM ± 1.9), and their responses decreased to a mean of 3.9 spikes/s (SEM ± 0.6). (Of the view cells, 5, 10, 2, and 9 were recorded in the different monkeys.) The responses of some of the other cells in the 461 recorded are described elsewhere (O'Mara et al., 1994).

Recording Sites and Electrophysiological Characteristics of View Neurons

The recording sites, based on reconstructions using the microlesions made through the recording microelectrode tips and the X radiographs, are indicated by a V in Figure 10b. Two labelled coronal sections through the right anterior hippocampus at the level of the uncus of the macaque monkey (at about 7 mm posterior to the sphenoid reference plane) and the posterior hippocampus (at about 13 mm posterior to the sphenoidal reference plane) are provided for orientation in Figure 10a. The cells described here were in at least the majority of cases likely to be pyramidal cells for the following reasons. First, the reconstruction of the recording sites based on microlesions made through the recording microelectrodes and the X radiographs showed that many of the cells were in the pyramidal cell region. Second, the

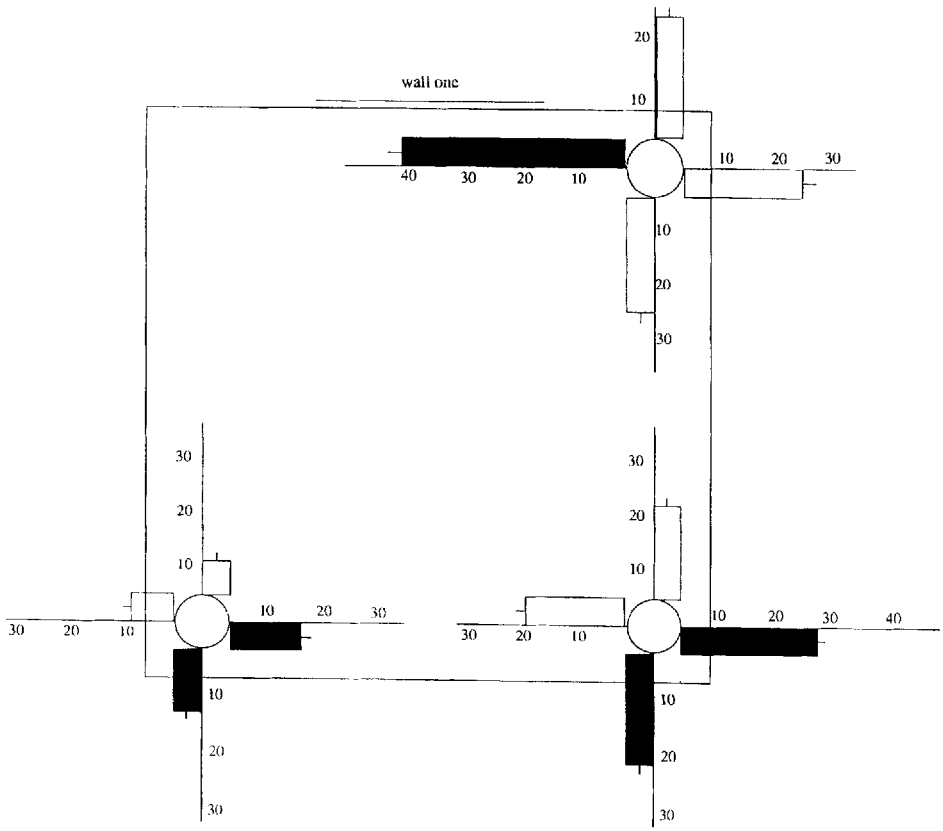


FIGURE 9. The responses of a neuron with activity that depended on a combination of the view the monkey had and of the place in the test chamber. Conventions as in Figure 3.

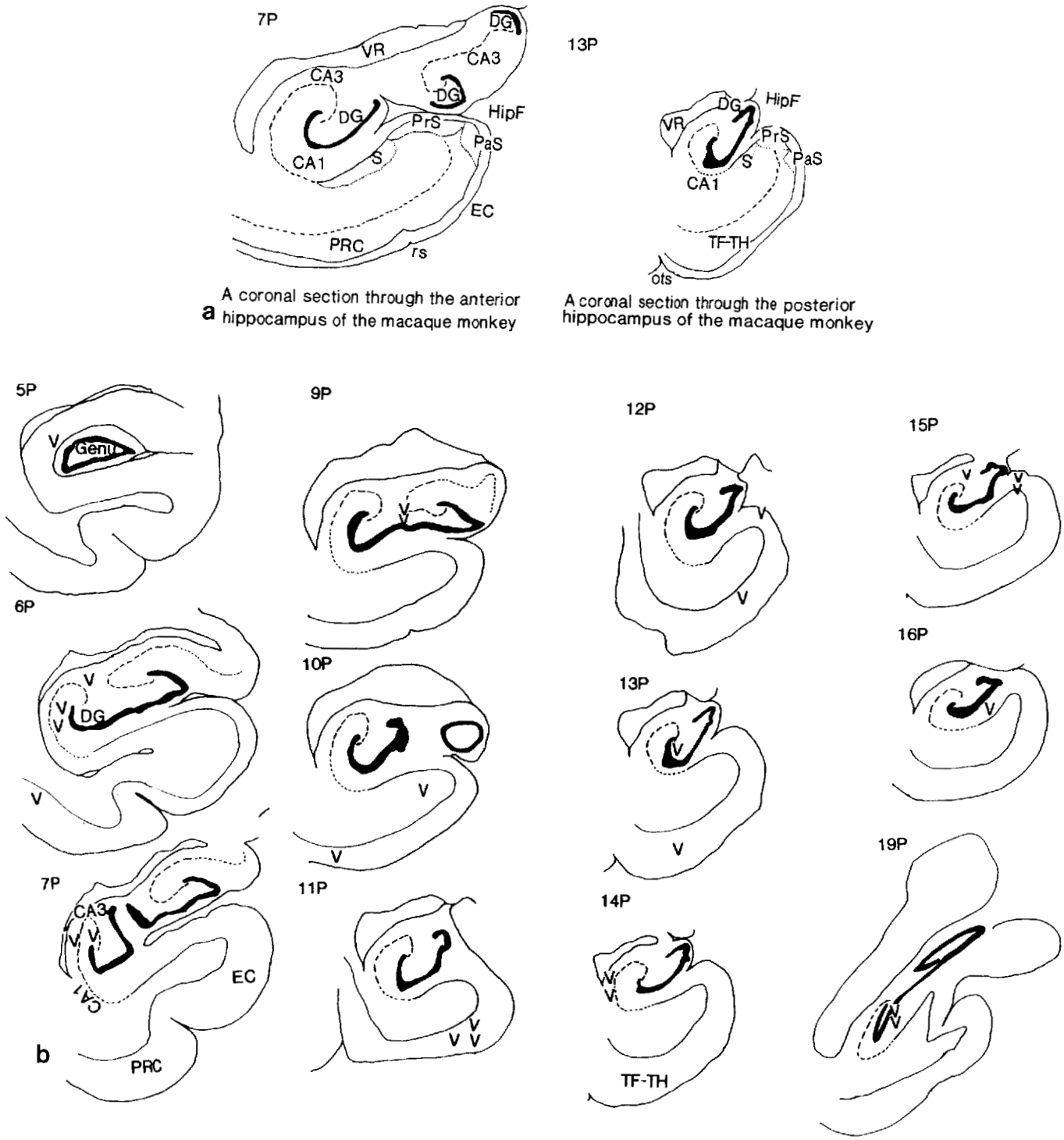


FIGURE 10. a: Two labelled coronal sections through the right anterior hippocampus at the level of the uncus of the macaque monkey (at about 7 mm posterior to the sphenoid reference plane) and the posterior hippocampus (at about 13 mm posterior to the sphenoidal reference plane). The terminology adopted is based on Amaral et al. (1984) and Rosene and Van Hoesen (1987). EC = entorhinal cortex; DG = dentate gyrus; HipF = hippocampal fissure; ots = occipito-temporal sulcus; PRC = perirhinal cortex; PrS = presubiculum; PaS = parasubiculum; rs = rhinal sulcus; S = subiculum; TF-TH = areas of the parahippocampal gyrus; VR = ventricle. b: The recording sites of the view-related neurons are indicated by a V in these coronal sections at different distances in millimeters posterior (P) to the sphenoid reference (see text). The dentate granule cells are indicated by the thick dark line, and the CA3 and CA1 pyramidal cells by the dotted line. EC = entorhinal cortex; DG = dentate gyrus; PRC = perirhinal cortex; rs = rhinal sulcus; TF-TH = areas of the parahippocampal gyrus.

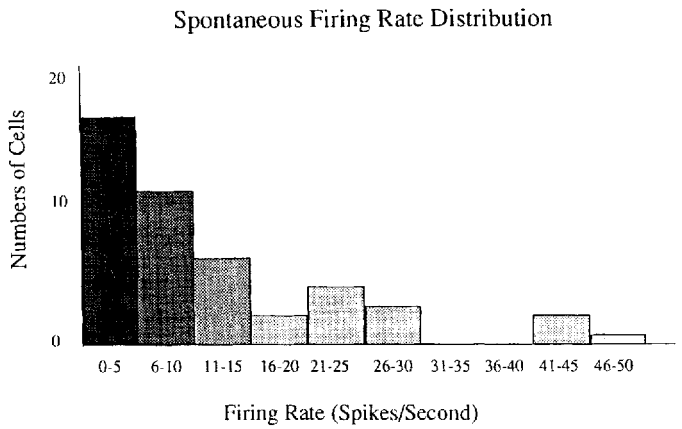


FIGURE 11. Distribution of spontaneous firing rates of the cells.

spontaneous firing rates of the majority of the cells were relatively low (see earlier and Fig. 11).

DISCUSSION

The main finding described in this paper is that there is a population of cells in the primate hippocampal complex with responses that depend on where in a spatial environment the monkey is looking (see Table 1). The responses of some of these cells are relatively little influenced by where the monkey is in the environment. In that the responses of these cells depend on the part of space where the monkey is looking in the environment, and not on the place where the monkey is, they are unlike place cells found in the rat (O'Keefe, 1979; Muller et al., 1991), and we call this type of cell found in the primate *space cells* (cf. Feigenbaum and Rolls, 1991) or, more descriptively and in the light of the findings described here, *view cells*. 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 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 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 monkeys might be in enabling a monkey to remember where it had seen ripe fruit. The representations of space provided by hippocampal view-responsive neurons may thus be useful in forming memories of spatial environments (for example, of where an object such as ripe fruit has been seen and of where the monkey is as defined by seen views). The representations of space provided by hippocampal view-responsive neurons may also, together with whole-body motion cells, be useful in remembering trajectories through environments, of use, for example, in short range spatial navigation (O'Mara et al., 1994).

The responses of some of these cells occurred to views of only some parts of the environment, but depended also partly on where the monkey was in the environment. One possibility for why the view-related responses of these cells depended in part on the place the monkey was is that the view of a position in space does, of course, depend to some extent on the place from which that part of space is viewed. Another possibility is that the cells responded to a combination of information held separately in other neurons about the part of space at which the monkey looked and the place where the monkey was. The paucity of cells found in this study that responded just to the place where the monkey was makes this not very likely. However, now that view cells have been found, it will be of interest in future work to separate these two possibilities by, for example, measuring exactly where the monkey is looking with the search coil technique, to investigate whether the major determinant of the responsiveness of such cells is the part of space where the monkey is looking, or the place where the monkey is. The measurement of eye position would also enable the size of the spatial view fields of the neurons described here to be determined. None of the view cells described here were head direction cells, in that whether the cells responded could be dissociated from head direction, as illustrated by the examples in Figures 3, 4, and 8.

The finding that some cells responded to views of the environment only during whole-body motion suggests that one aspect of what is made explicit in the neuronal representation of space in the primate hippocampus is related to the trajectory of a motion in space. This would be very useful in a system that is involved in remembering recent movements or trajectories in space, because the motion would not be represented in egocentric coordinates but instead as occurring in relation to a particular part of the environment. The one cell that responded only when the monkey was moving to a particular place would also be useful in relation to the memory of recently made trajectories during short range spatial navigation (see O'Mara et al., 1994).

The cells that responded either to wide or to restricted views of the environment provide further evidence that information about where the monkey is looking is present in the primate hippocampus. In this particular case the information is about whether the monkey was close to or far from a part of space defined by the walls of the environment. The information was not about the particular place in the environment where the monkey was, in that the response of these cells was similar at different places in the environment, and in that the response at any one place was determined by whether the monkey was viewing a wall close to or far from him.

There was a paucity of cells found in this study with activity related to the place in the environment where the monkey was. No cells were found with activity that depended only on where the monkey was, independently of where the monkey was looking in the environment, when the monkey was in that place. One cell was found that responded in relation to movement toward a place. One possible reason why cells with pure place-related activity were not found in this study is that the monkey was moved to a place in the environment by the experimenter. In the study of Ono et al. (1993), some cells were found that appeared to have place-related activity, and in that study the monkey held a lever to cause movement of the cab in which the monkey sat. It is possible that the more active engagement of the monkey in the move-

ment encouraged putative place cells to fire. In rats, it is known that if a rat is moved by an experimenter to a place, then place cells fire if the rat is allowed to move its head and feet while being held but do not respond if the rat is wrapped in a blanket and is fully inactive (Foster et al., 1989). It would be surprising if place cells became inactive in primates when a primate is transported to different places, as monkeys transported can perform a conditional discrimination based on where they are (Gaffan and Harrison, 1989), but the possibility that a factor such as this leads to inactivation of place cells that would otherwise be evident will be investigated. The monkeys certainly knew where they were in the study described here, in that they only reached for food when they were at the appropriate food wells in the spatial environment. Another possibility, that a richer spatial environment is important, needs to be investigated by performing the recordings in a large room that can be seen by the monkey. Whatever the outcome, the present results do show that there are view-related cells in the primate hippocampus. Moreover, it would be of interest to know whether the cells described by Ono et al. (1993) had activity reliably related to the place where the monkey was, independent of the direction in which the monkey faced in the environment and therefore independent of view. The present findings suggest that further investigation of the relative contribution of the place where the monkey is and the view the monkey has of the environment will be helpful in understanding the representation of spatial information in the primate hippocampus. It will also be of interest to define what it is about the view of a location that activates the cells described here. The cells might respond to one particular feature that defines a location in the environment, or might respond to any one of a number of features that can be used to define a spatial location. The possibility that it is reward that defines the responses of the cells described here can be rejected, because many of the cells responded differently to different spatial locations that were equally rewarded.

Occlusion of the view of the environment abolished the responses of the view cells described here, providing evidence that the visual input was a major factor that accounted for the firing of the neurons. The effects occurred rapidly so that the neuronal responses were under relatively direct control of the visual input and did not continue to respond and thus reflect a memory of the view in these experiments. However, it would be of interest to investigate this further under conditions in which the monkey had to remember where he was facing while in darkness. When the chamber was rotated round the monkey in darkness, one neuron rotated with the cues when the lights were turned on again, and another neuron stopped responding to the environmental cues. This was also a disorienting procedure for the tester, as under these conditions there was a conflict between the vestibular signals, indicating position and direction, and the environmental cues. The fact that the second cell did not respond to the cues in the same way as previously could reflect the general disturbance produced by the chamber rotation, or it could indicate that the responses of the cells are influenced not only by the external visual cues, but also by internal information about where parts of the environment should be. Whichever explanation is correct, the effects of these manipulations do show that visual inputs from spatial cues in the environment do affect the responses of these hippocampal neurons. Further investigation of whether there is a memory component reflected in the responses of these neurons would be of interest.

Corresponding with this evidence that visual inputs providing information about spatial location do affect the responses of hippocampal neurons in monkeys, there is also evidence that visual inputs contribute to the firing of place cells in rats. For example, O'Keefe and Conway (1978) showed in a cue-controlled environment that rat hippocampal place neurons could often respond when the rat was in a place on the basis of a subset of several different environmental cues that indicated to the rat its place in the environment. In rats, place fields may rotate when the whole environment is rotated around the rat (O'Keefe and Conway, 1978; Muller et al., 1991). (This typically can be repeated for only a few cue position rotations. The rat may ignore the cues if they rotate frequently and are in conflict with other, e.g., vestibular and proprioceptive, information; B. McNaughton, pers. comm., 1993.) Some place neurons lose their place fields in darkness (Quirk et al., 1990) or when all the cues are removed in the presence of the rat (O'Keefe and Speakman, 1987), but the majority maintain their place fields, showing that the majority can be influenced by memory and/or non-visual inputs, as well as by visual inputs.

The proportion of view cells found in this study was relatively low. One reason for this may have been that we explicitly designed a cue-controlled environment, which, in having only four spatial cues on the walls (so that effects of cue movement could potentially be investigated), meant that the chamber was in general rather visually limited, with matt black walls forming most of the environment. Having found view cells in the experiments described in this paper, we are now continuing the experimental investigations with a much richer spatial environment. We are already starting to find reasonable numbers of view cells with large neuronal responses in this richer environment (Rolls, et al., 1995). These new findings from the experiments now in progress are thus extending the results described here in a way consistent with the finding described here of view cells in the primate hippocampus.

One of the cells described here had a very high spontaneous firing rate (55 spikes/s) and was influenced by view (see Fig. 5). In the rat, cells with high firing rates are often thought to be interneurons (theta cells). Such cells in rats may show some dependence of their firing rate on place (Kubie et al., 1990), just as the cell referred to earlier was modulated by view.

In conclusion, we have described in this paper neurons in the hippocampal system of primates that have activity related to the view of a spatial environment. The neurons were recorded in a cue-controlled environment and had quite different properties from those described in analogous cue-controlled environments in rats (O'Keefe, 1983; O'Keefe and Speakman, 1987). The representations of space provided by the monkey hippocampal view-responsive neurons may be useful in forming memories of spatial environments (for example, of where an object has been seen, and

of where the monkey is as defined by seen views), and together with whole-body motion cells, in remembering trajectories through environments, of use, for example, in short range spatial navigation.

Acknowledgments

This research was supported by the Medical Research Council, grant PG8513790.

REFERENCES

Aggleton JP, Passingham RE (1981) Stereotaxic surgery under X-ray guidance in the Rhesus monkey, with special reference to the amygdala. Exp Brain Res 44:271–276.

Amaral DG, Insausti R, Cowan WM (1984) The commissural connections of the monkey hippocampal formation. J Comp Neurol 224:307–336.

Barnes CA (1988) Spatial learning and memory processes: The search for their neurobiological mechanisms in the rat. Trends Neurosci 11:163–169.

Cahusac PMB, Miyashita Y, Rolls ET (1989) Responses of hippocampal formation neurons in the monkey related to delayed spatial response and object-place memory tasks. Behav Brain Res 33:229–240.

Feigenbaum JD, Rolls ET (1991) Allocentric and egocentric information processing in the hippocampal formation of the behaving primate. Psychobiology 19:21–40.

Foster TC, Castro CA, McNaughton BL (1989) Spatial selectivity of rat hippocampal neurons: Dependence on preparedness for movement. Science 244:1580–1582.

Gaffan D (1974) Recognition impaired and association intact in the memory of monkeys after transection of the fornix. J Comp Physiol 86:1100–1109.

Gaffan D (1977) Monkey's recognition memory for complex pictures and the effects of fornix transection. Q J Exp Psychol 29:505–514.

Gaffan D, Harrison S (1988) A comparison of the effects of fornix section and sulcus principalis ablation upon spatial learning by monkeys. Behav Brain Res 31:207–220.

Gaffan D, Harrison S (1989) Place memory and scene memory: Effects of fornix transection in the monkey. Exp Brain Res 74:202–212.

Gaffan D, Saunders RC (1985) Running recognition of configural stimuli by fornix transected monkeys. Q J Exp Psychol 37B:61–71.

Gaffan D, Weiskrantz L (1980) Recency effects and lesion effects in delayed non-matching to randomly baited samples by monkeys. Brain Res 196:373–386.

Gaffan D, Gaffan EA, Harrison S (1984a) Effects of fornix transection on spontaneous and trained non-matching by monkeys. Q J Exp Psychol 36B:285–303.

Gaffan D, Saunders RC, Gaffan EA, Harrison S, Shields C, Owen MJ (1984b) Effects of fornix transection upon associative memory in monkeys: Role of the hippocampus in learned action. Q J Exp Psychol 26B:173–221.

Kubie JL, Muller RU, Bostock E (1990) Spatial firing properties of hippocampal theta cells. J Neurosci 10:1110–1123.

McNaughton BL, Barnes CA, O'Keefe J (1983) The contributions of position, direction, and velocity to single unit activity in the hippocampus of freely-moving rats. Exp Brain Res 52:41–49.

Merrill EG, Ainsworth A (1972) Glass-coated platinum-plated tungsten microelectrodes. Med Biol Eng 10:662–672.

Milner B (1972) Disorders of learning and memory after temporal lobe lesions in man. Clin Neurosurg 19:421–446.

Morris RGM, Garrud P, Rawlins JNP, O'Keefe J (1982) Place navigation impaired in rats with hippocampal lesions. Nature 297:681–683.

Muller RU, Kubie JL, Bostock EM, Taube JS, Quirk GJ (1991) Spatial firing correlates of neurons in the hippocampal formation of freely moving rats. In: Brain and space (Paillard J, ed), pp. 296–333. Oxford: Oxford University Press.

O'Keefe J (1979) A review of the hippocampal place cells. Prog Neurobiol 13:419–439.

O'Keefe J (1983) Spatial representation within and without the hippocampal formation. In: The neurobiology of the hippocampus (Seifert W, ed), pp 375–403. New York: Academic Press.

O'Keefe J, Conway DH (1978) Hippocampal place units in the freely moving rat: Why they fire when they fire. Exp Brain Res 31:573–590.

O'Keefe J, Nadel L (1978) The hippocampus as a cognitive map. Oxford: Clarendon Press.

O'Keefe J, Speakman A (1987) Single unit activity in the rat hippocampus during a spatial memory task. Exp Brain Res 68:1–27.

O'Mara SM, Rolls ET, Berthoz A, Kesner RP (1994) Neurons responding to whole-body motion in the primate hippocampus. J Neurosci 14:6511–6523.

Ono T, Nakamura K, Nishijo H, Eifuku S (1993) Monkey hippocampal neurons related to spatial and non-spatial functions. J Neurophysiol 70:1516–1529.

Owen MJ, Butler SR (1981) Amnesia after transection of the fornix in monkeys: Long-term memory impaired, short-term memory intact. Behav Brain Res 3:115–123.

Parkinson JK, Murray EA, Mishkin M (1988) A selective mnemonic role for the hippocampus in monkeys: Memory for the location of objects. J Neurosci 8:4059–4167.

Petrides M (1985) Deficits on conditional associative-learning tasks after frontal- and temporal-lobe lesions in man. Neuropsychologia 23:601–614.

Quirk GS, Muller RU, Kubie JL (1990) The firing of hippocampal place cells in the dark depends on the rat's recent experience. J Neurosci 10:2008–2017.

Rolls ET (1990) Functions of the primate hippocampus in spatial processing and memory. In: Neurobiology of comparative cognition (Olton DS, Kesner RP, eds), pp 339–362. Hillsdale, NJ: Lawrence Erlbaum.

Rolls ET (1991) Functions of the primate hippocampus in spatial and non-spatial memory. Hippocampus 1:258–261.

Rolls ET (1994) Neurophysiological and neuronal network analysis of how the primate hippocampus functions in memory. In: The memory system of the brain (Delacour J, ed), pp 713–744. London: World Scientific.

Rolls ET (1995) Brain mechanisms involved in perception and memory, and their relation to consciousness. In: Cognition, computation, and consciousness (Ito M, Miyashita Y, and Rolls ET, eds).

Rolls ET, O'Mara S (1993) Neurophysiological and theoretical analysis of how the hippocampus functions in memory. In: Brain mechanisms of perception and memory: From neuron to behavior (Ono T, Squire LR, Raichle ME, Perrett DI, Fukuda M, eds), pp 276–300. New York: Oxford University Press.

Rolls ET, Burton MJ, Mora F (1976) Hypothalamic neuronal responses associated with the sight of food. Brain Res 111:53–66.

Rolls ET, Sanghera MK, Roper-Hall A (1979) The latency of activation of neurones in the lateral hypothalamus and substantia innominata during feeding in the monkey. Brain Res 164:121–135.

Rolls ET, Miyashita Y, Cahusac PMB, Kesner RP, Niki H, Feigenbaum J, Bach L (1989) Hippocampal neurons in the monkey with activity related to the place in which a stimulus is shown. J Neurosci 9:1835–1845.

Rolls ET, Robertson R, and Georges-Francois P (1995) The representation of space in the primate hippocampus. Soc Neurosci Abstr Vol. 21.

Rosene DL, Van Hoesen GW (1977) Hippocampal efferents reach widespread areas of cerebral cortex and amygdala in rhesus monkey. Science 198:315–317.

Rupniak NMJ, Gaffan D (1987) Monkey hippocampus and learning about spatially directed movements. J Neurosci 7:2331–2337.

Scoville WB, Milner B (1957) Loss of recent memory after bilateral hippocampal lesions. J Neurol Neurosurg Psychiat 20:11–21.

Smith ML, Milner B (1981) The role of the right hippocampus in the recall of spatial location. Neuropsychologia 19:781–793.

Squire LR (1992) Memory and the hippocampus: A synthesis from findings from rats, monkeys and humans. Psych Rev 99:195–231.

Tamura R, Ono T, Fukuda M, Nakamura K (1990) Recognition of egocentric and allocentric visual and auditory space by neurons in the hippocampus of monkeys. Neurosci Lett 109:293–298.

Tamura R, Ono T, Fukuda M, Nakamura K (1992a) Monkey hippocampal neuron responses to complex sensory stimulation during object discrimination. Hippocampus 2:287–306.

Tamura R, Ono T, Fukuda M, Nakamura K (1992b) Spatial responsiveness of monkey hippocampal neurons to various visual and auditory stimuli. Hippocampus 2:307–322.

Treves A, Rolls ET (1994) A computational analysis of the role of the hippocampus in memory. Hippocampus 4:374–391.

Zola-Morgan S, Squire LR (1985) Medial temporal lesions in monkeys impair memory in a variety of tasks sensitive to human amnesia. Behav Neurosci 99:22–34.