Spatial representations in the primate hippocampus, and their functions in memory and navigation

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Abstract

Hippocampal spatial view neurons in primates respond to the place where a monkey is looking, with some modulation by place. In contrast, hippocampal neurons in rodents respond mainly to the place where the animal is located. We relate this difference to the development of a fovea in primates, and the highly developed primate visual system which enables identification of what is at the fovea, and a system for moving the eyes to view different parts of the environment. We show that the spatial view representation in primates is allocentric, and provide new animations using recorded neuronal activity to illustrate this. We also show that this spatial representation becomes engaged in tasks in which the location 'out there' in a scene of objects and rewards must be remembered. We show that this representation of space being viewed provides a framework for the encoding of episodic memory and the recall of these memories in primates including humans, with hippocampal neurons responding for example in a one-trial object / place recall task. These functions of the primate hippocampus in scene-related memory, provide a way for the primate hippocampus to contribute to actions in space and navigation. We consider in a formal model the mechanisms by which these different spatial representations may be formed given the presence of the primate fovea, and how these mechanisms may contribute to the representations found during navigation in a virtual environment.

Contents

1. Introduction

There has been great evolution of vision in primates compared to rodents. This involves great development of temporal and parietal visual cortical areas that provide inputs to the hippocampus via the perirhinal cortex and parahippocampal gyrus. It is therefore a fundamental issue to investigate whether hippocampal spatial processing, which utilizes visual inputs, in primates is identical to that in rats. In rodents, place cells are found (Hartley *et al.*, 2014; Markus *et al.*, 1995; McNaughton *et al.*, 1983; Muller *et al.*, 1991; O'Keefe, 1979, 1984). There is evidence that place is represented in the primate hippocampus (Rolls and O'Mara, 1995; Wirth *et al.*, 2017) as in the rodent hippocampus, but the major difference is that hippocampal spatial representation in primates stems from the elements of a scene that the animal foveates rather than where the animal is, and that is the focus of this paper. We propose that the difference between primates and rodents in the spatial representations in the hippocampus is related to the development in evolution of the fovea in primates, and of the cortical areas in the temporal lobe that are specialized for processing what is represented near the fovea in complex natural scenes (Rolls *et al.*, 2003), and of areas in the parietal lobes that guide eye movements to fixate parts of scenes (Bisley and Goldberg, 2003). We consider the implications of this difference in spatial representations for the functions of the hippocampus, and argue, inter alia, that this enables a primate located in one place to look at many locations in the environment, and associate in memory the objects or rewards present at each of those viewed locations, even though the primate is not at those locations, and remains in one place. We argue that this goes beyond the capabilities of rodent place cells that respond to places rather than locations being viewed. This is a fundamental difference important to understanding many aspects of primate including human episodic memory, which does implement this functionality of remembering objects or rewards present at viewed locations. We show that to analyse the nature of these representations,, it is necessary to perform testing while eye position is recorded when the subject is in different places, and is looking at different parts of a scene. The available evidence on this comes from neuronal recordings in macaques, with no assessment of this type performed yet in humans, and this is identified as an important area for future investigation in humans. However, we do refer to recordings and neuroimaging and lesion data for the human hippocampus and related areas, to assess to what extent they fit with the overall understanding of the functioning of the primate hippocampus described here.

We note that, consistent with the direct evidence on neuronal spatial representations in primates described here, it has recently been argued from neuropsychological and evolutionary perspectives across a range of vertebrates, that the primate hippocampus is involved in scene processing rather than place processing, related to the development of the primate fovea (Murray *et al.*, 2017). For example, lesions to the macaque hippocampal system impair remembering the place in a scene “out there” where an object was located (Gaffan, 1994; Murray *et al.*, 1998; Murray *et al.*, 2017).

However, we then build on the neurophysiological evidence to show that the same underlying computational principles may be involved in setting up and using the spatial representations in both the primate and rodent hippocampus (Rolls, 2016a). Understanding the differences between the spatial representations in primates vs rodents is very timely, because it is now becoming possible to record from neurons in the human hippocampus and related structures (Ekstrom, 2015; Ekstrom *et al.*, 2003; Ekstrom and Ranganath, 2017; Fried *et al.*, 1997; Kreiman *et al.*, 2000; Quiroga, 2012; Rey *et al.*, 2015). It is likely that what is found in the human hippocampus will reflect the evolution of foveally dominated vision in primates, and therefore how the human hippocampal system operates, and how it functions in human memory and navigation.

1.1. The great evolution of visual cortical and related areas in primates

The cortical systems from which the hippocampus receives its inputs have undergone great evolutionary development. Different evolutionary pressures have led to considerable differences between rodents and primates. The visual system is an important example. Rodents have a relatively poorly developed visual system, with a field of view that covers approximately 320 degrees, no fovea (Euler and Wassle, 1995; Hughes, 1979; Prusky and Douglas, 2004), and a limited system for eye movement control, although there is some progress in understanding eye movements in rodents (Payne and Raymond, 2017; Wallace *et al.*, 2013). Primates have evolved with forward facing eyes, well developed binocular vision which enables stereopsis, and a highly developed fovea which allows high visual acuity for the small part of the visual field being fixated (Crawford, 1977; Kaas, 2013). The presence of a fovea in primates is important for object representation in primates, in that

single neurons in the inferotemporal visual cortex respond to an object near to the fovea, and not to other objects in the surround (Rolls *et al.*, 2003), and this helps the interface to action, which can then be directed to the object at the fovea (Rolls, 2016a; Rolls *et al.*, 2003; Rolls and Deco, 2002). The presence of a fovea in primates and the cortical systems for object identification of what is at the fovea, and for directing eye movements to foveate objects, can been conceptualized as an adaptation of vision useful for finding and then reaching to obtain and grasp fruit in sylvian environments (Kaas, 2013). This primate visual capability is associated with a large system of highly developed visual cortical areas in the ventral visual stream, which provide input via the parahippocampal gyrus and retrosplenial / posterior cingulate areas to the hippocampus, and of a highly developed dorsal visual system, which includes mechanisms useful for the generation of the eye movements necessary to saccade to and then fixate objects in a scene (Fig. 1) (Bisley and Goldberg, 2010; Bremmer *et al.*, 2002a; Bremmer *et al.*, 2002b; Galletti and Fattori, 2017; Goodale, 2014; Rolls, 2012; Rolls, 2016a). All these specializations of visual processing in primates when compared to rodents are, we propose, necessary for understanding differences in the representations in the primate vs rodent hippocampus.

In the context of the evolutionary development of the primate cortex, which include hierarchical organization, the development of a fovea, and mechanisms for object recognition for what is at the fovea and for moving the fovea to fixate objects (Rolls, 2016a; Rolls and Webb, 2014), we describe some of the cortical connections of the primate hippocampus. These connections provide a foundation for understanding the neurons recorded in the primate including human hippocampus. Inputs reach the primate hippocampus as shown in Figs. 1 and 2 from the entorhinal cortex (area 28) which in turn receives from the considerably evolved parahippocampal gyrus (areas TH and TF) and from the perirhinal cortex. These two areas receive from the high levels of the hierarchically organised functional streams of the primate (including human) association neocortex, including the auditory and visual temporal cortical areas, the parietal cortical areas, and the prefrontal cortex (Amaral *et al.*, 1992; Burwell *et al.*, 1995; Suzuki and Amaral, 1994b; Van Hoesen, 1982). The hippocampus therefore has the potential to associate together object and spatial representations, including inputs from both the ventral and dorsal visual cortical streams, as shown in Fig. 1. In addition, the orbitofrontal cortex and amygdala send inputs to the entorhinal cortex, which provides reward- and punishment-related information to the hippocampus (Carmichael and Price, 1995; Pitkanen *et al.*, 2002; Rolls, 2015; Stefanacci *et al.*, 1996; Suzuki and Amaral, 1994a). Interestingly, reward-related information from the orbitofrontal cortex also reaches the posterior cingulate cortex (Vogt and Laureys, 2009; Vogt and Pandya, 1987), introducing reward information into the dorsal stream entry into the hippocampal system (Fig. 1). There are in addition subcortical inputs from e.g. the septum, and from the mammillary bodies which convey information about self-motion from the vestibular system. The hippocampus projects back to the neocortical areas from which it receives inputs (Van Hoesen, 1982) via the subiculum, entorhinal cortex and parahippocampal gyrus (see Figs. 1 and 2). The connectivity of the rat hippocampus is described elsewhere (Amaral and Lavenex, 2007; van Strien *et al.*, 2009). Some differences are a relatively larger olfactory input to the entorhinal cortex in the rodent compared to the primate (Steward, 1976), and a parietal cortex which projects to the parahippocampal regions less devoted to visual space processing in the rodent than in the primate (Whitlock, 2017).

However, the computational principles of the rodent and primate hippocampus are very similar, the difference being in the nature of the representations being processed in the rodent and primate hippocampus (Kesner and Rolls, 2015). Another possible difference is that the ventral and dorsal parts of the hippocampus have somewhat different connectivity, even within CA3, in rodents (Strange *et al.*, 2014). However, in primates the CA3 connectivity is much more widespread, allowing posterior and anterior parts of CA3 to be connected (Kondo *et al.*, 2009), providing a basis for object, location, and reward information to be brought together within the effectively single CA3 network in the primate hippocampal system (Kesner and Rolls, 2015; Rolls, 2016a) (Fig. 2).

1.2 Effects of hippocampal lesions in primates help to define the functions to be investigated neurophysiologically

In rodents, hippocampal lesions impair tasks such as the water maze and object-place memory tasks (Kesner *et al.*, 2008; Kesner and Rolls, 2015; Morris *et al.*, 1982). Lesion studies in primates have shown that hippocampal damage (or damage to the fornix) leads to learning deficits about the places where objects are located, and about the places where responses are required (Murray *et al.*, 2017). To provide an example, monkeys and humans with hippocampal damage or fornix section have deficits in memory tasks in which they must remember where objects have been

seen “out there” in space (Gaffan, 1994; Parkinson *et al.*, 1988; Smith and Milner, 1981). In macaques, parahippocampal cortex damage even impairs object-place associations with just one pair of trial-unique stimuli to be remembered (Malkova and Mishkin, 2003). Further, neurotoxic lesions of the primate hippocampus impair spatial scene memory (Murray *et al.*, 1998). Monkeys with fornix section also are impaired to use a viewed spatial location to learn which object to choose (Gaffan and Harrison, 1989). Hippocampal damage in macaques impairs the ability to remember the locations in an open field of rewarded objects (Hampton *et al.*, 2004). Also, in a foraging task, monkeys with hippocampal lesions could not use allocentric, room-based, spatial cues to find food (Banta Lavenex and Lavenex, 2009). Thus, lesion evidence implicates the primate hippocampus in spatial scene memory, and provides part of the background to neuronal recordings made in primates to analyze the actual information processing being performed by the primate hippocampus.

As described here, the tasks in which primate hippocampal neurons have been recorded include those impaired by hippocampal damage (Kesner and Rolls, 2015; Murray *et al.*, 2017) as described in section 3, and also other spatial situations described in section 2, because of what is known about spatial neurons in rodents.

2. On the nature of spatial representations in primates

Given the evidence from the effects of lesions in primates and the evidence for spatial representations in rodents (see McNaughton *et al.*, 1983; Morris *et al.*, 1982; Muller *et al.*, 1991; O'Keefe, 1984), Rolls and colleagues investigated the nature of spatial representations in primates, and how hippocampal neurons activity might be related to memory tasks including object-place memory. In this section (2) we describe the evidence on the representation of locations in space in the primate hippocampus. In section 3 we consider how these spatial representations can be associated with objects and rewards. In section 4 we discuss the implications for understanding hippocampal function of the properties of spatial cells in the primate hippocampus. We also discuss the similarities (of which there are many) and the differences in the spatial representations in the primate and rodent hippocampus. We argue that these advances in understanding neuronal representations in primates provide a foundation for understating neurons in the human hippocampus, and the functions being performed by the primate, including human, hippocampus in memory, action, and navigation.

2.1. An allocentric representation of space in the primate hippocampus

The reference frames of spatial representations are important to define, in order to understand functions. An egocentric frame of reference (relative to the body or head) is useful for actions made in nearby space. An allocentric frame of reference (i.e. world-based coordinates) is useful for remembering the location of objects and rewards in the world, independently of where one is located or one’s body or head orientation. The discovery that some hippocampal neurons respond to the location on a video screen in front of the macaque (Rolls *et al.*, 1989), and can even reflect the object shown in a location (Cahusac *et al.*, 1989), raised the issue of which coordinate frame was used by the primate hippocampus. Feigenbaum and Rolls (1991) analysed whether the neurons utilize allocentric or egocentric spatial coordinates. They moved the video screen and the macaque relative to each other, and to different places in the room. 46% of the spatial neurons had firing that occurred in the same position on the display, or in the laboratory, when the macaque was rotated or moved to a different place in the room. Thus these hippocampal cells had spatial representations in allocentric (i.e. world-based) and not in egocentric (relative to the body or head) coordinates. 10% of the spatial neurons had firing that stayed in the same place relative to the monkey’s body/head axis when the video monitor was displaced, or the macaque was rotated, or was displaced to a different place in the room. Thus 10% of the neurons represented space in egocentric coordinates, that is, relative to the head.

Feigenbaum and Rolls (1991) showed that there were two types of allocentric encoding. For the majority of the neurons, the spatial field was in terms of its position on the video screen, independently of the place of the screen relative to the monkey’s head axis, and independently of the place of the macaque and the monitor in the room. This type of neuron was termed “local frame of reference” allocentric, in that their spatial fields were defined by the local spatial frame that was provided by the video monitor. For the second type of allocentric encoding, the spatial field was defined by the place in the laboratory towards which the monkey was fixating, and was relatively independent of position with respect to the monkey’s body/head axis or to position on the face of the video screen. This type of neuron was termed “absolute” allocentric, in that their spatial view

fields were defined by the place in the laboratory that the animal foveated (Feigenbaum and Rolls, 1991). They were the first evidence for what Rolls and colleagues described as spatial view neurons. It would be of considerable interest to repeat these experiments with human hippocampal system recordings.

Allocentric encoding is also a property of rodent hippocampal place cells, but the encoding is of the place where the rat is, not of where in space the rat is looking. However, the parallel is that in both cases allocentric encoding is found, and this allocentric representation is important for hippocampal computation (Kesner and Rolls, 2015).

2.2. Spatial View Cells in the primate hippocampus

2.2.1 Responses when the primate is moved in a cue controlled environment to different places.

In rodents, place cells are found that fire based on the place where the rodent is located in the spatial environment (see McNaughton *et al.*, 1983; Muller *et al.*, 1991; O'Keefe, 1984). In order to analyse whether this was the type of representation found in the primate hippocampus, Rolls and O'Mara (1993; 1995) made recordings of the firing of single hippocampal neurons when macaques were in a small chair or robot on wheels moved to different places in a cue-controlled environment (a 2m x 2m x 2m chamber with matt black walls and floors, and four cue cards that could be moved to different locations on the walls to define the spatial environment and to enable testing of whether the neurons responded to or were influenced by the cues on the walls). This environment enabled systematic tests for several different places each with several different views of the walls, and each with several different head directions, so that place vs spatial view vs head direction encoding could be distinguished. The most frequent type of neuron found responded to part of the space when the monkey looked at that part of the space, independently of the place where the monkey was located. These were termed “view” neurons, and in some cases it could be shown that the responses moved if the wall cues moved (Rolls and O'Mara, 1995). As far as we know, nothing like this has been performed in humans. Some testing of this type, with several places from each of which the same parts of a scene are visible, might be practicable in humans, and would be of great interest for understanding human hippocampal function. Some other hippocampal neurons reflected place encoding, responding for example to the place where the macaque was located, to movement to a place, or to spatial view depending on the place where the monkey was located (Rolls and O'Mara, 1995).

2.2.2 Responses of hippocampal spatial view neurons during active locomotion.

In rats, place cells respond best during active locomotion (Foster *et al.*, 1989; Terrazas *et al.*, 2005). To test whether place cells might be more apparent in macaques during active locomotion, as active locomotion was thought to be a key issue in rodents (Foster *et al.*, 1989) and may be relevant in primates (Thome *et al.*, 2017), single hippocampal neurons were recorded while monkeys actively walked on all four legs around the test environment (Georges-François *et al.*, 1999; Robertson *et al.*, 1998; Rolls *et al.*, 1997a; Rolls *et al.*, 1998). Also, to provide a good opportunity for primate hippocampal spatial neurons to reveal how they encoded space, the simple cue-controlled environment (Rolls and O'Mara, 1995) was changed to a much richer open laboratory environment approximately 5x5 m (illustrated in Fig. 4, and with for example windows on walls 1 and 2) within which the macaque had a 2.5x2.5 m area in which to walk and forage for food. The place of the monkey and the head direction were tracked continuously while the monkey walked round the environment, and the eye position (which refers to the horizontal and vertical eye directions with respect to the head), were recorded continuously to enable measurement of where the monkey was looking in the environment at all times. The monkey walked round the test area, foraging for food, to enable measurements of neuronal firing for a wide range of places, head directions, and spatial views in a very wide range of different combinations to allow analysis of the relative importance of these factors in what was encoded by the neurons.

The firing of a hippocampal neuron during active locomotion in this spatial testing environment is illustrated in Fig. 3. The neuron fired primarily while the macaque looked at a part of wall three, as emphasized in Figs. 3b and 3c that show a spot on a wall where the monkey was looking when the firing rate was greater than 12 action potentials per s, half of the maximum firing rate. Fig. 3b illustrates the finding that the neuron responded while the monkey was looking from different places in the room at the spatial view field on wall 3. The range of different places and head directions over which the neuron fired is illustrated in Fig. 3c. Analyses showed that this neuron responded to where the monkey was looking in space relatively independently of the place where

the monkey was located, and of head direction and eye position. Moreover, the spatial view fields of the neuron were similar when the monkey was actively walking, and also when he was stationary but actively exploring with eye movements different parts of the spatial environment (Georges-François *et al.*, 1999).

The firing of a different hippocampal cell is provided in Fig. 4, to show with a different type of analysis, how the firing is related to spatial view, and not to place, or to head direction, or to eye position. The highest firing of the cell, with the macaque at the place and with the head direction shown in Fig. 4a, occurred when the macaque looked 10° left. With the monkey in another place and with a different head direction, the highest firing was when the macaque was looking 30° right, but at the same spatial view (Fig. 4b). Fig. 4c shows the firing with the macaque at a different place (but the same head direction as in 4b), and the firing was now when the monkey looked approximately 30° left. The spatial view field was at the same place on Wall one as in Figs 4a and 4b. Previously unpublished examples of video animations to illustrate the firing of macaque hippocampal spatial view neurons are provided in the Supplementary Material.

These experiments show that it is the spatial view towards which the monkey looks that determines the neuronal responses, and not a particular place where the monkey was located, or head direction, or eye position, and this was confirmed with analyses of variance (Georges-François *et al.*, 1999). It was found that on average the spatial view cells encoded considerably more information about spatial view (0.47 bits) than about eye position (0.017 bits), head direction (0.005 bits), or place in the room (0.033 bits) (Georges-François *et al.*, 1999). This shows that the encoding by these primate hippocampal neurons may reflect some information about place etc but is primarily about spatial view.

The spatial view fields of these neurons typically occupy a region of space that is approximately as large as 1/16 of all the four walls of the laboratory (Rolls *et al.*, 1998). Each neuron responds to a different view, and the partly overlapping view fields thus provide precise information about the region of space being looked at. Information theoretic measures showed that the information about spatial view increases almost linearly as the number of neurons in the sample increases, thus showing that each of the neurons makes an independent contribution within the population to representing allocentric space (Rolls *et al.*, 1998). Given that Shannon information is a logarithmic measure, this evidence indicates that the number of spatial views (or the accuracy of the spatial representation) increases exponentially as the number of neurons in the ensemble increases. This is an important result in terms of how information is encoded by hippocampal as well as by neurons in other brain areas (Rolls, 2016a; Rolls and Treves, 2011). Moreover, this is a firing rate code, with much information present in the number of spikes from a single neuron (Panzeri *et al.*, 1999; Rolls, 2016a; Rolls and Treves, 2011).

Many hippocampal spatial view (or "space" or "view") cells were found in these experiments (Georges-François *et al.*, 1999; Robertson *et al.*, 1998; Rolls *et al.*, 1997a; Rolls *et al.*, 1998). In the initial sample of 352 cells recorded under these conditions, the number of spatial view cells was 40, or 11.4% (Rolls *et al.*, 1997a). This was in a single environment (Georges-François *et al.*, 1999; Robertson *et al.*, 1998; Rolls *et al.*, 1997a; Rolls *et al.*, 1998), and of course the proportion of neurons would be expected to be higher if testing included several different environments. The spontaneous firing rate of these neurons was low (mean 0.5 spikes/s), and their mean peak firing rate was 17 spikes/s (interquartile range 11-20 spikes/s), consistent with these being hippocampal pyramidal cells, which were in both the CA1 and CA3 regions.

The finding from rodents that place cells respond better during active locomotion than passive motion (Foster *et al.*, 1989) made it important to investigate primate hippocampal neurons during active locomotion (see also Thome *et al.*, 2017). Having said this, Rolls and colleagues found that primate hippocampal spatial view cells have similar responses during active locomotion as when the monkey is not locomoting, but is looking around and actively exploring the spatial environment with eye movements. This is shown by the fact that spatial view fields are present when the monkey is stationary as illustrated in Fig. 4, or are walking as in Fig. 3 (Georges-François *et al.*, 1999; Robertson *et al.*, 1998; Rolls *et al.*, 1997a); are found when the monkey is tested only when stationary (Rolls and O'Mara, 1995; Rolls and Xiang, 2005, 2006; Rolls *et al.*, 2005); and as illustrated in the videos provided in the Supplementary Material. Indeed, it is an interesting hypothesis that this active exploration of a spatial environment, by moving the eyes from location to location in a scene in primates, is analogous to the active exploration performed by a rodent when it is locomoting from one place to another.

2.2.3 The testing of hypotheses for spatial view vs place vs head direction vs eye position encoding.

To assess whether a neuron in the primate, including human hippocampal system, responds to the place where the individual is rather than spatial view, or head direction, or eye position, extensive testing with contrasts of these different hypotheses is needed (Georges-François *et al.*, 1999). (Eye position refers to the horizontal and vertical angles of the eye in the orbit.) If the views visible from different places differ, showing that the firing depends on the place where the individual is located is insufficient, because so does the spatial view. To separate spatial view from place cells, neurons must be tested while the individual is in one place with all of the different spatial views visible from there. Further, the same neuron must also be tested when the individual is located in a different place, but with at least many of the same spatial views visible, as has been implemented in Rolls and colleagues' recordings in macaques. Indeed, although hippocampal neurons in squirrel monkeys were found to respond when the monkeys were in a particular location in a 3D chamber (Ludvig *et al.*, 2004), where the monkeys were looking was not measured, so we cannot contrast spatial view with place coding in this case. Similarly, Ono et al (1993) found that when a monkey sitting in a cab was moved, some neurons responded when the cab was in specific places in the room. However, they were not able to factor out place from spatial view encoding in the type of factorial design that is necessary. These points will need to be taken into account for future investigations of hippocampal neuronal activity in humans and other primates (cf. Ekstrom, 2015; Ekstrom *et al.*, 2003; Fried *et al.*, 1997; Kreiman *et al.*, 2000; Miller *et al.*, 2013), and recording simultaneously the eye position, head direction, and head position is needed.

Having said this, it is nevertheless of interest that for humans there is now some evidence for medial temporal lobe neurons with properties like those of spatial view cells (Ekstrom *et al.*, 2003; Miller *et al.*, 2013), even though direct measures of eye position were not conducted. For example, in the study by Ekstrom and colleagues, cells were found to represent the interaction between the place and the view faced by the patient. It is also of interest that in humans some medial temporal lobe neurons reflect the learning of paired associations between views of places, and people or objects (Ison *et al.*, 2015), and this implies that views of scenes are important for human hippocampal function. Consistent with this, human functional neuroimaging studies do show hippocampal activation when scenes or parts of scenes are viewed even when the human is fixed in one place for neuroimaging (Brown *et al.*, 2016; Burgess, 2008; Chadwick *et al.*, 2010; Chadwick *et al.*, 2013; Epstein and Kanwisher, 1998; Hassabis *et al.*, 2009; Maguire, 2014; O'Keefe *et al.*, 1998; Zeidman and Maguire, 2016). Further evidence on the functioning of the human hippocampus is considered in sections 3 and 4.4.

2.2.4 Spatial view cells, and the representation of place in the primate hippocampus.

With the discovery of spatial view cells in macaques, unlike what is found in rodents, there was a strong focus on elucidating the properties of spatial view neurons. Nevertheless, as noted above some hippocampal cells with place-related activity were found, as was modulation of some spatial view neurons by place (Rolls and O'Mara, 1995). Further evidence of place-related firing of hippocampal neurons in primates, and the situations that may facilitate place-related activity, are described in sections 2.3, 4.2 and 4.4.

An interesting associated point is what happens to a spatial view cell if it is tested in the place for which it is tuned. Robertson et al (1998) provide an example in their Fig. 1, in which a spatial view cell responded to a landmark, a table, when the monkey was distant from and looked at the table, and also responded when the macaque was at the table, provided that in both cases the macaque was looking at the table. This type of evidence shows that a primate spatial view cell can respond to a landmark or spatial view when the primate is actually at the place where the landmark is located (Robertson *et al.*, 1998; Rolls *et al.*, 1997a).

2.2.5 Comparison of primate hippocampal spatial view cells with other types of neuronal response.

To further elucidate the properties of primate hippocampal place cells, they are compared next to object cells in the macaque inferior temporal visual cortex, and then to 'concept' cells in humans, and then to head direction cells.

Hippocampal spatial view cells are quite different to inferior temporal visual cortex (IT) cells that respond to faces or objects wherever they are moved to in a spatial environment (Aggelopoulos *et al.*, 2005; Rolls, 2012; Rolls, 2016a; Rolls *et al.*, 2003). On the other hand, it is normally the combination of a set of features in a fixed position relative to each other in the world that activates spatial view neurons (Feigenbaum and Rolls, 1991). A helpful distinction is that objects can be moved to different places in the environment, and visual temporal cortex object-selective neurons respond to an object independently of its location in a scene (Aggelopoulos *et al.*,

2005; Rolls *et al.*, 2003). In contrast, parts of a spatial scene are fixed with respect to other parts of the scene, and cannot be moved independently with respect to the other parts. Thus, although hippocampal spatial view cells can respond to stimuli that are a fixed part of a spatial scene (e.g. the table T2 in Fig. 1 of Robertson et al (1998) referred to above), the point is that this is a fixed part of a continuous spatial scene. Spatial scene representations may be learned by associating together features in a scene that have a fixed spatial relationship to each other (Rolls and Stringer, 2005; Stringer *et al.*, 2005), and this is quite different from invariant visual object learning in which the features of a single object are associated together, because of regular association of the parts of a single object that are independent of the background scene and other objects in the scene that are not constant (Rolls, 2012; Rolls, 2016a; Stringer and Rolls, 2008; Stringer *et al.*, 2007). The inputs to the hippocampal formation that help it to form spatial view representations may come from areas such as the occipital place area (Julian *et al.*, 2016), and from scene processing areas in the macaque temporal cortex (Kornblith *et al.*, 2013).

Another difference from IT neurons is that many hippocampal spatial view neurons, because they represent parts of space, can respond even when the scene is not visible but that part of space is looked at (Rolls *et al.*, 1997b); and can be updated idiothetically, that is by self-motion, in that spatial view neurons respond when a macaque moves the eyes to a location in space even when no scene is visible, and in darkness (Rolls *et al.*, 1997b) (see section 2.4).

Another difference is that IT neurons respond well to visual stimuli in an object-reward association task (Rolls *et al.*, 2003; Rolls *et al.*, 1977), but hippocampal neurons have weak responses to objects in this type of non-hippocampal-dependent task, compared to the stronger object-related responses that can occur in an object-place, hippocampus-dependent, task (Rolls and Xiang, 2005).

In primates, hippocampal neurons have been described that respond in an invariant way to the sight of individual faces (Quiroga *et al.*, 2005; Sliwa *et al.*, 2016). The neurons found in humans described as 'concept cells', an example of which is a neuron that responded to Jennifer Aniston, may respond not only to Jennifer Aniston, but also to other actors in the same movie, and the places with which they are associated (De Falco *et al.*, 2016; Quiroga, 2012; Quiroga *et al.*, 2005; Rey *et al.*, 2015). Object-place cells in macaques have some similar 'concept' properties, in that they can be activated either by the object, or by the place, in object-place memory tasks (Rolls and Xiang, 2006; Rolls *et al.*, 2005). Similar properties have been described for human hippocampal neurons, in a task in which a human was associated with a place (Ison *et al.*, 2015).

It can also be emphasised that spatial view hippocampal cells are quite distinct from head direction cells, found in the primate presubiculum and parahippocampal gyrus (Robertson *et al.*, 1999). For instance, if the head direction remains constant when the macaque is moved to different places in the environment where the spatial view differs, spatial view cells provide different responses. On the other hand, head direction cells have activity that remains constant for a particular head direction, even though the spatial view differs completely (Robertson *et al.*, 1999).

2.3. Visually supported spatial representations in primates in a virtual environment

Virtual environments are increasingly being used to analyse spatial representations in rodents and primates including humans. Advantages are that the virtual environment can be easily changed, specified, and controlled. The recordings can be made in a stable situation, visual inputs can be tested without vestibular or locomotor inputs, and eye movements can be easily measured (Minderer *et al.*, 2016). On the other hand, there is uncoupling of visual, vestibular and locomotor signals, and so what happens in the natural world may not be fully captured (Minderer *et al.*, 2016). However, macaques explore virtual environments and make inferences about objects in virtual space in a similar way to real space (Sato *et al.*, 2004; Washburn and Astur, 2003). Moreover, the use of a virtual environment provides an opportunity to test situations that cannot easily be implemented with primates in real space, such as large scale mazes requiring way finding towards a goal. To test the nature of hippocampal cell activity in a context requiring that animals compute a trajectory and move to a goal (at which a hidden reward was given) using landmarks, Wirth and colleagues developed a virtual environment - a star maze - in which animals navigated using a joystick (Wirth *et al.*, 2017). The test situation simulated a large environment (radius of 16 meters) and was presented on a large screen that covered 70 percent of the field of view in stereo to provide depth. The virtual environment created a perception of self-motion. The maze had 5 landmarks, and could be used to locate the position of a hidden reward located between two of the landmarks (Fig. 5A). Wirth and colleagues recorded from 270 cells throughout the hippocampus, with 189 out of these providing more than 100 spikes per session for analysis. It was found that 28% (53/189) of hippocampal cells fired when the

animals looked at one or sometimes more than one of the landmarks (Fig. 5B, C). Of these, the response of 83% were modulated by the position of the animal (Fig. 5D). This is illustrated by the fact that the great majority of cells responded to a landmark when it was viewed from one position only as illustrated in Fig. 5. This point is brought out by the high firing rate when the monkey looked towards the ball landmark when it is in place p1 (Fig. 5F), but no or less firing when the monkey is in place p2 or p3 (Fig 5G) (Wirth and Baraduc, 2018; Wirth *et al.*, 2017). In addition, 17% of the total population responded when the animal was in one or more places in the virtual environment without significant modulation by where the animal was looking. Earlier results in a virtual environment had provided evidence for place-related firing, but eye position was not recorded, so it was difficult to separate view-related from place firing or head direction (Furuya *et al.*, 2014; Hori *et al.*, 2005).

Further, by using a task requiring navigation towards a goal, Wirth and colleagues found that some neurons responded to combinations of view, place, and task context (Wirth *et al.*, 2017). More precisely, some cells were active in only some segments of the possible trajectories that could be followed in the environment to reach the goal. A state space representation accounts best for the activity of these cells. The state space allows separation of the activity of cells for all possible trajectories in the maze, and showed that neurons differentiated common segments between trajectories even when the view and place were identical. This suggests that the cells encoded useful information that reflects the progression along a particular trajectory during navigation rather than purely view or position information. This provides evidence that in primates in a virtual environment requiring active navigation, spatial information is anchored on what the animal foveates, but also is related to task-relevant information (Wirth *et al.*, 2017).

This description bears similarities with spatial view cells described by Rolls and colleagues, and confirms that what the animal looks at modulates the activity. However, it suggests additionally that the modulation by cognition can have a strong influence on the expression of the firing rate. Rolls and O'Mara (1995) did find that spatial view cells could be influenced by place. What Wirth and colleagues showed is that this influence is strong in a task in which the animal needs to base its behaviour on the landmarks and where the animal is located (Wirth *et al.*, 2017).

The development of virtual reality techniques in rodents allows a timely cross-species comparison of the types of hippocampal activity observed during virtual navigation in primates (described above) and rodents. In rats and mice it was shown that navigation to a goal could occur in a virtual environment with visual cues (Cushman *et al.*, 2013; Holscher *et al.*, 2005; Youngstrom and Strowbridge, 2012). These studies showed that without vestibular input, visual cues are sufficient to support a flexible route to a rewarded goal provided that the visual environment took into account the rodent's wide-angle visual system (approximately 320 degrees (Hughes, 1979)). Further, patterns of neuronal activation were similar in virtual environments (often termed virtual reality "VR") compared to the real world when the environments were linear tracks (Chen *et al.*, 2013; Dombeck *et al.*, 2010; Harvey *et al.*, 2009). However, in one study comparing directly real world and VR, Ravassard et al (2013) showed that VR recruited fewer rat hippocampal neurons than the real world, and the firing rates were more unstable in VR. Consistently, in macaques fewer CA1 neurons were activated in a virtual environment than in real spatial environments (Thome *et al.*, 2017).

While the first studies in VR in rodents were obtained as animals ran on 1D linear tracks, recent studies used 2D environments in which the animal, placed on a floating ball, can rotate and run in all directions. One such VR study found that hippocampal system neurons responded in VR similarly to in a real environment with place, border and head direction cells (Aronov and Tank, 2014). In another study however, in a similar 2D VR environment, place selectivity was absent when animal performed a random foraging task. However, place selectivity was reinstated when distinct landmarks at fixed locations indicated the reward position (Aghajan *et al.*, 2015). The authors suggested that spatial selectivity can arise in 1D linear tracks and in 2D - if a visual cue shapes behaviour - because of the repeated pairing between distal visual cues and locomotion cues along systematic paths (Aghajan *et al.*, 2015). This second condition in which landmarks are used is similar to primate studies in which spatial selectivity is found when the primates use distal room cues to plan trajectories and find a goal (Furuya *et al.*, 2014; Hori *et al.*, 2005; Wirth *et al.*, 2017).

One striking property of place cells in linear real environments is direction selectivity (Navratilova *et al.*, 2012), which is generally absent in real 2D environments in which random foraging takes place with no strong directional component to the behaviour. However, Mehta and colleagues showed that in real-world random foraging, 30% of place cells can have a directional component, i.e. respond preferentially to some head directions (Acharya *et al.*, 2016). This direction

selectivity was also present in a random foraging VR task in 23% of the neurons despite no place cell responsiveness. Because this was in a VR environment (where there is reduced vestibular input), this demonstrates that visual cues alone can promote this directional selectivity (Acharya *et al.*, 2016). It should be noted that these neurons in rodents are modulated by the direction in which the head is facing, and are different from primate hippocampal spatial view cells, which are not modulated by head direction, but respond to the location in the environment where the monkey is looking (Georges-François *et al.*, 1999). Consistent with this, in macaques navigating a virtual environment to locate a reward, hippocampal cells code for what the animal looked at from a specific viewpoint (Wirth *et al.*, 2017).

In summary, the comparison of findings in VR from primate and rodent studies supports the conclusion that hippocampal cells can be driven by an environment bearing visual cues only with minimal vestibular input besides optic flow. The extent to which place selectivity and head direction selectivity are modulated by the use of visual cues in a goal oriented manner is still to be determined. The fact that direction selectivity exists in VR suggests a homology between primates and rodents, in that a visual non-vestibular input may act as an external reference for the cells. However, because the findings by Acharya et al. (2016) were reported in a task in which animals performed a random foraging task, further rodent studies in which place and direction selectivity are measured in a goal oriented task would be helpful. Likewise, more studies modulating the task demand in primates would be helpful to determine what controls the emergence of target of gaze selectivity and place selectivity in hippocampal neurons.

2.4. Idiothetic (self-motion) update of spatial view cells

In rats, the representation of place by place cells, can be updated by self-motion, e.g. running in the dark (Jeffery *et al.*, 1997; McNaughton *et al.*, 1991; Quirk *et al.*, 1990). In monkeys, the representation of the place in the scene encoded by spatial view cells can be updated by self-motion, e.g. by the monkey moving the eyes in the dark, or by the monkey turning or walking in the dark. This was shown in experiments on these spatial view cells, in which the view was obscured by black curtains, in which many of the cells could still respond when the macaque moved his eye position to look towards where the view was visible previously (Robertson *et al.*, 1998) (see example in Fig. 6). This idiothetic update also occurs when the monkey locomotes in the dark, and then looks to a spatial view location. Some drift of the spatial view field over a few minutes when the curtains were closed was typical, consistent with the hypotheses that self-motion updating was occurring, and that the visual view details of the scene normally define the spatial view field of a neuron. These experiments (Robertson *et al.*, 1998; Rolls *et al.*, 1997a) show that primate hippocampal system spatial view neurons can be updated by self-motion for short periods by idiothetic information including eye position, head direction, and place movements made by the monkey, and that the drift related to the temporal integration of these signals can be corrected when the scene again becomes visible. These experiments also show that these hippocampal system spatial view cells are different from the much more visual perception-related responses of inferior temporal cortex objects and face cells, which stop responding when the object or face is removed from visibility (Rolls, 2003; Rolls and Tovee, 1994).

The neurons with only a small decrease of their response when the room was placed into darkness and/or the view details were obscured with curtains were present in CA1, the parahippocampal gyrus, and the presubiculum. On the other hand, CA3 neurons had a larger decrease (on average to 23% of their normal response) when the macaque looked towards the normally effective location in the environment but the view was not visible. There may be partial recovery of information in the CA3 network using autoassociation, and further recovery in the associative synapses from CA3 to CA1, as has been shown analytically (Schultz and Rolls, 1999) and by simulations (Rolls, 1995). Another contributory factor of the difference might be the direct perforant path input to the CA1 neurons (Rolls, 2016a; Rolls and Treves, 1998).

What may be a related phenomenon discovered by Wirth and colleagues is that some of the hippocampal cells responded in anticipation of the eyes reaching a landmark in a virtual environment, even before the landmark towards which the eyes were moving had appeared on the projection screen (Wirth *et al.*, 2017). To demonstrate this, the activity of hippocampal cells was calculated for their preferred landmark as a function of the eccentricity of the landmark from the fovea for 3 different conditions (Fig. 7A). 1) 500 ms before the landmark was projected on the screen. 2) For 500 ms after the landmark appeared on the screen. 3) For 500 ms starting 1 s after the landmark had appeared on the screen. As illustrated in Fig. 7B, the cells were significantly active before the landmark was shown on the screen. Further, cells showed less activity for the condition in which the

landmark had already been visible for 1 s (green in Fig 7B), providing evidence that these hippocampal neurons fire more when a landmark is first acquired, and after that tend to show a smaller response. In summary, these results indicate that hippocampal cells anticipate a landmark, using predictive recall based on knowledge of the spatial environment.

The relation between eye movements and memory has been highlighted by Buffalo and colleagues (Meister and Buffalo, 2016). Interestingly, it has been reported that some hippocampal neurons respond when eye position must be maintained in the dark (Nowicka and Ringo, 2000), and there is additional evidence about how macaque hippocampal neurons may alter their activity when the eyes are moved (Ringo *et al.*, 1994; Sobotka *et al.*, 1997; Sobotka and Ringo, 1997), with consistent evidence in humans (Hannula and Ranganath, 2009; Liu *et al.*, 2017; Shen *et al.*, 2016). Two additional phenomena relevant to anticipatory effects have been reported previously. First, it was observed that sharp wave ripples were enhanced near remembered visual objects (Leonard and Hoffman, 2017). Second, oscillatory activity was found to synchronize with visual exploration, through a theta phase reset at saccades (Hoffman *et al.*, 2013; Jutras *et al.*, 2013). Buffalo and colleagues described hippocampal neurons with spatial responses at different positions on a screen, that responded at different times primarily after a saccade to the effective location on the screen (Meister and Buffalo, 2016). Together, these results suggest that there is a strong relationship between visual exploration and information uptake and recall in the hippocampus. Indeed, attention has been drawn to the role of visual exploration of the world "out there" using eye movement as an important feature of primate behaviour that has implications for understanding the functioning of the hippocampus in primates (Buffalo, 2015) including humans (Ekstrom, 2015), and how this may serve memory functions of the hippocampus (Rueckemann and Buffalo, 2017).

2.5. Responses of neurons in the primate hippocampus to whole body motion

To perform idiothetic update of a spatial representation (such as that provided by spatial view or place cells), a self-motion signal is needed to update the spatial representation. The idiothetic signal might usefully be a velocity of movement signal. This velocity signal might have its origin in vestibular signals about motion, in optic flow, and/or in corollary motor discharge (Bremmer *et al.*, 2002a; Bremmer *et al.*, 2002b). Neurons that do respond to self-motion signals have been discovered in the primate hippocampus, in an investigation in which the monkey was moved while sitting on a robot with defined axial rotations and linear translations, and in a test situation in which optic flow visual motion cues could also be produced by rotating the whole environment round the monkey (O'Mara *et al.*, 1994). The neurons respond to the velocity of whole body motion (O'Mara *et al.*, 1994), which is idiothetic information. For instance, some neurons have larger responses for clockwise than for anti-clockwise whole body rotation. Occlusion of the visual field showed that some of these neurons depend on visual input. For other neurons there was no requirement for visual input, and these neurons probably responded to vestibular input. Other neurons responded to a combination of whole-body motion and view or place. Of the 45 neurons with responses related to whole body motion (9.8% of the population of hippocampal neurons recorded), 13 responded to axial rotation only, 9 to linear translation only, and 20 neurons to axial rotation or to linear translation. The sign of the motion was important for some of the neurons, with different responses for clockwise vs anticlockwise rotation, or for forward vs backward linear translation, which are different velocities. Some neurons responded to a combination of whole body motion and either a local view (n=2) or a place towards which the macaque was moving (n=1). Whole-body motion neurons are likely to be a useful component of a memory system for memorising spatial trajectories through environments for path integration that is useful in short range spatial navigation (O'Mara *et al.*, 1994). They may provide self-motion information useful to provide the idiothetic update of spatial view cells. Consistent with this discovery (O'Mara *et al.*, 1994), neurons have more recently been found in the rat entorhinal cortex that have a linear response with linear running speed, and have been termed 'speed cells' (Hinman *et al.*, 2016; Kropff *et al.*, 2015).

2.6. Grid cells in rodents and spatial view grid cells in the primate entorhinal cortex

In the rodent entorhinal cortex, grid cells that represent places by hexagonal place grids and are involved in idiothetic update of place have been described (Kropff and Treves, 2008; Moser *et al.*, 2015). In macaques, a grid-cell like representation in the entorhinal cortex has been found, but the neurons have grid-like firing as the monkey moves the eyes across a spatial scene (Killian *et al.*, 2012; Meister and Buffalo, 2018; Rueckemann and Buffalo, 2017). Similar competitive learning processes to those suggested for rodents (Rolls *et al.*, 2006) may transform these primate entorhinal cortex 'spatial view grid cells' into primate hippocampal spatial view cells, and may contribute to

the idiothetic (eye movement-related) update of spatial view cells (Robertson *et al.*, 1998). The existence of spatial view grid cells in the entorhinal cortex of primates is predicted from the presence of spatial view cells in the primate CA3 and CA1 regions (Kesner and Rolls, 2015; Rolls, 2013; Rueckemann and Buffalo, 2017). Moreover, some of these 'spatial view grid cells' have their responses aligned to the visual image (Meister and Buffalo, 2018), as predicted (Kesner and Rolls, 2015).

In the human entorhinal and cingulate cortex neurons with grid-like response properties are found (Jacobs *et al.*, 2013; Nadasdy *et al.*, 2017), and there is neuroimaging evidence that is consistent with this (Julian *et al.*, 2018; Nau *et al.*, 2018). This is further evidence for the concept that representations of places being viewed in space "out there" is a key property of spatial representations in the hippocampal system of primates including humans.

3. Properties of primate hippocampal spatial representations related to object and reward memory associations

Primates have a highly developed ventral stream cortical visual system that utilises information from the fovea for object recognition, and a highly developed eye movement control system to bring the fovea to objects, using mechanisms described elsewhere (Rolls, 2012; Rolls, 2016a; Rolls *et al.*, 2003; Rolls and Webb, 2014). These developments enable primates to explore and remember information about what is present at places seen "out there" in the spatial environment without having to visit those places. Spatial view cells would accordingly be useful as part of a memory system by providing a representation of space that does not depend on where the primate is, and that could be associated with items such as objects or rewards in those viewed spatial locations. This could enable a monkey to remember where it had seen ripe fruit, or a human to remember where in a spatial scene they had seen a person. Primate hippocampal system spatial view neurons may therefore be important in forming memories of what has been seen and where it has been seen even on a single occasion, a key component of an episodic memory. Episodic memories of this type would be useful for spatial navigation or action in space, for which according to Rolls' hypothesis the hippocampus would implement the memory but not the spatial computation component (Kesner and Rolls, 2015), with evidence for this provided in section 4.4.

We now consider evidence that these hippocampal spatial view neurons have activity that is involved in memory-related spatial functions.

3.1. Object-place neurons in the primate hippocampus

A key issue is whether the primate including human hippocampus is for memory, or for navigation. There is emphasis on navigation for place cell function in rodents (Burgess *et al.*, 2000; Burgess and O'Keefe, 1996; Hartley *et al.*, 2014; O'Keefe, 1979, 1991). However, the hippocampus is implicated in episodic memory in which the place, or temporal place in a sequence of a single episodic memory is associated with for example the associated objects or rewards (Dere *et al.*, 2008; Eichenbaum *et al.*, 2012; Kesner and Rolls, 2015; Rolls, 1990; Treves and Rolls, 1994; Zeidman and Maguire, 2016). If the hippocampus helps to implement episodic memory, then object information would need to reach the hippocampus, where it might be combined with spatial view information to form for example, an episodic memory of a person or object seen in a viewed location.

To investigate the fundamental question of whether object information, as well as spatial information, is provided in the primate hippocampus, single hippocampal neurons were recorded during an object-place memory task in which the monkeys had to learn associations between objects and where they were shown in an open laboratory (Rolls *et al.*, 2005). Some neurons (10%) responded to an object independently of its location; other neurons (13%) responded to spatial view independently of the object shown; and some neurons (12%) fired to a combination of a particular object and the particular place where it was shown in the laboratory. Thus in the primate hippocampus, there are separate as well as combined representations of objects and of their locations in space. These properties are needed in an episodic memory system, for associations between objects and where they are seen are prototypical for episodic memory. These discoveries provide evidence that a key requirement for a human episodic memory system, both separate and combined neuronal representations of objects and their locations "out there", are present in the primate hippocampus (Rolls *et al.*, 2005). These neurons might also be termed object-spatial view neurons, to emphasize the difference from what is found in rodents. Neurons that correspond have now been described in rodents, but they, as expected, encode item-place, not item-spatial view, combinations (Komorowski *et al.*, 2009). In the rodent investigation, the items were odors.

Consistent with these discoveries, the hippocampus receives projections from the temporal

cortical areas specialized for objects or faces, and neurons responsive for particular individuals were found both in the human medial temporal lobe (Kreiman *et al.*, 2000; Quiroga, 2012) and the monkey hippocampus (Sliwa *et al.*, 2016).

3.2. One-trial, object-place, recall-related neurons in the primate hippocampus

A feature of the theory of the hippocampus in episodic memory is that object and location memories should be capable of being formed in one trial, in order to be relevant to the timescale of episodic memory, and that the whole memory can be recalled from any part (Kesner and Rolls, 2015; Rolls, 1989, 1996, 2016a; Rolls and Kesner, 2006; Treves and Rolls, 1994). This has been tested in macaques in a one-trial object-place memory task. The task involved the storage of object-place information, and then the recall of the object when the place was presented as a recall cue, and the recall of the place when the object was presented as a recall cue (Fig. 8a). The design is similar to that of a one-trial odor-place recall memory task that is hippocampal-dependent in rats (Day *et al.*, 2003), and is quite different from a long-term visual-visual associative memory task which is implemented in the perirhinal and related cortex (Fujimichi *et al.*, 2010; Hirabayashi *et al.*, 2013; Naya *et al.*, 2001). Images of novel objects were used every day, and within a day the same objects were used, so that the one-trial recall task was difficult. Recordings were made from 347 hippocampal neurons during the performance of the object-place recall task (Rolls and Xiang, 2006). Some neurons performed object recall, when the recall cue was a place (Fig. 8b). Some neurons performed place recall, when the recall cue was an object (Fig. 8c). The recall-related firing is evident in stage 4, when the object or place was being recalled with no stimulus present on the screen. Details of the results are provided elsewhere (Rolls and Xiang, 2006). The findings provide evidence that the macaque hippocampus can provide for one-trial object-view association learning of the type that is prototypical for episodic memory (Rolls and Xiang, 2006). Rapid changes in neuronal response properties as a result of learning associations between items such as individuals and places have been confirmed in humans (Ison et al., 2015).

In humans, in an object-place recall task in virtual reality, some neurons during recall also reflect the recall of the place when the object recall cue is provided (Miller *et al.*, 2013). Further, it has been shown that time as well as space is encoded in the primate hippocampus, and that some hippocampal neurons recalled the time at which a specific object was seen (Naya and Suzuki, 2009).

3.3. Reward-place neurons in the primate hippocampus

Information about where rewards are located is a key attribute of an episodic memory system. The anterior hippocampus of primates (which corresponds to the ventral hippocampus of rodents) has inputs from brain areas such as the orbitofrontal cortex and amygdala that perform reward processing (Carmichael and Price, 1995; Pitkanen *et al.*, 2002; Stefanacci *et al.*, 1996; Suzuki and Amaral, 1994a).

To analyse reward-related input to the primate hippocampal system, neuronal activity was recorded during a reward-place association task in monkeys in which one location in each spatial scene on a video monitor, when touched, resulted in a fruit juice reward, and a second location resulted in a less preferred juice reward. The different scenes had different locations for the two reward types (Rolls and Xiang, 2005). 18% of 312 hippocampal cells analysed responded in different scenes to the location of the preferred reward, and 5% to the place of the less preferred reward (Rolls and Xiang, 2005). Of 44 neurons tested, 60% reversed the location to which they responded when the locations of the preferred rewards were reversed in the scenes, providing evidence that the reward-place associations could be relearned in a few trials. Most (82%) of the 44 location-reward neurons in the hippocampus did not respond to object-reward associations in a visual discrimination task. Thus the macaque hippocampus represents the reward associations of places being viewed "out there", and can store affective information as part of an episodic memory. This provides a way in which the current mood or reward/non-reward state may influence the retrieval of episodic memories, which is of interest for psychiatric disorders in which sad memories may be emphasized because of altered functional connectivity with the orbitofrontal cortex with hippocampal memory mechanisms (Cheng *et al.*, 2016; Cheng *et al.*, 2018a; Rolls, 2016b, 2017a, 2018a; Rolls *et al.*, 2018).

There is further evidence that neurons in the primate hippocampus are influenced by rewards (Wirth *et al.*, 2009). Wirth and colleagues described cells that encoded the reward outcome of a trial in an object-place association task. The task required the macaques to learn a set of object-place response associations and was learned through trial and error. While animals learned which responses (an early or a late bar release) had to be coupled to one of 4 possible object-place combinations, Wirth at al described two types of neuron. First, they found neurons that signalled

correct reward outcomes by an increase in firing rate. These neurons did not increase their firing rates for rewards that were given randomly, but fired only after a correct response was made in the task. A second type of neuron fired more following an error (which could be the wrong bar release, but also a trial that was aborted). However, only the cells that fired for the correct outcomes were found to discriminate better between the stimuli (the object-place combinations) that were used in the set. This increase in stimulus selectivity was only found in trials and in sessions in which the animals had learned, suggesting that it is part of what helps the task to be learned (Wirth *et al.*, 2009). These findings have been extended by showing that hippocampal neurons reflect outcome information more than prefrontal cortex neurons (Brincat and Miller, 2015).

The results indicate that the primate hippocampus can learn associations between viewed locations and objects (Rolls *et al.*, 2005) or rewards (Rolls and Xiang, 2005), and may even shape the stimulus selective response properties to favour a better neuronal discrimination of the stimulus combination (here object-place-response) that leads to a reward (Wirth *et al.*, 2009). Perhaps correspondingly but with a different representation of space, the responsiveness of rodent place cells can be influenced by where rewards are available (Hölscher *et al.*, 2003; Tabuchi *et al.*, 2003). The principle is that the hippocampus may encode information about where emotion-related (rewarding or punishing) events happened; may be involved in the recall of emotions when particular places are seen later; and may provide mechanisms by which the current mood can influence the memories that are recalled (Rolls, 2015, 2018a).

3.4. Neurons involved in learning associations between visual stimuli and spatial responses

The learning of associations between visual stimuli and spatial responses may be involved in some types of navigation. This was investigated in a task for which the primate hippocampus is needed, in which monkeys learned which spatial response to make to different visual stimuli. 14% of hippocampal neurons were found to respond to combinations of visual stimuli and spatial responses (Miyashita *et al.*, 1989). In a subsequent study by Cahusac et al (1993) to investigate the learning, 22% of such neurons in the hippocampus and parahippocampal gyrus modified their responses to become progressively different to the two stimuli while the macaque learned to make different spatial responses to the two visual stimuli (Cahusac *et al.*, 1993). For different neurons this occurred just before, at, or just after the time when the macaque monkey learned the correct responses to make to the stimuli. The hypothesis is that, when new associations between objects and places are learned (in this case the places for responses), some hippocampal neurons learn the new object-to-spatial response associations that are required. Learning of this type could be involved in navigation in which behavioral responses such as a left turn might need to be made when a visual stimulus was seen.

In line with this interpretation, Wirth and colleagues (2003) found that when the monkeys had to learn which of four targets to reach by an eye movement within each of four visual images, the cells became more selective by gradually discriminating between the four stimulus-response associations while they were being learned. The implication that these neurons were involved in the learning was strengthened by findings that well-learned associations were represented by a sharper selectivity in these hippocampal neurons than new associations (Yanike *et al.*, 2009).

These neurons are related to actions made in space to the locations of objects and are another example of object-spatial associative memories supported by the hippocampus.

We have now described the types of neuron found in the primate hippocampus, and move next to compare these primate hippocampal neurons with rodent hippocampal neurons. We show that there are many similarities, though the representation of space provided is very different.

4. Discussion: functions of hippocampal spatial representations in primates, and comparison with rodents

4.1. Self-organization by learning of primate spatial view cells related to foveal vision, and of rodent place cells related to a wide field of view

Primates, including humans, have a highly developed fovea, and visual cortical areas for object recognition for what is at the fovea, and an eye movement control system for foveation, and can explore, and remember, what is present at places ‘out there’ in the environment without needing to visit those places. Spatial view cells in primates, given the evidence described here, are likely to be of fundamental use in a primate memory system, by providing a representation of a part of space that would not depend on exactly where the monkey or human was located, and that could be

associated with objects or rewards present in those viewed spatial locations. This would enable humans for example to remember the viewed location where a person had been seen. These primate spatial representations would also be useful in remembering trajectories through gazing at landmarks, of use for example in spatial navigation (Wirth *et al.*, 2017).

The spatial representation in the rodent hippocampus, of the place where the rodent is, may be related to their large visual field of view compared to the primate. A hypothesis on how this difference could be produced by a similar computational process in rodents and primates follows (de Araujo *et al.*, 2001).

We start with the concept that in both primates and rodents, the dentate granule cells and the CA3 and CA1 neurons respond to combinations of their inputs. In primates the fovea provides high spatial resolution over a typical viewing angle of 5-10 degrees in a complex natural scene as shown by the responses of macaque inferior temporal visual cortex (IT) neurons (with a mean receptive field size of 9 degrees) (Aggelopoulos and Rolls, 2005; Rolls *et al.*, 2003). As a result, a combination of visual features in the spatial environment will produce a spatial view cell, the effective trigger for which will be a combination of visual features within a small part of space. This is illustrated in Fig. 9 top right, where a primate hippocampal neuron responding to C_1, C_2 and C_3 will effectively define a spatial view field. In rodents, in contrast, given the very wide visual field subtended by the retina, which may extend more than 270 degrees, and the absence of a fovea, a combination of visual features learned over such a wide visual angle would define a position in space that is a place. This is illustrated in Fig. 9 top left, where a rodent hippocampal neuron responding to C_1, C_2 and C_3 with large angles between these cues will effectively define a place field. The computational processes by which the hippocampal neurons would learn to respond to feature combinations in rats and primates could be similar, and include competitive learning in the dentate granule cells, autoassociation learning in CA3 cells, and competitive learning in CA1 cells (Rolls, 2016a; Treves and Rolls, 1994). Thus the properties of primate spatial view cells and rodent place cells might arise by a similar computational learning process, but produce spatially different representations because primates are foveate and view a small part of the visual field at any one time, whereas rodents have a very wide visual field (see de Araujo et al (2001)).

This was tested in a simulation in which the animal explored its spatial environment, and hippocampal cells are activated by particular visual cues currently within the field of view, and learn by synaptic modification about these conjunctions of cues. If the field of view is 270°, then place cells were produced as a result of this exploration and learning, as shown in Fig. 9. If the field of view was 30° in the simulations, then spatial view cells were produced as a result of this exploration and learning (Fig. 9). Thus the same computational learning process can lead to place cells with a large field of view as in rodents, and to spatial view cells in foveate animals such as primates including humans. This is Rolls' hypothesis about how spatial view cells are formed in primates as a result of foveate vision (de Araujo *et al.*, 2001).

There is a hint of something similar in rodents to what is produced by the fovea in primates, in that, when a rat is running along a linear track in which it can see primarily in one direction, then place cells can show more directional properties, in that they respond at a place when the rodent can see one view, but not if the rodent is in the same place and sees the other view (Acharya *et al.*, 2016; McNaughton *et al.*, 1983; Muller *et al.*, 1994). We predict that if a rat's visual field was restricted, by for example a cone over the head, or in a virtual reality environment, then during learning new environments, or during development, the rat hippocampal neurons might become more like macaque spatial view neurons.

This model thus shows that spatial representations may be produced by similar mechanisms in rodents and primates, but become different because of the primate fovea. Spatial view representations open up the issue of memory functions of the hippocampus involved in remembering where objects and rewards are in spatial scenes, an episodic memory function. The difference in spatial representations in the rodent and primate hippocampus does have implications for understanding how the hippocampus operates in spatial function and memory in primates including humans.

The actual implementation in the brain of the learning process to associate a combination of features, to produce a feature-combination neuron, might include a short-term memory trace in the associative synaptic learning rule that would make inputs that occur close together in time become associated together, in the same way as it is proposed helps to form invariant representations for object vision (Rolls, 2012; Rolls, 2016a). If different head directions occurred close together in time as in an open field, this might produce in rodents place cells with activity that was relatively invariant with respect to head direction. On the other hand, if the rodent was running in a straight arm of a

maze, then the place cells would be predicted to respond primarily to the head direction in which the rodent was running, and the place cell shape would be predicted to be elongated in the direction of travel. The statistics of the spatial inputs when rodents reach a boundary and have to stop may also contribute to the formation of boundary cells in rodents.

4.2. Comparison of representations in primates and rodents

Despite the major differences in the spatial representations in the primate and rodent hippocampus, there are important similarities between the operation of the rodent and primate hippocampus, which indicate that the operation of these neural systems is comparable in rodents and primates, even though what is represented is different, as shown in this paper. Some of the similarities of the hippocampal system in primates and rodents are as follows.

First, the spatial representations are in both cases by most spatial view and place cells primarily allocentric. In monkeys, hippocampal spatial view cells during active locomotion in an open environment respond allocentrically to the view of a position in a spatial scene, relatively independently of the place where the monkey is in the open environment, of head direction, of eye position, and of where the spatial view field is relative to the monkey (Georges-François *et al.*, 1999; Rolls and O'Mara, 1995). In a virtual environment, many of the neurons still respond to landmarks and have an allocentric representation (Wirth *et al.*, 2017).

Second, the spatial representations can be updated idiothetically, by one's body or eye motion in primates, as in the rat.

Third, in both cases the firing rates are low: in primates with a typical mean rate of 0.5 spikes/s, and a typical peak response rate of 17-20 spikes/s (Rolls *et al.*, 1997a; Wirth *et al.*, 2017). This matches numerous accounts of firing properties in rat hippocampus.

Fourth, spatial view cells may fire just before the eyes reach the centre of the spatial view field, and may have their maximal response soon after the eyes reach the spatial view field, and decrease somewhat after that, i.e. show some adaptation (Wirth *et al.*, 2017). Analogous findings have been described for rodent hippocampal cells which generate spike sequences lasting about 2 seconds as rats traverse a place field. The firing rate in the place field shows an asymmetry which changes with experience: as rats become familiar with an environment, cells show an increase in rate before animals reach the place field, followed by a gradual decrease as rats leave the field (Mehta *et al.*, 2000).

Fifth, in macaques, there is evidence for independent representation about spatial view by hippocampal neurons, in that the information rises linearly with the number of neurons (Rolls *et al.*, 1998). This independence arises when the response profiles of the neurons are uncorrelated (Rolls and Treves, 2011). This is a powerful encoding, because the number of stimuli (e.g. spatial views) rises exponentially with the number of neurons. (Of course this independence applies only in a high-dimensional environment, and saturates to the limit in lower dimensional environments (Rolls, 2016a; Rolls and Treves, 2011).) Ensemble encoding by populations of neurons is found in rodents (Wilson and McNaughton, 1993), and it would be interesting to know whether the coding by different neurons is independent.

Sixth, rodent place cells may respond differently on the trajectory to approach a goal depending on the state of the animal (Ferbinteanu *et al.*, 2011; Fyhn *et al.*, 2002; Wood *et al.*, 2000), as in primates (Wirth *et al.*, 2017). This implies that place cells support cognition in both species.

Seventh, in macaques, object-spatial view neurons are found (Rolls *et al.*, 2005), and one-trial object-place learning and recall can occur (Rolls and Xiang, 2006). In rodents object-place or odor-place neurons have been described (Kim *et al.*, 2011; Komorowski *et al.*, 2009). The presence of a barrier, which might be thought of as an object, in a place, may also be encoded by rodent hippocampal neurons (Rivard *et al.*, 2004).

Eighth, in macaques, reward-spatial view neurons are found (Rolls and Xiang, 2005), and cells are found to encode reward outcomes (Brincat and Miller, 2015; Wirth *et al.*, 2009). In rodents reward-place neurons have been described (Tabuchi *et al.*, 2003), and it was found that place cells are more active after the receipt of a reward (Singer and Frank, 2009).

Ninth, in rodents, distal room cues can influence place cells (Acharya *et al.*, 2016; Aronov and Tank, 2014; Knierim and Rao, 2003; Shapiro *et al.*, 1997). However, this is different to the encoding of a location in a scene that is provided by primate spatial view cells, in that in rodents the distal room cues are used to encode the place where the rodent is located.

Tenth, in both primates and rodents restricting the view of the environment may have analogous effects. In primates navigating through spatial trajectories in a star maze, many neurons had their responses influenced by place, the direction in which the macaque was facing, and by the

part of the trajectory being performed (Wirth *et al.*, 2017). In rats tested in an open foraging environment in which all places and head directions occur, rat place cells tend to have only small directional selectivity. However, in rats tested in linear runways in which a task may be performed and in which only some combinations of head direction and place are common, place cells may be quite directional (Acharya *et al.*, 2016). A possibility is that in the foraging situation used by Rolls and colleagues, all places, views, and head directions occurred, and the cells were dominated by where the animal looked, and not by place or head direction (Georges-François *et al.*, 1999). In contrast, if the macaque in a VR environment was constrained by the star maze to visit only certain places with particular view and head directions common in those places, and was performing a task that required a trajectory to a goal, then the neurons might reflect not only where the macaque was looking in the environment, but also the place etc. (Wirth *et al.*, 2017).

Eleventh, whole body motion cells which respond to either linear velocity or angular velocity are present in the macaque hippocampus (O'Mara *et al.*, 1994), and have more recently been described as speed cells in the rodent entorhinal cortex (Kropff *et al.*, 2015).

Twelfth, macaques (Robertson *et al.*, 1999; Rolls, 2005), as well as rodents (Taube *et al.*, 1996; Taube *et al.*, 1990), have head direction cells in the presubiculum / subiculum.

These considerable similarities between the responses of neurons found in the rodent and primate hippocampal system provide evidence that the systems operate in similar ways in primates and rodents, but with different spatial representations. The different representations we relate to the evolution of the primate fovea, and its effects on object representations in the ventral cortical visual stream, and on systems in the dorsal visual stream for eye movements to produce foveation and for an interface to produce visually guided actions in the connected parietal cortical areas. Moreover, we see foveation of an object as an efficient way to transmit the coordinates for reaching movements etc to the dorsal visual system (Rolls *et al.*, 2003; Rolls and Deco, 2002). Further, the saccadic system of primates (including humans) enables a primate in one place to look towards one part of a scene and recall the object there, and then to saccade to another point in the scene and recall the object there. We know of nothing similar in rodents, and this highlights an important difference between primate and rodent hippocampal spatial representation and memory systems that arises because of the fovea.

4.3. Hippocampal computational similarities between primates and rodents

Although the spatial representations in the primate and rodent hippocampus are different (section 4.2), we propose that the underlying computations performed are similar.

A quantitative and detailed theory and model of how the hippocampus operates as a memory system, and of the way in which information stored in the hippocampus could be recalled back to the neocortex, has been developed (Kesner and Rolls, 2015; Rolls, 1989, 2016a, 2018b; Treves and Rolls, 1992, 1994), with the architecture illustrated in Fig. 2. In the theory, the CA3 network forms an autoassociative or attractor memory, given the associatively modifiable recurrent connectivity between CA3 neurons. According to this theory, this system operates similarly in rodents and primates, to allow arbitrary associations between places in rodents, or spatial views in primates, and objects or rewards to be rapidly formed, and later the whole memory to be recalled from a part. For example, the location of an object might be recalled in CA3 when an object recall cue was presented. Temporal sequences may be remembered by replacing the location cells with the timing cells described by Eichenbaum and colleagues (Eichenbaum, 2014; Howard and Eichenbaum, 2015; Howard *et al.*, 2014; Macdonald *et al.*, 2011), and this applies to primates too (Naya and Suzuki, 2009). Further, it has been proposed that the number of neurons used to represent an episodic memory is similar in rodents and primates (Thome *et al.*, 2017).

The leading factor in the number of memories that can be stored and successfully recalled in this system is the number of synapses onto any one CA3 neuron by the associatively modifiable synapses from the recurrent collaterals of other CA3 neurons. With sparse representations, the number of memories that can be stored is in the order of the number of synapses onto each CA3 neuron (Treves and Rolls, 1991). It is interesting that an important difference in evolution arises in humans, in which the CA3 neurons are not well connected across the midline by the hippocampal commissure, given what is found in macaques (Amaral *et al.*, 1984). In rodents, the CA3-CA3 in the two hippocampi are as much connected as within the hippocampus on one side in the brain, and this enables the rodent CA3 hippocampal network to operate as a single hippocampus (Rolls, 2016a). In humans, there appear to be effectively separate left and right CA3 hippocampal networks given the poor commissural connectivity. Consistent with this point, there is evidence that the right human hippocampus specialises in spatial including object-place and reward-place memories, and the left

hippocampus specialises in more language/word-related memory processes (Barkas *et al.*, 2010; Bonelli *et al.*, 2010; Burgess *et al.*, 2002; Crane and Milner, 2005; Sidhu *et al.*, 2013). The adaptation here is that humans have twice the memory capacity of a hippocampal system connected across the midline as in rodents; and that associations are not typically made between words and their position in space, for the latter are not part of what is implemented for human language.

4.4. Functions performed by the primate hippocampus in memory, and thereby in action and navigation

Given that the hippocampus is involved in object-place recall, we now consider how information recalled within the hippocampus contributes to navigation and action. After recall by the hippocampal CA3 autoassociation network of, for example, the place where an object was seen, the place can be recalled to the neocortex by the multistage backprojection pathways starting with CA1 to the neocortex (Rolls, 1989) shown in Fig. 2, using mechanisms for which there is a detailed and quantitative theory (and which accounts for why there are as many backprojections as forward projections between adjacent areas in a cortical hierarchy) (Rolls, 2016a; Treves and Rolls, 1994). These neocortical areas involve the parietal cortex -including the retrosplenial cortex- and the posterior cingulate cortex. Having reinstated the representation of the place in the parietal cortex at which the object was seen, our working hypothesis is that the parietal visual and movement-related cortex can then direct eye movements to that location in space, and organise the arm movements required to reach for the object in space. This is an example of a top-down type of attentional, but also action, guidance of the parietal cortex implemented by the hippocampal memory system. Much of the primate parietal cortex is devoted to the organisation of eye movements necessary to foveate objects in a scene, and then to direct actions to a place in the scene (Andersen, 1995; Andersen *et al.*, 2000; Bisley and Goldberg, 2010; Gnadt and Andersen, 1988). Further, recalling the locations of rewards and objects in scenes from the hippocampus to the neocortex may be an important contribution to navigation, with the details of the computations required to perform the navigation implemented in the neocortex.

Pursuing this approach further, if the hippocampal system with its spatial representations is useful for episodic memory, an implication is that other cortical system would be more involved in navigation. The mechanisms here are less well understood, but lesions to the neocortex can produce topographical agnosia and inability to navigate (Barton, 2011; Kolb and Whishaw, 2015), and the retrosplenial cortex is implicated in navigation (Alexander and Nitz, 2015; Byrne *et al.*, 2007; Epstein, 2008; Vann *et al.*, 2009; Vedder *et al.*, 2016). In more detail, lesions restricted to the hippocampus in humans result only in slight navigation impairments in familiar environments, but rather strongly impair learning or imagining new trajectories (Bohbot and Corkin, 2007; Clark and Maguire, 2016; Maguire *et al.*, 2016; Spiers and Maguire, 2006; Teng and Squire, 1999). In contrast, lesions in regions such as the parietal cortex or the retrosplenial cortex produce strong topographical disorientation in both familiar and new environments (Aguirre and D'Esposito, 1999; Habib and Sirigu, 1987; Kim *et al.*, 2015; Maguire, 2001; Takahashi *et al.*, 1997). This suggests that the core navigation processes (which may include transformations from allocentric representations to egocentric motor commands) is performed independently by neocortical areas outside the hippocampus, which may utilize hippocampal information related to recent memories (Ekstrom *et al.*, 2014; Miller *et al.*, 2013).

Consistent with the spatial view cells found in non-human primates, regions of the human hippocampal formation can become activated when people look at spatial views (Epstein and Kanwisher, 1998; O'Keefe *et al.*, 1998). Moreover, the right human hippocampus is activated during mental navigation in recently learned but not in highly familiar environments (Hirshhorn *et al.*, 2012). Mental navigation in familiar environments produces activation of cortical areas such as the lateral temporal cortex, posterior parahippocampal cortex, lingual gyrus, and precuneus (Hirshhorn *et al.*, 2012). Further, as noted above, patients with anterograde amnesia may not be impaired in navigation in familiar environments, as contrasted with new environments (Clark and Maguire, 2016; Maguire *et al.*, 2016). The implication is that, at least in primates, the hippocampus may be involved in episodic memory, and that neocortical regions implement navigation (helped when it is useful by recent memories recalled from the hippocampus). In this context, we note that head direction cells (Butler *et al.*, 2017), grid cells, and whole body motion (speed) cells are not necessarily only for navigation: idiothetic update may be useful for a memory system too, so that the location can be updated and then the updated location can be associated with whatever is found there.

In contrast, the view has often been held that the rodent hippocampus implements navigation.

Indeed, in rodents, the existence of place cells has led to hypotheses that the rodent hippocampus provides a spatial cognitive map, and can implement spatial computations to perform navigation. These navigational hypotheses could not account for what is found in the primate hippocampus. An alternative that is suggested is that, in both rodents and primates, hippocampal neurons provide a representation of space (which for rodents is the place where the rat is located, and for primates includes positions "out there" in space), which are used as part of an episodic memory system. In primates this would enable formation of a memory of where an object was seen (Rolls, 1987, 1989, 2016a; Rolls and Kesner, 2006). In rodents, this would enable the formation of memories of where particular objects (defined by olfactory, tactile, and taste inputs for instance) were found (Kesner and Rolls, 2015). Consistent with this theory of hippocampal function, one-trial object-place memory in rodents requires the hippocampus (Day *et al.*, 2003; Kesner and Rolls, 2015; Takeuchi *et al.*, 2014); texture sensed by whiskers and the places of rewards are reflected in neuronal firing (Itskov *et al.*, 2011); some hippocampal neurons respond to behavioral, perceptual, or cognitive events, independently the place where these events occurred, and may thus be useful for memory functions (Komorowski *et al.*, 2009; Wood *et al.*, 1999; Wood *et al.*, 2000); hippocampal neurons may be activated following relocation of a target object to a new place (Fyhn *et al.*, 2002); some hippocampal neurons alter their response when a different recording chamber is placed in the same location in the room (Leutgeb *et al.*, 2005); and another continuous dimension than place, namely auditory frequency, can be mapped by rodent hippocampal neurons (Aronov *et al.*, 2017). Thus in primates, and probably also in rodents, the hippocampal representation of space may be appropriate for the formation of memories of episodic events (for which there is typically a spatial component). These memories would be of use in spatial navigation. We note that in accordance with this analysis, entorhinal cortex grid cells would be useful for not only the idiothetic update of hippocampal representations for memory-related functions, but also for use in neocortical systems involved in navigation.

We now propose a hypothesis about how the primate hippocampus may contribute to navigation and route-finding. We start with the evidence that hippocampal spatial representations are built from the information provided by the environment, resulting in spatial view cells if a wide range of spatial views are seen from a wide range of places (de Araujo *et al.*, 2001), as illustrated in Fig. 9 (right) for primates. If in contrast the primate is restricted to particular paths through a maze, then each spatial view will be seen from only a subset of places as in Wirth et al., (2017), shown in Fig. 5. Neurons would then learn to respond to spatial views in a place-dependent way. Further, other details present during maze learning, such as any foreground showing the maze itself, or also whole body motion signals such as turning left, would become associated into the responses of hippocampal neurons by the associative learning. The hippocampal neurons that respond to these different combinations of several possible subsets of spatial view, maze details, place, and whole body motion, would then be activated in a sequence as the animal progressed through the different parts of the maze, forming a trajectory through a state space which could itself be learned as a continuous attractor or chart for that maze learning task. Computational charts of this type are important in hippocampal computation, but are applied not just to place or spatial view representations as in the earlier proposal (Battaglia and Treves, 1998), but now to the trajectory through the state space of combination-sensitive neurons that could be expected to be found when trajectories are limited as in a maze. Indeed, these concepts, we suggest, help to account for the types of neuronal response found when macaques have learned a star maze (Wirth *et al.*, 2017), and also apply in an analogous way to the learning of mazes in rodents. Thus we propose that hippocampal spatial representations in primates could be used not only for object-place episodic memory, but could also be useful for route-finding when only certain trajectories in the environment are possible. This corresponds to what appears to take place in rodents performing learning tasks in restricted environments such as linear parts of a maze (Acharya *et al.*, 2016).

Although we have shown here, that the primate hippocampus relates to information from the ventral and dorsal primate visual streams, we note that some of the information for building spatial scene representations comes from the ventral visual system. In particular, inputs to the spatial view cells described here may come at least in part from temporal lobe and related cortical areas that respond to scenes or parts of scenes (Kornblith *et al.*, 2013; Nasr *et al.*, 2011) (Figs. 1 and 2). On the other hand, the idiothetic update of spatial view cells involves inputs from the spatial view grid cells in the macaque medial entorhinal cortex (Killian *et al.*, 2012; Meister and Buffalo, 2018). The medial entorhinal cortex receives its inputs via the parahippocampal gyrus (areas TH and TF, Fig. 2), which in turn receives it inputs from dorsal stream visual areas including VIP, in which neurons

that respond to signals related to self-motion are found (Bremmer *et al.*, 2002b; Galletti and Fattori, 2017).

4.5. Building episodic memories from associations between objects and places

It has been argued that the hippocampus would help to form an episodic memory, and that this episodic information could be retrieved to the neocortex from the hippocampus to help create neocortical semantic memories (Rolls, 2016a). We now clarify how we think this system operates, for comparison with other concepts of episodic and semantic memory. The hippocampal CA3 network as a single attractor network is in Rolls' theory of the hippocampus specialised to perform associations between any object and any place – 'arbitrary associations'. This is an unstructured type of information storage: the information is stored in unstructured form as it arrives. The object, in this definition, is essentially something with a discrete representation (with a random set of neurons active for any one object (Rolls, 2016a)), and this might include a person, an object such as a bicycle, an odor, a taste, or an emotion (Rolls, 2015). The place, in this definition, is a continuous representation, e.g. provided by place or spatial view cells with approximately Gaussian receptive fields that overlap. In the theory, time cells (Eichenbaum, 2014), can substitute for place cells, to enable the order of the presentation of objects to be stored (Kesner and Rolls, 2015), which may be an important part of an episodic memory. This was evidenced by time cells found in primates (Sakon *et al.*, 2014), which coded the trial context of a time interval, such as the object-place combination that preceded that interval in the trial. This enables an episodic memory to be an association between an object and/or place and/or time. An episodic memory can be recalled from the hippocampus in response to a partial cue (e.g. the object or the place) first in CA3, and then the original neocortical representations present during the original episode can be recalled to the neocortex. It is likely that only useful information will be recalled. For example, one does not need to remember from one's hippocampal system the room number from a hotel several meetings earlier. Once the episode is recalled to the neocortex, it can then be formed into a structured 'semantic' memory, which may be a slower process than the 'on the fly' hippocampal episodic memory storage process. The formation of the semantic memory might take place in higher order cortical areas, for example in the temporal lobe, and may have specialised subtypes, including autobiographical, geographical etc. During the recall process from the hippocampus, earlier neocortical areas may feed their information into these multimodal semantic areas. Part of the process that builds semantic memories may be associative, but there is a need to remove exceptions, and that may require more complex processing (McClelland *et al.*, 1995; McClelland and Rumelhart, 1986). Because these are structured memories, semantic memories can incorporate information about relations, as in a family tree, or an allocentric 'geographical' map in which again the relations are embodied. For example, if one makes several journeys to different places in France, each might have much that is episodic (unstructured); but then when one recalls each of the episodic memories, one can build an explicit semantic representation about the relations between the parts. We can make declarations about both episodic and semantic memory. (However, it is also the case that the hippocampal map or chart of an environment does contain information implicit in it about the spatial relations between the places (Battaglia and Treves, 1998).)

If an episodic memory is needed after a long time, it may still be recalled from the hippocampus in its unstructured form if it has never (or rarely) been recalled previously and has not therefore been structured into a semantic memory. However, because the memory capacity of the CA3 network is limited, overwriting of old episodic memories must occur, and that is an important aspect of forgetting, which is essential in such a memory system (Rolls, 2016a). This theory of hippocampal operation thus sees a great advantage in the structuring of semantic memories during active recall and reorganization of semantic memory, and sees passive recall and neocortical consolidation during sleep as not being attractive (Rolls, 2016a), although it is noted that there is an alternative view that hippocampal replay during sleep is involved in memory consolidation (Foster, 2017; Wilson and McNaughton, 1994).

The types of information that the hippocampus appears to be involved in associating consists of continuous representations of location (place cells and spatial view cells) or time (Eichenbaum, 2014; Kesner and Rolls, 2015) with discrete representations of objects, faces etc. (Kesner and Rolls, 2015; Rolls, 2016a, 2018b). A single attractor network, with CA3 in mind, can associate such continuous and discrete representations (Rolls *et al.*, 2002). The hippocampus is implicated in forming memories of other types of continuous representation, including images that vary continuously from each other (Constantinescu *et al.*, 2016), and auditory tones (Aronov *et al.*, 2017). The hippocampus is not involved however in forming many associations between stimuli that do not

include stimuli with continuous representations, such as one-trial visual object to taste reward associations in the orbitofrontal cortex (Rolls, 2017a, 2018a), which are not hippocampus-dependent (Kesner and Rolls, 2015), and which do not engage hippocampal neurons in primates (Rolls and Xiang, 2005). Similarly, auditory to olfactory associations would not be expected to require the hippocampus, unless perhaps the auditory stimuli consisted of pure tones on a continuum, instead of for example the voice of a particular person, which is a discrete entity. What may be a key concept here is that because the CA3 network is effectively a single attractor network, it can form continuous representations of the whole of a continuous space in the single network, any part of which can then be associated with discrete representations of objects, faces, taste, etc. (Rolls, 2016a, 2018b).

Although many have considered that the rodent hippocampus is used for navigation (Burgess *et al.*, 2000; Burgess and O'Keefe, 1996; Hartley *et al.*, 2014; O'Keefe, 1979, 1991), there is much evidence that the rodent hippocampus can be used for memory (Buzsaki and Moser, 2013; Day *et al.*, 2003; Eichenbaum *et al.*, 1999; Kesner and Rolls, 2015; Wood *et al.*, 2000).

4.6. The human hippocampus and the art of memory

A central feature of the approach described here is that the primate including human hippocampus is involved in storing and later recalling where objects or people have been seen in spatial scenes. The theory has been developed that the art of memory or the method of loci used since Roman times (Cicero, 55 BC) to remember the order of items in a speech by associating each item with a location in a scene, moving from one end of the scene to the other end, utilizes this hippocampal memory system (Rolls, 2017b). A key part of the theory is that spatial scenes are stored in a continuous attractor network in CA3, in which items can be associated with each location in the scene. Because a continuous attractor network has overlap of each location in the scene with the next location, starting at one end of the space and working through the space recalls each spatial item in the correct order, and thus the item association with each location in the scene. The theory is that the art of memory or the method of loci utilizes the inherent continuity of space stored in this way in the hippocampus to recall items in the correct sequence by working from one end of the scene to the other (Rolls, 2017b). This can all be achieved by standing in one place and looking at or imagining a spatial scene out there, and working through the viewed or imagined spatial locations, which might be places at which one had never been located. This is thus a natural feature of the representations of space 'out there' in primates. This could not be performed by place cells (which respond primarily to the place where the individual is located or navigating; or recalling such as in a sharp wave ripple burst), for the place from which the speech was delivered would probably be constant for the whole speech. In contrast, the individual while located in one place could sequentially view different parts of an imagined scene that the individual may never have been placed at and set up place cells for, and recall whatever had been associated previously with that location in the scene.

The point being made can be further clarified as follows. A distinction between rodents and primates, is that rodent place cells can represent a place where the animal is located, or the memory of a place where the animal has been located previously. In contrast, spatial view cells can represent the locations "out there" in space viewed at a distance, and these locations can often be places that the primate has never been located at and could not ever be located at. The logic of the point being made is that primates never need to have been located at the place to which a spatial view cell responds: spatial view cells represent the space being viewed. In contrast, although memory recall in rodents can lead to the recall of a place (Foster and Wilson, 2006) or trajectory planning to a place (Pfeiffer and Foster, 2013), this is a place or sequence of places representation, and is of places at which the rodent has been located previously (or would later visit (Olafsdottir *et al.*, 2015)).

This theory thus helps to draw out the difference between the representations of space in the primate and rodent hippocampus. The theory thus provides a useful illustration of how hippocampal spatial view cells could contribute to memory function in humans, in a clear situation in which the human is always in one place, but remembers objects or people at different locations in viewed spatial scenes which may include locations never visited by the individual.

5. Concluding points, and future research

A major conclusion is that the direct evidence considered here from neuronal activity indicates that the primate hippocampus has very different spatial representations to the rodent hippocampus; and we relate this to the development of the primate fovea, and to hierarchically organized multiple cortical visual areas in the ventral visual stream for recognising objects at the fovea, and in the dorsal visual stream for moving the eyes to foveate an object in a complex natural scene. The primate hippocampus has representations of spatial scenes using spatial view cells, with

some modulation by place, whereas the rodent hippocampus contains neuronal representations of where the rodent is located, 'place cells'. We have related this to the development of the primate fovea, which, we have shown in a formal model, helps primates to build primate spatial view neurons, rather than rodent place cells (de Araujo *et al.*, 2001). Complementary indirect evidence from for example lesion studies (Murray *et al.*, 2017) supports our earlier evidence on primate hippocampal representations (Georges-François *et al.*, 1999; Robertson *et al.*, 1998; Rolls *et al.*, 1997a; Rolls *et al.*, 1998), and also our hypothesis that the foveal representation of primates is one contributor to this difference (de Araujo *et al.*, 2001). We do not of course exclude the possibility that some place cells may be present in the primate hippocampus. Indeed, we argue that the environment in which the neurons are tested can have an influence on the responses found, in primates as well as in rodents. If all spatial views can be seen from all places, as in a random foraging task, then spatial view cells with little place modulation may be likely. If on the other hand the testing is in a maze in which the environment is more restricted in that certain views can be seen from certain places, and trajectories through the maze must be learned, then primate hippocampal neurons may be more likely to be modulated by place, and the responses that must be made at different parts of a trajectory.

The investigations described in this paper provide fundamental evidence about how information is represented in the primate hippocampus, and provide a foundation for a theory of what the primate (including human) hippocampus implements, and how it functions as a memory system (Rolls, 2016a; Rolls and Treves, 1998). The relevance of this primate research is shown by human neuroimaging studies which show that looking at spatial views can activate the hippocampus and related areas (for example, Epstein and Kanwisher, 1998; and O'Keefe *et al.*, 1998). We make the point that neuron-level investigations are needed to assess the coordinates for the encoding, (Georges-François *et al.*, 1999), the representation of the information (with its implications for the storage of information) (Rolls *et al.*, 1998), and the similarity of the recall state to the stored memory when retrieval is with a partial cue (Robertson *et al.*, 1998). While neuroimaging studies are of great value, they cannot whether there is an allocentric representation of space "out there" accessible either by looking directly at that location, or by using another head direction / eye position (and even head position) combination to look towards the same spatial location. Further, neuroimaging studies can not show that, for example, that some hippocampal whole body motion neurons respond to vestibular input, others to optic flow, and others to either. Neuronal level analyses are important by providing evidence the information represented in the brain and how it is represented, by helping to reveal how a part of the brain operates, by showing the information that is being exchanged between the neurons, which are the computing elements of the brain (Rolls, 2016a).

This analysis presented here also leads to suggestions for critical areas for future research. It has been predicted that if rodents had a restricted visual field (using for example a cone around the head or a restricted view in virtual reality), then neurons more like spatial view cells might develop in rodents. This would be a useful test of the theory proposed by de Araujo et al (2001).

The posterior cingulate and retrosplenial cortex is a key convergence area that receives information from both the ventral and dorsal processing streams (Vogt and Laureys, 2009; Vogt and Pandya, 1987) and projects to and receives projections from the primate hippocampus, and evidence on neuronal spatial representations in it will be important in understanding the operation of the hippocampal system in primates.

To understand the number of memories that can be stored in the primate and human hippocampus, investigations of the numbers of spines devoted to CA3-CA3 recurrent collaterals in macaques and humans are important, as this sets the capacity of the hippocampal memory system (Kesner and Rolls, 2015; Rolls, 2016a).

To understand neuronal representations better in the human hippocampus, it will be important to know how neurons respond to spatial scenes when eye movements are recorded to show which part of the spatial scene is being viewed, and it will be important to do this when the recordings are made with the human moves or is moved to different places, though this may be difficult in view of the ethical limitations that of course are involved when recording neuronal activity in humans (Fried *et al.*, 2014). It will also be of importance to develop virtual reality testing situations for humans and macaques that enable the participant to view the same location in a scene from different places, so that scene and place representations can be adequately distinguished, as was possible in investigations in an open laboratory environment in which the macaque actively walked (Georges-François *et al.*, 1999).

Finally, further investigation of the clinical implications of the points about memory-related functions of the hippocampus and its related system will be of interest. It has been noted above for example, that patients with anterograde amnesia may not be impaired in navigation in familiar

environments, as contrasted with new environments (Clark and Maguire, 2016; Maguire *et al.*, 2016). Further implications of the memory-related hypothesis of the function of the hippocampal system with its spatial view cells to provide a spatial component and its inputs from the orbitofrontal cortex system involved in emotion (Rolls, 2014, 2017a) is that the hippocampal connectivity may be altered in patients with mood disorders who keep ruminating about sad memories. Indeed, a start in this area has already been made, in that the parahippocampal gyrus has reduced functional connectivity with the medial orbitofrontal cortex reward system in patients with major depressive disorder (Cheng *et al.*, 2016; Rolls, 2016b); and the lateral orbitofrontal cortex non-reward / punishment system has increased functional connectivity with the posterior cingulate gateway into the hippocampus (Cheng *et al.*, 2018a), and the closely related precuneus (Cheng *et al.*, 2018b). These changes may together contribute to the fewer happy memories and the bias towards sad memories and ruminations in people with depression (Rolls, 2016b, 2017a, 2018a).

6. Supplementary Material.

Videos that illustrate the responses of macaque hippocampal spatial view cells are available at http://www.oxcns.org/publications.html . An example of a spatial view cell is in file az033.mp4, which illustrates a small part of the data from this neuron that was included in the analysis of the coordinate system used by spatial view neurons (Georges-François *et al.*, 1999). The enclosure is the central square, the 4 walls are the rectangles surrounding the square with the height on the wall indicated by the distance in the wall rectangle away from the centre of the diagram, and a red dot is added to this wall plot whenever the cell fires an action potential. The position and head direction of the macaque are indicated by the triangle, and the eye gaze direction by the line projected to the edge of the enclosure, which is black when the cell is not firing, and red when the cell fires.

Programs written in Matlab (which also run under the freeware Octave) to illustrate the operation of autoassociation (attractor) and related networks are available in connection with *Cerebral Cortex: Principles of Operation* (Rolls, 2016a) at
http://www.oxcns.org/NeuronalNetworkSimulationSoftware.html
with Appendices explaining their operation available at http://www.oxcns.org/papers/Cerebral%20Cortex%20Rolls%202016%20Contents%20and%20Appendices.pdf

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Figure Legends

Fig. 1. Cortical connections of the primate hippocampus. A medial view of the macaque brain is shown below, and a lateral view is above. The entorhinal cortex area 28 is the main entry for cortical connections to and from the hippocampus. The forward projections to the hippocampus are shown with large arrowheads, and the backprojections with small arrowheads. The main ventral stream connections to the hippocampus which convey information about objects, faces, etc are in blue, and the main dorsal stream connections which convey 'where' information about space and movements are in red. The ventral 'what' visual pathways project from the primary visual cortex V1 toV2, then V4, then posterior inferior temporal visual cortex (PIT), then anterior inferior temporal visual cortex (AIT), then perirhinal cortex (areas 35/36), and this to entorhinal cortex. The dorsal 'where' visual pathways project from V1 to V2, then MT (middle temporal), then LIP (lateral intraparietal), then parietal area 7 (lateral) and medial (including the precuneus), then to posterior cingulate cortex areas 23/32) including the retrosplenial cortex (areas 29/30) and thus to parahippocampal gyrus (areas TF and TH), and then perirhinal and entorhinal cortex. Area 22 is superior temporal auditory association cortex. Reward information reaches the hippocampus from the orbitofrontal cortex (OFC), anterior cingulate cortex (areas 32 and 25), and amygdala. The lateral prefrontal cortex areas 9 and 46 involved in working memory connect via the posterior cingulate cortex. The hippocampus enables all the high order cortical regions to converge into a single network in the hippocampal CA3 region which is made clear in Fig. 2 (Rolls, 2015, 2016a). Other abbreviations: as–arcuate sulcus; cs–central sulcus; ips–intraparietal sulcus; ios–inferior occipital sulcus; ls–lunate sulcus; sts–superior temporal sulcus. (HippConnsDV.eps)

Fig. 2. Connections from different cortical areas converge into a single network in hippocampal CA3, which provides a basis for associating 'what', 'where', and reward information. The forward connections are shown in blue solid lines, and the backward connections used for recall of information from the hippocampus are shown in green dashed lines. The triangles represent pyramidal cell bodies, and the thick lines above them the dendrites. The CA3 cells have a highly developed recurrent collateral (rc) system of connections. The CA3 cells receive their inputs from both dentate granule cells (DG) via the mossy fibres (mf), and also directly from the perforant path (pp). Abbreviations: D-Deep pyramidal cells. F-Forward inputs to high-level cortical areas from preceding cortical areas in the hierarchy. PHG-parahippocampal gyrus. S-Superficial pyramidal cells. 2, 3, 5-pyramidal cells in layers 2, 3 and 5 respectively of the entorhinal cortex. (hipconns2acolor.eps)

Fig. 3. A hippocampal spatial view cell (az033) recorded while a monkey walked around in an open field area 2.5x2.5 m shown as the square within a rich and large laboratory environment. In (a) every time that the cells fired is shown by a spot in the outer rectangles each of which represents one of the four walls of the room. The inner rectangles show where the monkey looked on the walls. The neurons has a spatial view field on wall 3. The places to which the monkey walked are shown by the triangles, with the pointed end showing the head direction. (b) shows some of the many different places at which the monkey was located when the neuron fired, and the lines show where the monkey was fixating when the spatial view cell fired. (c) provides more evidence about the places where the monkey was located when the cell fired because he was looking at the view field on wall 3. This helps to show that the neuron responds to spatial view, and not to the place where the monkey was located. C1 to c4 are cups containing food to encourage the monkey to forage. T1 was a trolley and T2 a table. Details are provided by Georges-François, Rolls and Robertson, 1999. (hipsvc.eps)

Fig. 4. Testing of a hippocampal spatial view neuron (av216) to show that it has allocentric encoding, and that the response does not depend on where the monkey is located. The firing rate is shown as a function of the horizontal and vertical eye position, where positive values indicate right or up. The neuron responded when the monkey looked towards its view field (indicated with a hatched bar) relatively independently of place, eye position, or head direction. ANOVAs and information theory analyses performed on the same data cast in different ways conformed this: for spatial view, the ANOVA was $p<0.001$ with 0.217 bits in a 500 ms period for the average Shannon mutual information; for place $p=0.9$ with 0.001 bits; for head direction $p=0.5$ with 0.0 bits; and for eye position $p=0.8$ with 0.006 bits. (Modified from Georges-François, Rolls and Robertson, 1999.) (av216col.eps)

Fig. 5. Recordings in a virtual environment. A: top view of the maze illustrating the layout. The reward is located at the end of one of the arms, but nothing indicates its position on the arm. Thus the animal has to learn which of the 5 landmarks neighbour the rewarded arm. The animal receives a reward when he reaches the end of that arm. B: Example of the firing rate map for a hippocampal cell as a function of the animal's point of gaze in the environment. The cell fires when the animal looks in the direction of the south west landmark (the ball). C. Position firing rate map of the cell shown in C. The cell fires preferentially when the animal is on the track turning toward the south west entry. D. The left panel represents the gaze density map overlaid on a screen shot of what the monkey sees when he is in position 1 (P1), as represented in the middle schematics. The right panel illustrates the firing rates as a function of the animal's eye position for the view from position 1. The cell fires when the south west landmark enters the field of view and the animal foveates it. E and F. The same conventions as D, but from different positions from which the ball is visible. The cell does not fire at all or very little when the animal is in position 2 (P2) or 3 (P3). (After Wirth and Baraduc, 2018.) (figure5_wirth_29_08.eps)

Fig. 6. Self-motion (idiothetic) update of the firing of a hippocampal spatial view cell occurred for a few minutes even when the view details were obscured by floor to ceiling curtains (B). M shows the place of the monkey in the room, with the head direction indicated by the arrow. The self-motion consisted in the case illustrated of eye movements made by the monkey, but also occurred during locomotion. (Modified from Robertson, Rolls, and Georges-François, 1998.) (av216Curtains17.eps)

Figure 7: Hippocampal neurons can anticipate the appearance of a landmark. A. Schematic of the landmark positions relative to the fovea for the computation of the firing rate as a function of landmark eccentricity. The red triangle represents the actual Field of View (FOV) of the animal in the virtual environment. The dotted lines represent the animal's point of gaze used for the calculation. On the left is shown an instance for which the landmark was at 20° from the fovea but not yet visible. On the right is shown an example for which the landmark is already in the FOV and at 30° from the fovea. B. Population average of the firing rates of the cells for their preferred landmark, as a function of landmark eccentricity. The red plot shows that the firing occurred even before the part of the scene towards which the monkey moved the gaze had appeared in the virtual environment testing situation. After Wirth et al 2017.) (figure7_wirth.eps)

Fig. 8a. Firing of hippocampal neurons in a one trial object-place recall task. (a) In stage 1, object 1 was shown in a position of the screen being viewed, and in stage 2 object 2 was shown. In stage 3 one of the objects was shown at the top centre of the screen, and the monkey had to touch the location of the screen where that object had been shown in order to obtain a juice reward. (b) A neuron that was selective for object 1 (O1) responded even in stage 4 when the object was not visible but the object and its location had to be recalled. (c) A neuron that was selective for place 1 (P1) responded even in stage 4 when the object was not visible but the object and its place on the screen being viewed had to be recalled. The average firing rate in spikes/s across trials ± sem is shown. ** $p<0.01$; * $p<0.05$. (Modified from Rolls and Xiang 2006.) (HippRecall.eps)

Fig. 9. Simulation of rodent place cells (left) vs primate spatial view cells (right). The agent moved through a grid of all 200x200 places x,y. At each place the head direction θ was rotated 5 degree increments. Hippocampal cells are activated by a set of 3 or more landmark visual cues within the field of view of the agent α. The firing rates of the hippocampal neurons depended on the angles φ subtended by the landmarks. The top left shows that for a rodent with a 270° field of view a combination of such cues defines a place. The top right shows that for a primate with a 30° field of view the combination of cues defines a spatial view. The sizes of the fields of view are shown by shading. The bottom left shows that in the simulations place fields arise with a 270° field of view, and the bottom right that spatial view fields arise on one of the walls indicated by the rectangles when the field of view is 30°. High firing rates are indicated by yellow-red. (Details are provided in DeAraujo, Rolls and Stringer 2001.) (hipViewSim.eps)

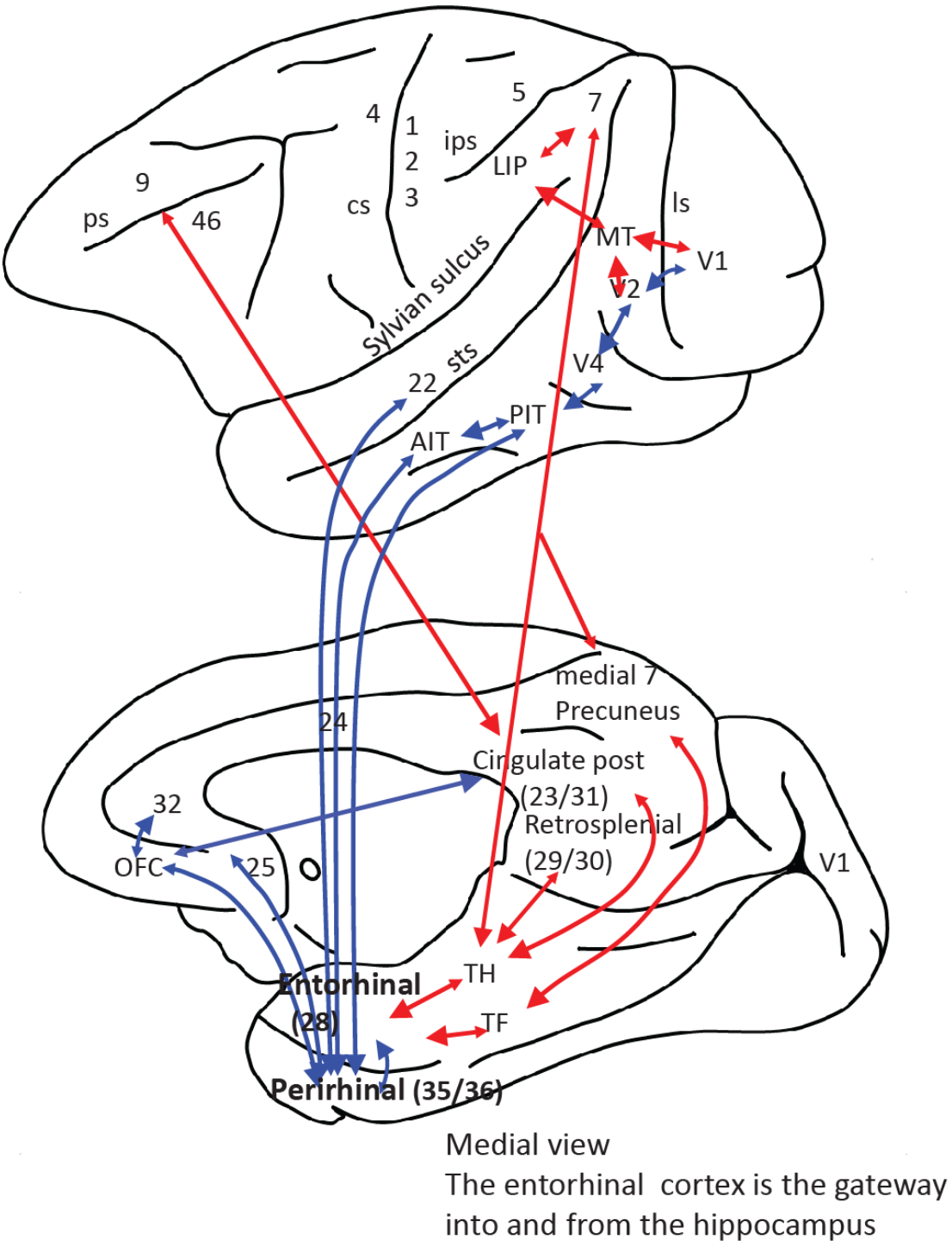
4
1
2
3
ips
5
7
LIP
9
ps
46
cs
ls
MT
V1
V2
Sylvian sulcus
sts
22
V4
PIT
AIT
medial 7
Precuneus
24
Cingulate post
(23/31)
32
Retrosplenial
(29/30)
OFC
25
V1
TH
Entorhinal
(28)
TF
Perirhinal (35/36)
Medial view
The entorhinal cortex is the gateway
into and from the hippocampus

Figure 1

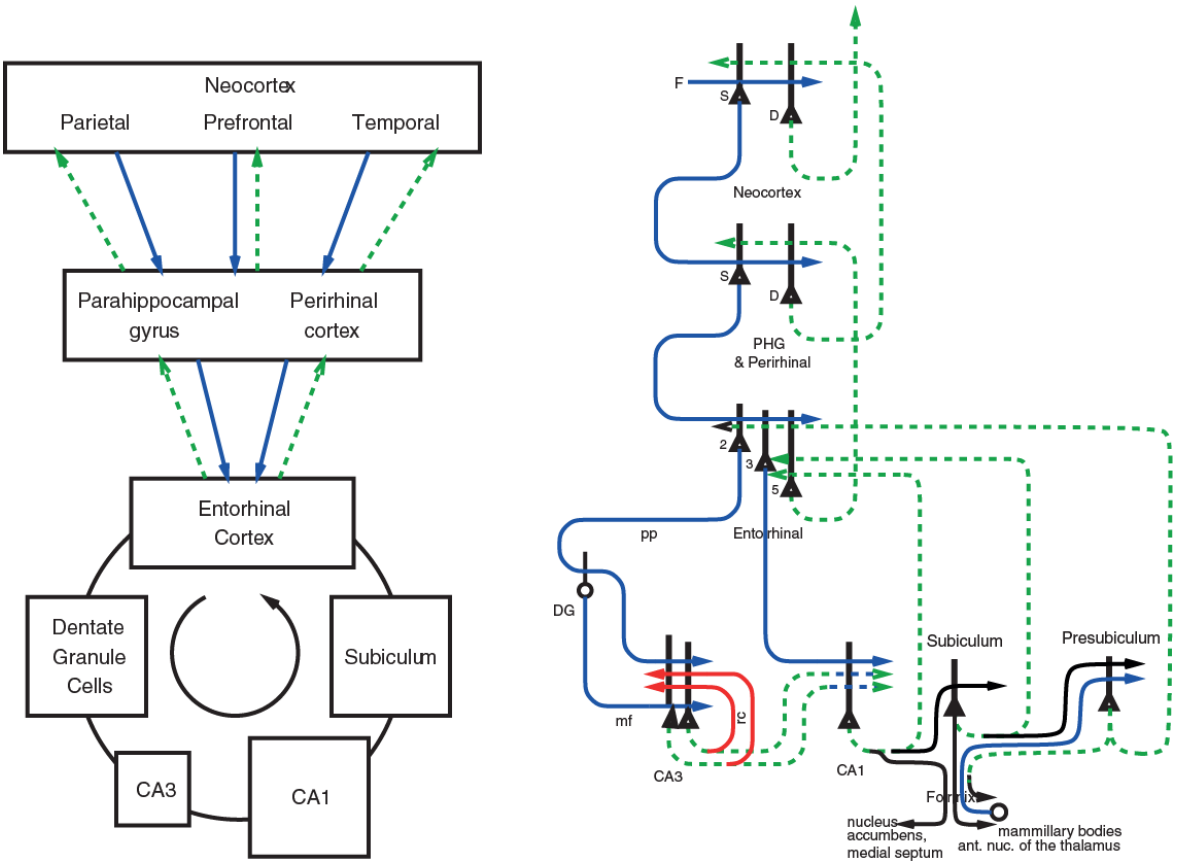
Neocortex
Parietal
Prefrontal
Temporal
Parahippocampal gyrus
Perirhinal cortex
Entorhinal Cortex
Dentate Granule Cells
Subiculum
CA3
CA1
F
S
D
Neocortex
PHG & Perirhinal
2
3
5
pp
Entorhinal
DG
mf
fc
CA3
CA1
Subiculum
Presubiculum
Fornix
nucleus accumbens, medial septum
mammillary bodies
ant. nuc. of the thalamus

Figure 2

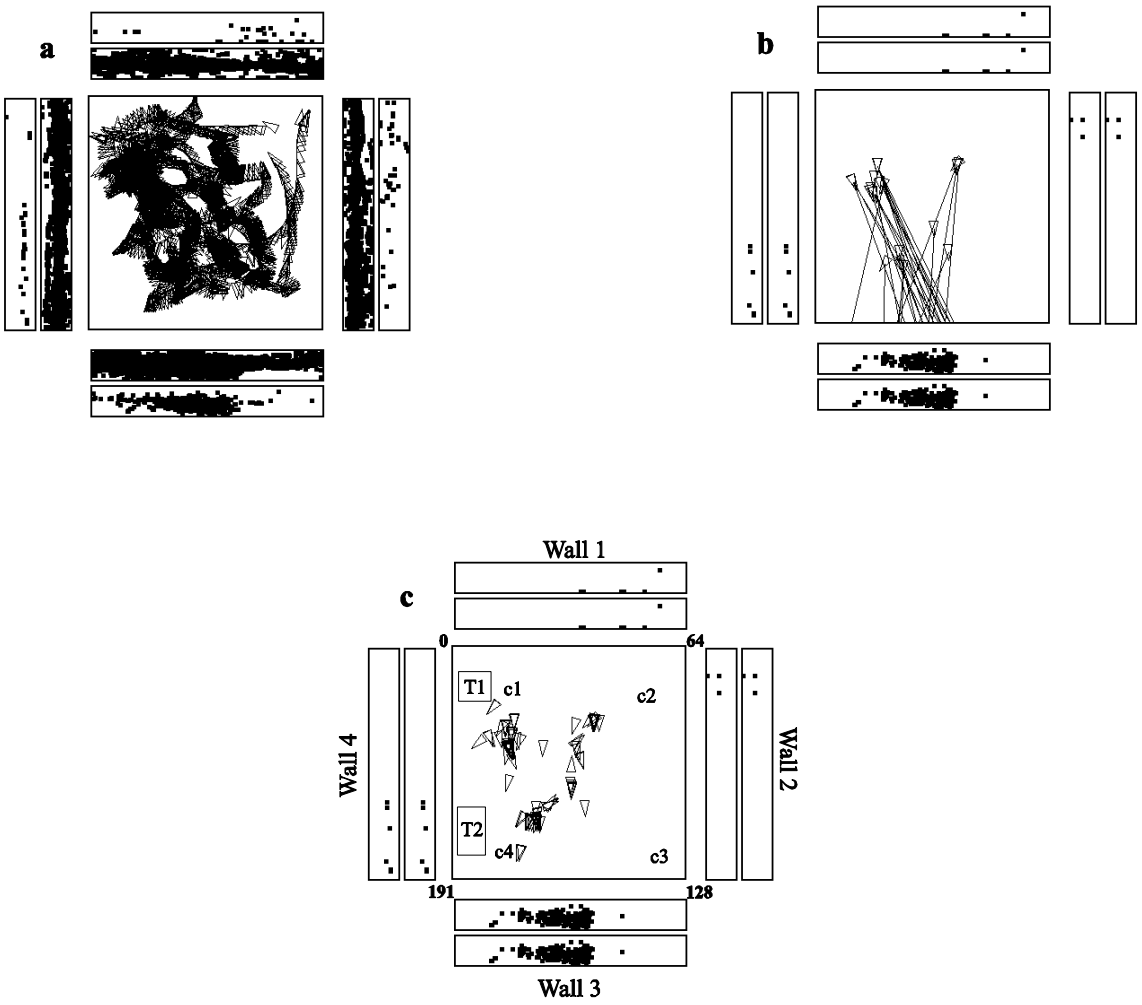

Figure 3

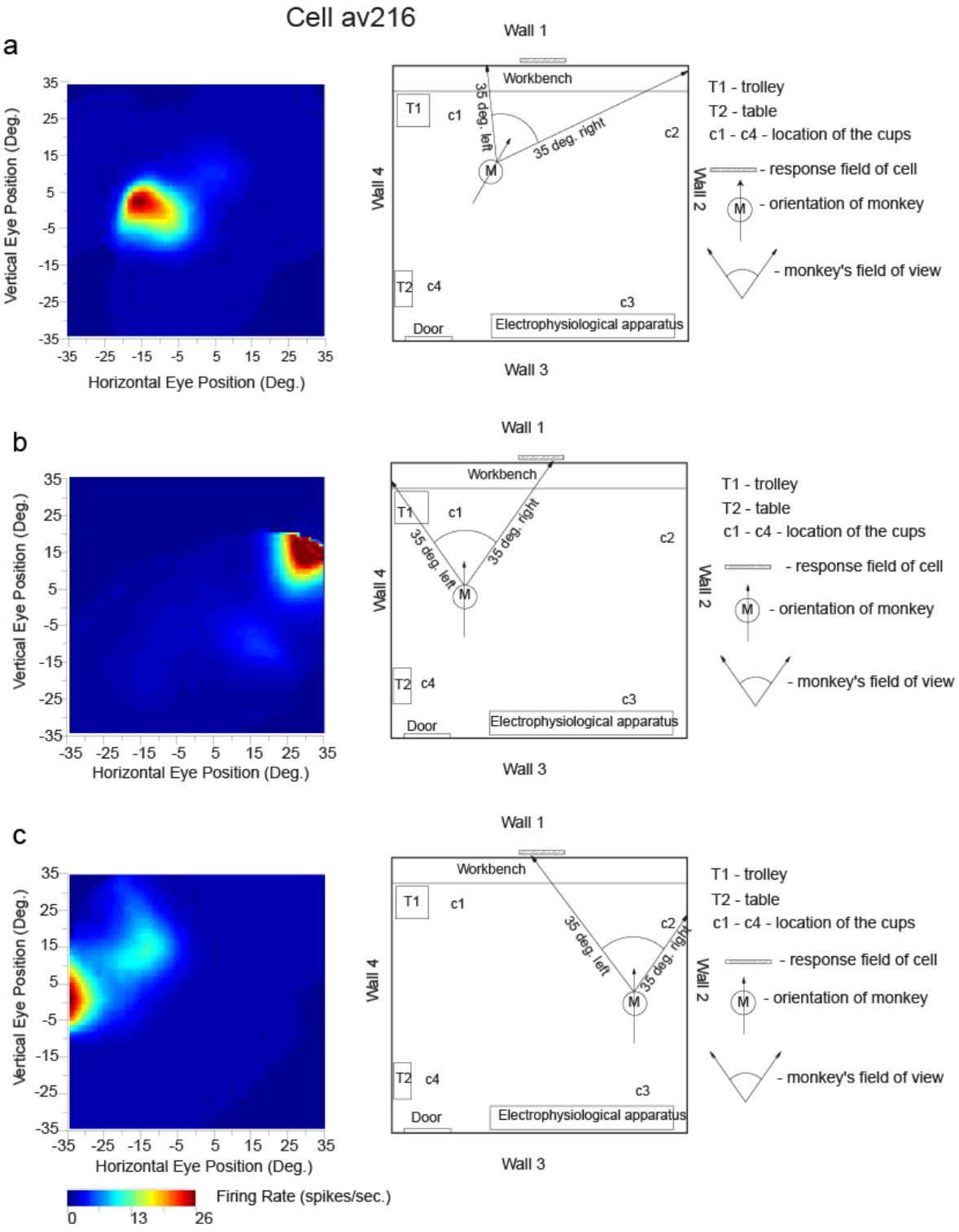
Cell av216
a
Vertical Eye Position (Deg.)
Horizontal Eye Position (Deg.)
Wall 1
Workbench
T1
c1
c2
35 deg. left
35 deg. right
M
Wall 4
Wall 2
T2
c4
c3
Door
Electrophysiological apparatus
Wall 3
T1 - trolley
T2 - table
c1 - c4 - location of the cups
- response field of cell
- orientation of monkey
- monkey's field of view
b
c
Firing Rate (spikes/sec.)
0
13
26

Figure 4

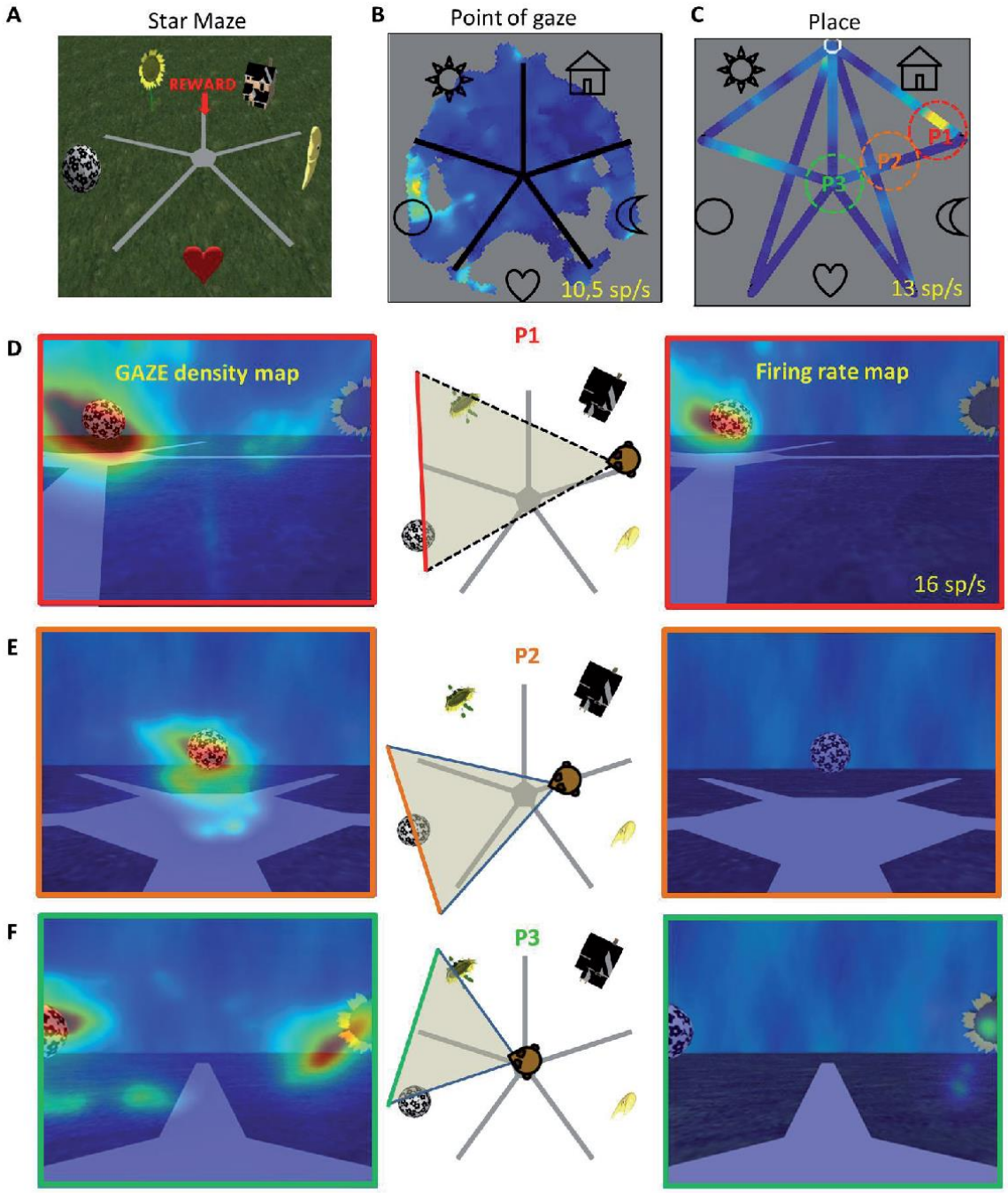
A
Star Maze
REWARD
B
Point of gaze
10,5 sp/s
C
Place
P1
P2
P3
13 sp/s
D
GAZE density map
P1
Firing rate map
16 sp/s
E
P2
F
P3

Figure 5

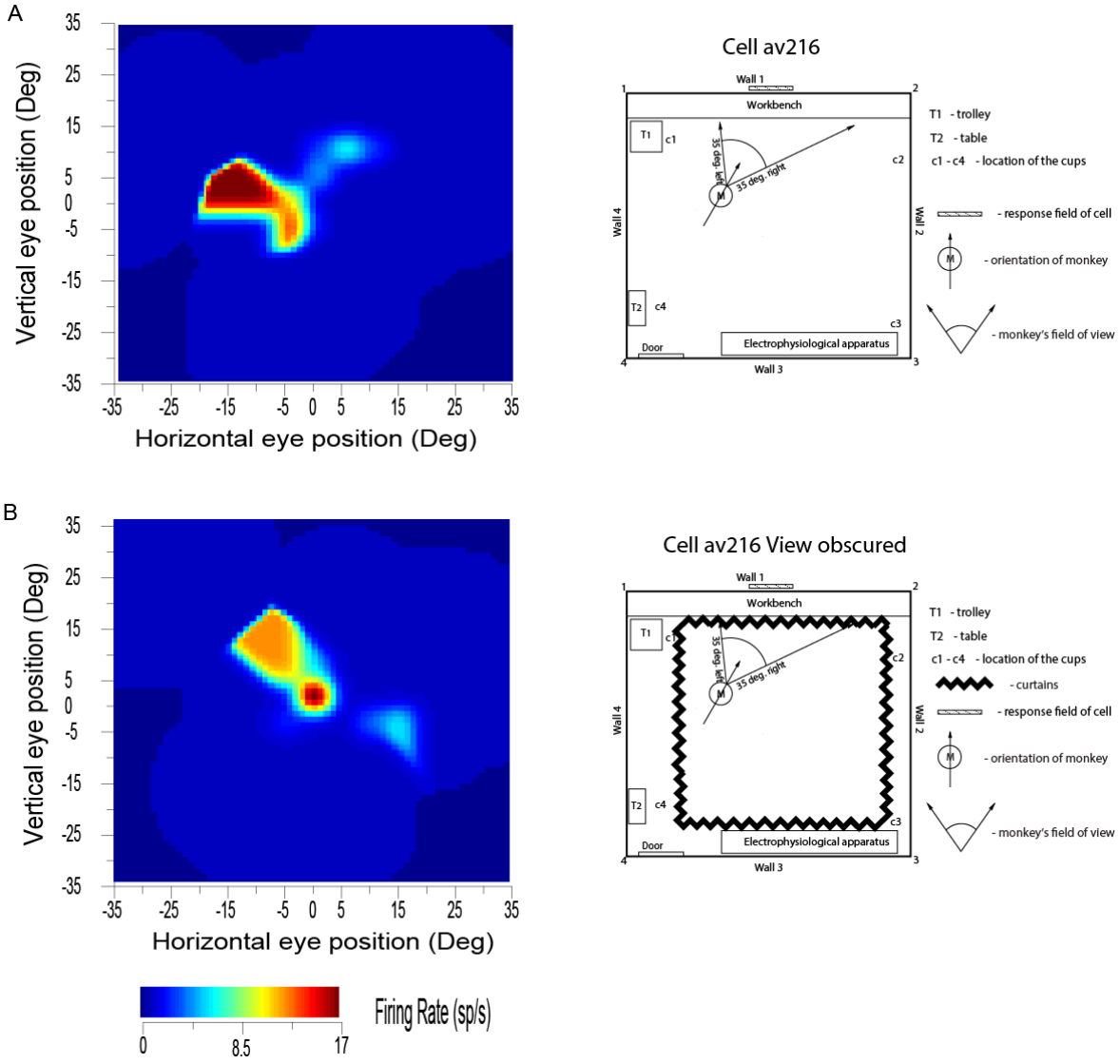
A
Vertical eye position (Deg)
Horizontal eye position (Deg)
Cell av216
Wall 1
Workbench
T1 - trolley
T2 - table
c1 - c4 - location of the cups
- response field of cell
- orientation of monkey
- monkey's field of view
Wall 4
Wall 2
Wall 3
Door
Electrophysiological apparatus
35 deg. left
35 deg. right
B
Cell av216 View obscured
- curtains
Firing Rate (sp/s)
0
8.5
17

Figure 6

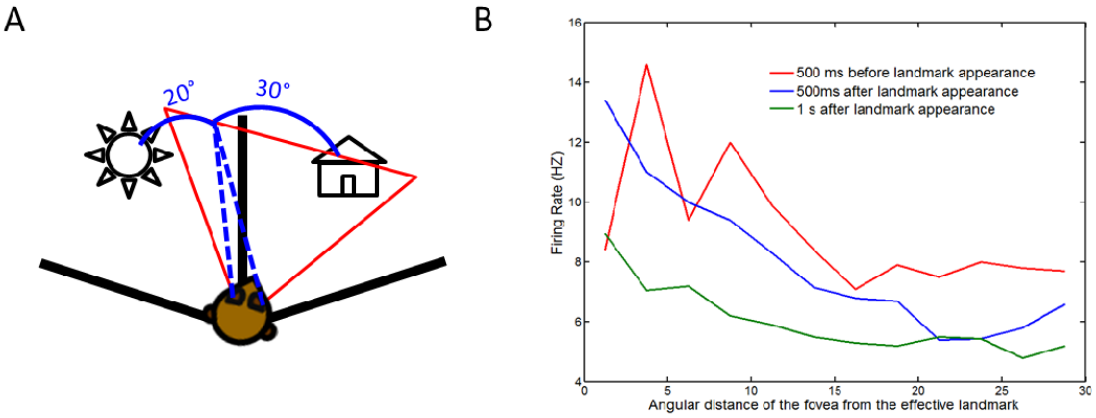
A
20°
30°
B
500 ms before landmark appearance
500ms after landmark appearance
1 s after landmark appearance
Firing Rate (HZ)
Angular distance of the fovea from the effective landmark

Figure 7

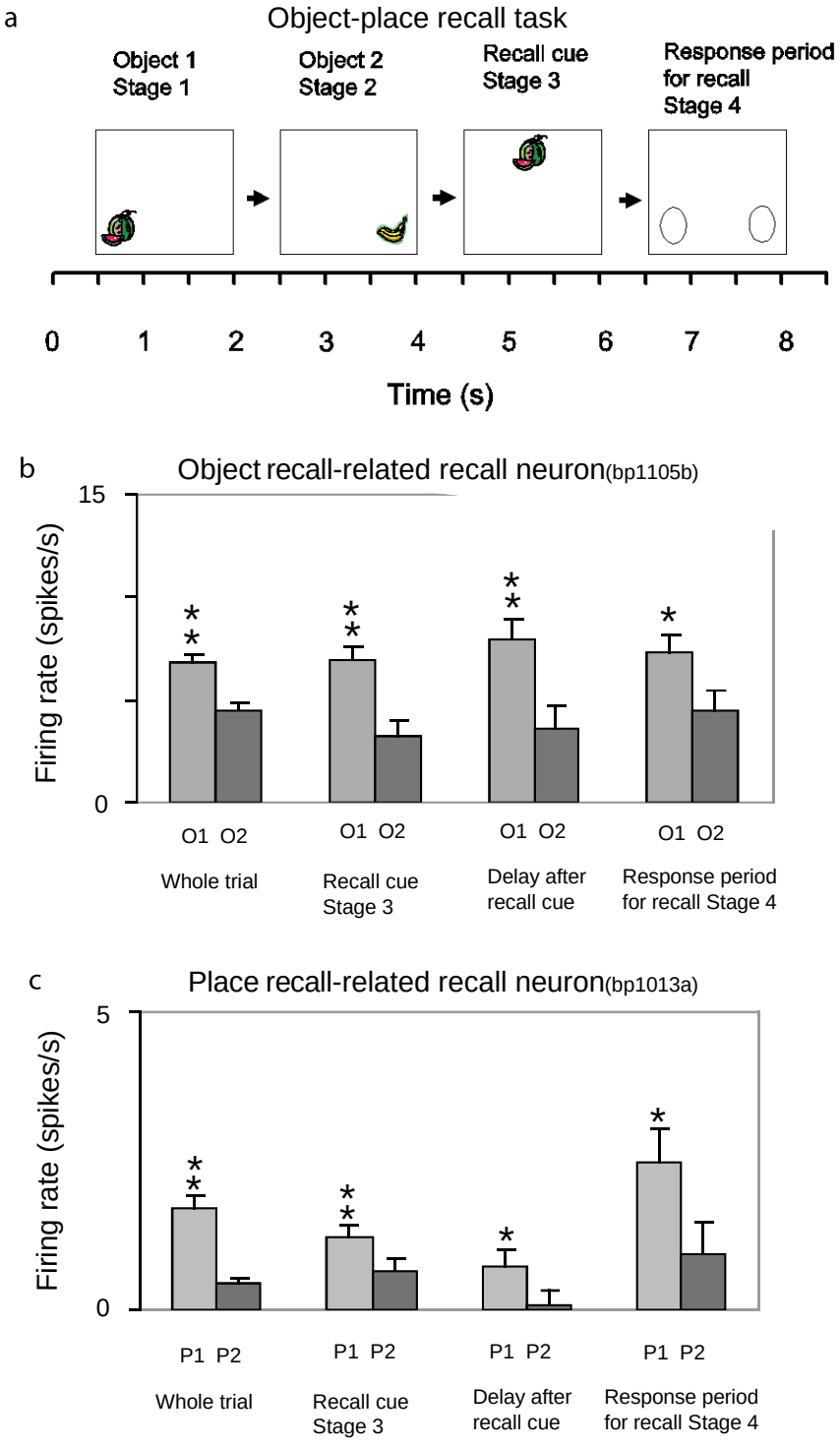
a
Object-place recall task
Object 1
Stage 1
Object 2
Stage 2
Recall cue
Stage 3
Response period
for recall
Stage 4
0 1 2 3 4 5 6 7 8
Time (s)
b
Object recall-related recall neuron(bp1105b)
15
0
Firing rate (spikes/s)
O1 O2
Whole trial
Recall cue
Stage 3
Delay after
recall cue
Response period
for recall Stage 4
c
Place recall-related recall neuron(bp1013a)
5
0
Firing rate (spikes/s)
P1 P2
Whole trial
Recall cue
Stage 3
Delay after
recall cue
Response period
for recall Stage 4

Figure 8

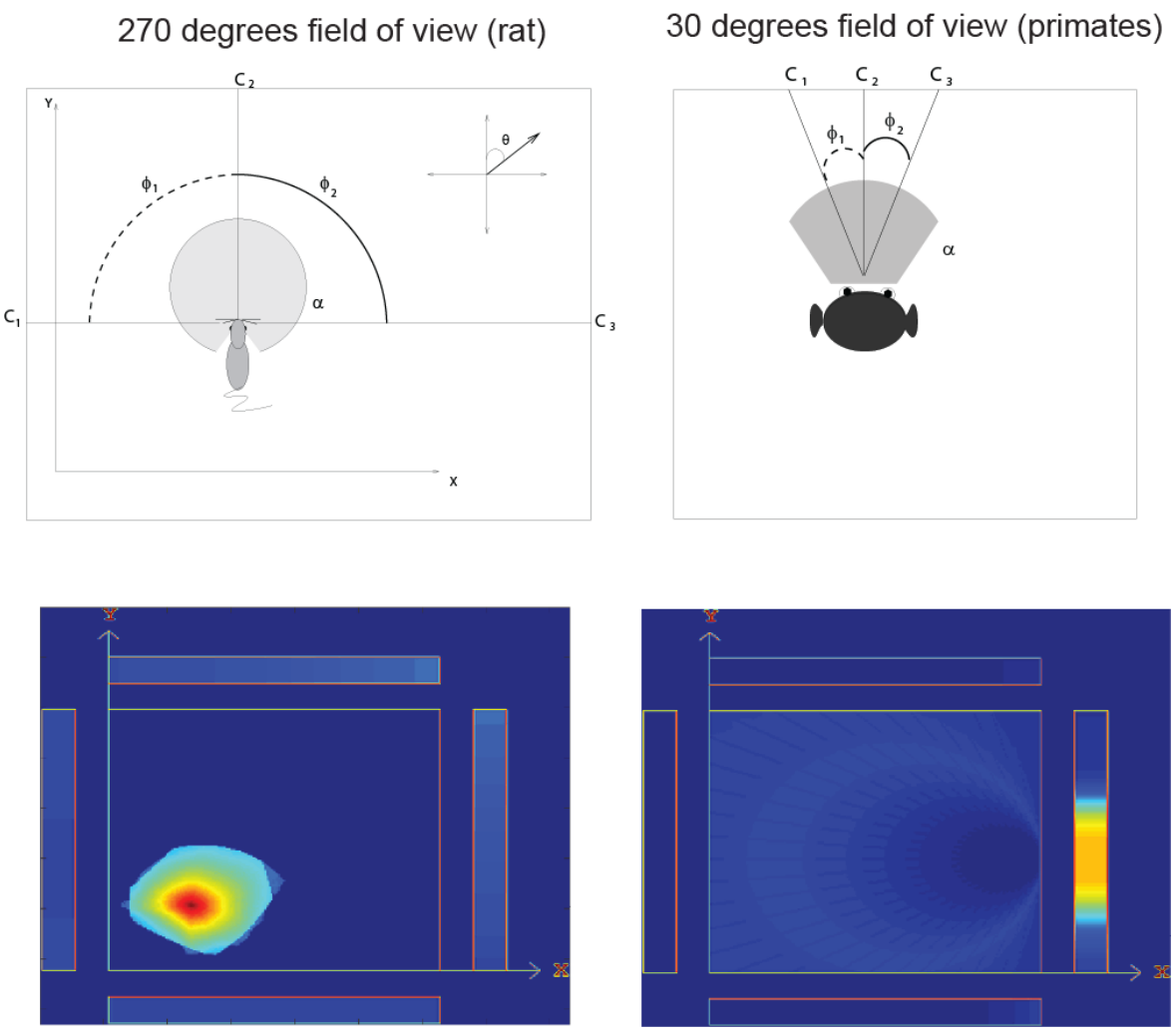
270 degrees field of view (rat)
30 degrees field of view (primates)
C2
C1
C3
ϕ1
ϕ2
α
θ
Y
x
C1
C2
C3
ϕ1
ϕ2
α

Figure 9

References

Acharya, L., Aghajan, Z. M., Vuong, C., Moore, J. J. and Mehta, M. R. (2016) Causal Influence of Visual Cues on Hippocampal Directional Selectivity. *Cell* **164,** 197-207.

Aggelopoulos, N. C., Franco, L. and Rolls, E. T. (2005) Object perception in natural scenes: encoding by inferior temporal cortex simultaneously recorded neurons. *J. Neurophysiol.* **93,** 1342-1357.

Aggelopoulos, N. C. and Rolls, E. T. (2005) Natural scene perception: inferior temporal cortex neurons encode the positions of different objects in the scene. *Eur. J. Neurosci.* **22,** 2903-2916.

Aghajan, Z. M., Acharya, L., Moore, J. J., Cushman, J. D., Vuong, C. and Mehta, M. R. (2015) Impaired spatial selectivity and intact phase precession in two-dimensional virtual reality. *Nat. Neurosci.* **18,** 121-128.

Aguirre, G. K. and D'Esposito, M. (1999) Topographical disorientation: a synthesis and taxonomy. *Brain* **122 (Pt 9),** 1613-1628.

Alexander, A. S. and Nitz, D. A. (2015) Retrosplenial cortex maps the conjunction of internal and external spaces. *Nat. Neurosci.* **18,** 1143-1151.

Amaral, D. G., Insausti, R. and Cowan, W. M. (1984) The commissural connections of the monkey hippocampal formation. *J. Comp. Neurol.* **224,** 307-336.

Amaral, D. G. and Lavenex, P. (2007) Hippocampal anatomy. In: *The Hippocampus Book*. pp. 37-114. Eds. P. Andersen, R. Morris, D. Amaral, T. V. P. Bliss, J. O'Keefe. Oxford University Press: Oxford.

Amaral, D. G., Price, J. L., Pitkanen, A. and Carmichael, S. T. (1992) Anatomical organization of the primate amygdaloid complex. In: *The Amygdala*. pp. 1-66. Ed. J. P. Aggleton. Wiley-Liss: New York.

Andersen, R. A. (1995) Coordinate transformations and motor planning in posterior parietal cortex. In: *The Cognitive Neurosciences*. pp. 519-532. Ed. M. S. Gazzaniga. MIT Press: Cambridge, Mass.

Andersen, R. A., Batista, A. P., Snyder, L. H., Buneo, C. A. and Cohen, Y. E. (2000) Programming to look and reach in the posterior parietal cortex. In: *The New Cognitive Neurosciences*. pp. 515-524. Ed. M. S. Gazzaniga. MIT Press: Cambridge, MA.

Aronov, D., Nevers, R. and Tank, D. W. (2017) Mapping of a non-spatial dimension by the hippocampal-entorhinal circuit. *Nature* **543,** 719-722.

Aronov, D. and Tank, D. W. (2014) Engagement of neural circuits underlying 2D spatial navigation in a rodent virtual reality system. *Neuron* **84,** 442-456.

Banta Lavenex, P. and Lavenex, P. (2009) Spatial memory and the monkey hippocampus: not all space is created equal. *Hippocampus* **19,** 8-19.

Barkas, L. J., Henderson, J. L., Hamilton, D. A., Redhead, E. S. and Gray, W. P. (2010) Selective temporal resections and spatial memory impairment: cue dependent lateralization effects. *Behav. Brain Res.* **208,** 535-544.

Barton, J. J. (2011) Disorders of higher visual processing. *Handb. Clin. Neurol.* **102,** 223-261.

Battaglia, F. P. and Treves, A. (1998) Attractor neural networks storing multiple space representations: a model for hippocampal place fields. *Physical Review E* **58,** 7738-7753.

Bisley, J. W. and Goldberg, M. E. (2003) Neuronal activity in the lateral intraparietal area and spatial attention. *Science* **299,** 81-86.

Bisley, J. W. and Goldberg, M. E. (2010) Attention, intention, and priority in the parietal lobe. *Annu. Rev. Neurosci.* **33,** 1-21.

Bohbot, V. D. and Corkin, S. (2007) Posterior parahippocampal place learning in H.M. *Hippocampus* **17,** 863-872.

Bonelli, S. B., Powell, R. H., Yogarajah, M., Samson, R. S., Symms, M. R., Thompson, P. J., Koepp, M. J. and Duncan, J. S. (2010) Imaging memory in temporal lobe epilepsy: predicting the effects of temporal lobe resection. *Brain* **133,** 1186-1199.

Bremmer, F., Duhamel, J. R., Ben Hamed, S. and Graf, W. (2002a) Heading encoding in the macaque ventral intraparietal area (VIP). *Eur. J. Neurosci.* **16,** 1554-1568.

Bremmer, F., Klam, F., Duhamel, J. R., Ben Hamed, S. and Graf, W. (2002b) Visual-vestibular interactive responses in the macaque ventral intraparietal area (VIP). *Eur. J. Neurosci.* **16,** 1569-1586.

Brincat, S. L. and Miller, E. K. (2015) Frequency-specific hippocampal-prefrontal interactions during associative learning. *Nat. Neurosci.* **18,** 576-581.

Brown, T. I., Carr, V. A., LaRocque, K. F., Favila, S. E., Gordon, A. M., Bowles, B., Bailenson, J. N. and Wagner, A. D. (2016) Prospective representation of navigational goals in the human hippocampus. *Science* **352,** 1323-1326.

Buffalo, E. A. (2015) Bridging the gap between spatial and mnemonic views of the hippocampal formation. *Hippocampus* **25,** 713-718.

Burgess, N. (2008) Spatial cognition and the brain. *Ann. N. Y. Acad. Sci.* **1124,** 77-97.

Burgess, N., Jackson, A., Hartley, T. and O'Keefe, J. (2000) Predictions derived from modelling the hippocampal role in navigation. *Biol. Cybern.* **83,** 301-312.

Burgess, N., Maguire, E. A. and O'Keefe, J. (2002) The human hippocampus and spatial and episodic memory. *Neuron* **35,** 625-641.

Burgess, N. and O'Keefe, J. (1996) Neuronal computations underlying the firing of place cells and their role in navigation. *Hippocampus* **6,** 749-762.

Burwell, R. D., Witter, M. P. and Amaral, D. G. (1995) Perirhinal and postrhinal cortices of the rat: a review of the neuroanatomical literature and comparison with findings from the monkey brain. *Hippocampus* **5,** 390-408.

Butler, W. N., Smith, K. S., van der Meer, M. A. A. and Taube, J. S. (2017) The Head-Direction Signal Plays a Functional Role as a Neural Compass during Navigation. *Curr. Biol.* **27,** 1259-1267.

Buzsaki, G. and Moser, E. I. (2013) Memory, navigation and theta rhythm in the hippocampal-entorhinal system. *Nat. Neurosci.* **16,** 130-138.

Byrne, P., Becker, S. and Burgess, N. (2007) Remembering the past and imagining the future: a neural model of spatial memory and imagery. *Psychol. Rev.* **114,** 340-375.

Cahusac, P. M. B., Miyashita, Y. and Rolls, E. T. (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.

Cahusac, P. M. B., Rolls, E. T., Miyashita, Y. and Niki, H. (1993) Modification of the responses of hippocampal neurons in the monkey during the learning of a conditional spatial response task.

Hippocampus **3,** 29-42.

Carmichael, S. T. and Price, J. L. (1995) Limbic connections of the orbital and medial prefrontal cortex in macaque monkeys. *J. Comp. Neurol.* **363,** 615-641.

Chadwick, M. J., Hassabis, D., Weiskopf, N. and Maguire, E. A. (2010) Decoding individual episodic memory traces in the human hippocampus. *Curr. Biol.* **20,** 544-547.

Chadwick, M. J., Mullally, S. L. and Maguire, E. A. (2013) The hippocampus extrapolates beyond the view in scenes: an fMRI study of boundary extension. *Cortex* **49,** 2067-2079.

Chen, G., King, J. A., Burgess, N. and O'Keefe, J. (2013) How vision and movement combine in the hippocampal place code. *Proc. Natl. Acad. Sci. U. S. A.* **110,** 378-383.

Cheng, W., Rolls, E. T., Qiu, J., Liu, W., Tang, Y., Huang, C. C., Wang, X., Zhang, J., Lin, W., Zheng, L., Pu, J., Tsai, S. J., Yang, A. C., Lin, C. P., Wang, F., Xie, P. and Feng, J. (2016) Medial reward and lateral non-reward orbitofrontal cortex circuits change in opposite directions in depression. *Brain* **139,** 3296-3309.

Cheng, W., Rolls, E. T., Qiu, J., Xie, X., Wei, D., Huang, C.-C., Yang, A. C., Tsai, S.-J., Li, Q., Meng, J., Lin, C. P., Xie, P. and Feng, J. (2018a) Increased functional connectivity of the posterior cingulate cortex with the lateral orbitofrontal cortex in depression. *Translational Psychiatry* **8,** 90.

Cheng, W., Rolls, E. T., Qiu, J., Yang, D., Ruan, H., Wei, D., Zhao, L., Meng, J., Xie, P. and Feng, J. (2018b) Functional connectivity of the precuneus in unmedicated patients with depression. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging***,** doi: 10.1016/j.bpsc.2018.1007.1008.

Cicero, M. T. (55 BC) *De Oratore II*. Cicero: Rome.

Clark, I. A. and Maguire, E. A. (2016) Remembering preservation in hippocampal amnesia. *Annu. Rev. Psychol.* **67,** 51-82.

Constantinescu, A. O., O'Reilly, J. X. and Behrens, T. E. J. (2016) Organizing conceptual knowledge in humans with a gridlike code. *Science* **352,** 1464-1468.

Crane, J. and Milner, B. (2005) What went where? Impaired object-location learning in patients with right hippocampal lesions. *Hippocampus* **15,** 216-231.

Crawford, M. L. (1977) Central vision of man and macaque: cone and rod sensitivity. *Brain Res.* **119,** 345-356.

Cushman, J. D., Aharoni, D. B., Willers, B., Ravassard, P., Kees, A., Vuong, C., Popeney, B., Arisaka, K. and Mehta, M. R. (2013) Multisensory control of multimodal behavior: do the legs know what the tongue is doing? *PLoS One* **8,** e80465.

Day, M., Langston, R. and Morris, R. G. (2003) Glutamate-receptor-mediated encoding and retrieval of paired-associate learning. *Nature* **424,** 205-209.

de Araujo, I. E. T., Rolls, E. T. and Stringer, S. M. (2001) A view model which accounts for the spatial fields of hippocampal primate spatial view cells and rat place cells. *Hippocampus* **11,** 699-706.

De Falco, E., Ison, M. J., Fried, I. and Quian Quiroga, R. (2016) Long-term coding of personal and universal associations underlying the memory web in the human brain. *Nat Commun* **7,** 13408.

Dere, E., Easton, A., Nadel, L. and Huston, J. P. Eds (2008) *Handbook of Episodic Memory*. Elsevier: Amsterdam.

Dombeck, D. A., Harvey, C. D., Tian, L., Looger, L. L. and Tank, D. W. (2010) Functional

imaging of hippocampal place cells at cellular resolution during virtual navigation. *Nat. Neurosci.* **13,** 1433-1440.

Eichenbaum, H. (2014) Time cells in the hippocampus: a new dimension for mapping memories. *Nat. Rev. Neurosci.* **15,** 732-744.

Eichenbaum, H., Dudchenko, P., Wood, E., Shapiro, M. and Tanila, H. (1999) The hippocampus, memory, and place cells: is it spatial memory or a memory space? *Neuron* **23,** 209-226.

Eichenbaum, H., Sauvage, M., Fortin, N., Komorowski, R. and Lipton, P. (2012) Towards a functional organization of episodic memory in the medial temporal lobe. *Neurosci. Biobehav. Rev.* **36,** 1597-1608.

Ekstrom, A. D. (2015) Why vision is important to how we navigate. *Hippocampus* **25,** 731-735.

Ekstrom, A. D., Arnold, A. E. and Iaria, G. (2014) A critical review of the allocentric spatial representation and its neural underpinnings: toward a network-based perspective. *Front. Hum. Neurosci.* **8,** 803.

Ekstrom, A. D., Kahana, M. J., Caplan, J. B., Fields, T. A., Isham, E. A., Newman, E. L. and Fried, I. (2003) Cellular networks underlying human spatial navigation. *Nature* **425,** 184-188.

Ekstrom, A. D. and Ranganath, C. (2017) Space, time, and episodic memory: The hippocampus is all over the cognitive map. *Hippocampus*.

Epstein, R. and Kanwisher, N. (1998) A cortical representation of the local visual environment. *Nature* **392,** 598-601.

Epstein, R. A. (2008) Parahippocampal and retrosplenial contributions to human spatial navigation. *Trends Cogn. Sci.* **12,** 388-396.

Euler, T. and Wassle, H. (1995) Immunocytochemical identification of cone bipolar cells in the rat retina. *J. Comp. Neurol.* **361,** 461-478.

Feigenbaum, J. D. and Rolls, E. T. (1991) Allocentric and egocentric spatial information processing in the hippocampal formation of the behaving primate. *Psychobiology* **19,** 21-40.

Ferbinteanu, J., Shirvalkar, P. and Shapiro, M. L. (2011) Memory modulates journey-dependent coding in the rat hippocampus. *J. Neurosci.* **31,** 9135-9146.

Foster, D. J. (2017) Replay Comes of Age. *Annu. Rev. Neurosci.* **40,** 581-602.

Foster, D. J. and Wilson, M. A. (2006) Reverse replay of behavioural sequences in hippocampal place cells during the awake state. *Nature* **440,** 680-683.

Foster, T. C., Castro, C. A. and McNaughton, B. L. (1989) Spatial selectivity of rat hippocampal neurons: dependence on preparedness for movement. *Science* **244,** 1580-1582.

Fried, I., MacDonald, K. A. and Wilson, C. L. (1997) Single neuron activity in human hippocampus and amygdala during recognition of faces and objects. *Neuron* **18,** 753-765.

Fried, I., Rutishauser, U., Cerf, M. and Kreiman, G. (2014) *Single Neuron Studies of the Human Brain: Probing Cognition*. MIT Press: Cambridge, MA.

Fujimichi, R., Naya, Y., Koyano, K. W., Takeda, M., Takeuchi, D. and Miyashita, Y. (2010) Unitized representation of paired objects in area 35 of the macaque perirhinal cortex. *Eur. J. Neurosci.* **32,** 659-667.

Furuya, Y., Matsumoto, J., Hori, E., Boas, C. V., Tran, A. H., Shimada, Y., Ono, T. and Nishijo, H. (2014) Place-related neuronal activity in the monkey parahippocampal gyrus and hippocampal

formation during virtual navigation. *Hippocampus* **24,** 113-130.

Fyhn, M., Molden, S., Hollup, S., Moser, M. B. and Moser, E. (2002) Hippocampal neurons responding to first-time dislocation of a target object. *Neuron* **35,** 555-566.

Gaffan, D. (1994) Scene-specific memory for objects: a model of episodic memory impairment in monkeys with fornix transection. *J. Cogn. Neurosci.* **6,** 305-320.

Gaffan, D. and Harrison, S. (1989) A comparison of the effects of fornix section and sulcus principalis ablation upon spatial learning by monkeys. *Behav. Brain Res.* **31,** 207-220.

Galletti, C. and Fattori, P. (2017) The dorsal visual stream revisited: Stable circuits or dynamic pathways? *Cortex*.

Georges-François, P., Rolls, E. T. and Robertson, R. G. (1999) Spatial view cells in the primate hippocampus: allocentric view not head direction or eye position or place. *Cereb. Cortex* **9,** 197-212.

Gnadt, J. W. and Andersen, R. A. (1988) Memory related motor planning activity in posterior parietal cortex of macaque. *Exp. Brain Res.* **70,** 216-220.

Goodale, M. A. (2014) How (and why) the visual control of action differs from visual perception. *Proc. Biol. Sci.* **281,** 20140337.

Habib, M. and Sirigu, A. (1987) Pure topographical disorientation: a definition and anatomical basis. *Cortex* **23,** 73-85.

Hampton, R. R., Hampstead, B. M. and Murray, E. A. (2004) Selective hippocampal damage in rhesus monkeys impairs spatial memory in an open-field test. *Hippocampus* **14,** 808-818.

Hannula, D. E. and Ranganath, C. (2009) The eyes have it: hippocampal activity predicts expression of memory in eye movements. *Neuron* **63,** 592-599.

Hartley, T., Lever, C., Burgess, N. and O'Keefe, J. (2014) Space in the brain: how the hippocampal formation supports spatial cognition. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **369,** 20120510.

Harvey, C. D., Collman, F., Dombeck, D. A. and Tank, D. W. (2009) Intracellular dynamics of hippocampal place cells during virtual navigation. *Nature* **461,** 941-946.

Hassabis, D., Chu, C., Rees, G., Weiskopf, N., Molyneux, P. D. and Maguire, E. A. (2009) Decoding neuronal ensembles in the human hippocampus. *Curr. Biol.* **19,** 546-554.

Hinman, J. R., Brandon, M. P., Climer, J. R., Chapman, G. W. and Hasselmo, M. E. (2016) Multiple running speed signals in medial entorhinal cortex. *Neuron* **91,** 666-679.

Hirabayashi, T., Takeuchi, D., Tamura, K. and Miyashita, Y. (2013) Functional microcircuit recruited during retrieval of object association memory in monkey perirhinal cortex. *Neuron* **77,** 192-203.

Hirshhorn, M., Grady, C., Rosenbaum, R. S., Winocur, G. and Moscovitch, M. (2012) The hippocampus is involved in mental navigation for a recently learned, but not a highly familiar environment: a longitudinal fMRI study. *Hippocampus* **22,** 842-852.

Hoffman, K. L., Dragan, M. C., Leonard, T. K., Micheli, C., Montefusco-Siegmund, R. and Valiante, T. A. (2013) Saccades during visual exploration align hippocampal 3-8 Hz rhythms in human and non-human primates. *Front. Syst. Neurosci.* **7,** 43.

Hölscher, C., Jacob, W. and Mallot, H. A. (2003) Reward modulates neuronal activity in the hippocampus of the rat. *Behav. Brain Res.* **142,** 181-191.

Holscher, C., Schnee, A., Dahmen, H., Setia, L. and Mallot, H. A. (2005) Rats are able to navigate in virtual environments. *J. Exp. Biol.* **208,** 561-569.

Hori, E., Nishio, Y., Kazui, K., Umeno, K., Tabuchi, E., Sasaki, K., Endo, S., Ono, T. and Nishijo, H. (2005) Place-related neural responses in the monkey hippocampal formation in a virtual space. *Hippocampus* **15,** 991-996.

Howard, M. W. and Eichenbaum, H. (2015) Time and space in the hippocampus. *Brain Res.* **1621,** 345-354.

Howard, M. W., MacDonald, C. J., Tiganj, Z., Shankar, K. H., Du, Q., Hasselmo, M. E. and Eichenbaum, H. (2014) A unified mathematical framework for coding time, space, and sequences in the hippocampal region. *J. Neurosci.* **34,** 4692-4707.

Hughes, A. (1979) A schematic eye for the rat. *Vision Res.* **19,** 569-588.

Ison, M. J., Quian Quiroga, R. and Fried, I. (2015) Rapid Encoding of New Memories by Individual Neurons in the Human Brain. *Neuron* **87,** 220-230.

Itskov, P. M., Vinnik, E. and Diamond, M. E. (2011) Hippocampal representation of touch-guided behavior in rats: persistent and independent traces of stimulus and reward location. *PLoS One* **6,** e16462.

Jacobs, J., Weidemann, C. T., Miller, J. F., Solway, A., Burke, J. F., Wei, X. X., Suthana, N., Sperling, M. R., Sharan, A. D., Fried, I. and Kahana, M. J. (2013) Direct recordings of grid-like neuronal activity in human spatial navigation. *Nat. Neurosci.* **16,** 1188-1190.

Jeffery, K. J., Donnett, J. G., Burgess, N. and O'Keefe, J. M. (1997) Directional control of hippocampal place fields. *Exp. Brain Res.* **117,** 131-142.

Julian, J. B., Keinath, A. T., Frazzetta, G. and Epstein, R. A. (2018) Human entorhinal cortex represents visual space using a boundary-anchored grid. *Nat. Neurosci.* **21,** 191-194.

Julian, J. B., Ryan, J., Hamilton, R. H. and Epstein, R. A. (2016) The Occipital Place Area Is Causally Involved in Representing Environmental Boundaries during Navigation. *Curr. Biol.* **26,** 1104-1109.

Jutras, M. J., Fries, P. and Buffalo, E. A. (2013) Oscillatory activity in the monkey hippocampus during visual exploration and memory formation. *Proc. Natl. Acad. Sci. U. S. A.* **110,** 13144-13149.

Kaas, J. H. (2013) The evolution of the visual system in primates. In: *The New Visual Neurosciences*. Eds. J. Werner, L. Chalupa. MIT Press: Cambridge, MA.

Kesner, R. P., Hunsaker, M. R. and Warthen, M. W. (2008) The CA3 subregion of the hippocampus is critical for episodic memory processing by means of relational encoding in rats. *Behav. Neurosci.* **122,** 1217-1225.

Kesner, R. P. and Rolls, E. T. (2015) A computational theory of hippocampal function, and tests of the theory: new developments. *Neurosci. Biobehav. Rev.* **48,** 92-147.

Killian, N. J., Jutras, M. J. and Buffalo, E. A. (2012) A map of visual space in the primate entorhinal cortex. *Nature* **491,** 761-764.

Kim, J., Delcasso, S. and Lee, I. (2011) Neural correlates of object-in-place learning in hippocampus and prefrontal cortex. *J. Neurosci.* **31,** 16991-17006.

Kim, J. G., Aminoff, E. M., Kastner, S. and Behrmann, M. (2015) A Neural Basis for Developmental Topographic Disorientation. *J. Neurosci.* **35,** 12954-12969.

Knierim, J. J. and Rao, G. (2003) Distal landmarks and hippocampal place cells: effects of relative translation versus rotation. *Hippocampus* **13,** 604-617.

Kolb, B. and Whishaw, I. Q. (2015) *Fundamentals of Human Neuropsychology*. Worth: New York.

Komorowski, R. W., Manns, J. R. and Eichenbaum, H. (2009) Robust conjunctive item-place coding by hippocampal neurons parallels learning what happens where. *J. Neurosci.* **29,** 9918-9929.

Kondo, H., Lavenex, P. and Amaral, D. G. (2009) Intrinsic connections of the macaque monkey hippocampal formation: II. CA3 connections. *J. Comp. Neurol.* **515,** 349-377.

Kornblith, S., Cheng, X., Ohayon, S. and Tsao, D. Y. (2013) A network for scene processing in the macaque temporal lobe. *Neuron* **79,** 766-781.

Kreiman, G., Koch, C. and Fried, I. (2000) Category-specific visual responses of single neurons in the human medial temporal lobe. *Nat. Neurosci.* **3,** 946-953.

Kropff, E., Carmichael, J. E., Moser, M. B. and Moser, E. I. (2015) Speed cells in the medial entorhinal cortex. *Nature* **523,** 419-424.

Kropff, E. and Treves, A. (2008) The emergence of grid cells: Intelligent design or just adaptation? *Hippocampus* **18,** 1256-1269.

Leonard, T. K. and Hoffman, K. L. (2017) Sharp-wave ripples in primates are enhanced near remembered visual objects. *Curr. Biol.* **27,** 257-262.

Leutgeb, S., Leutgeb, J. K., Barnes, C. A., Moser, E. I., McNaughton, B. L. and Moser, M. B. (2005) Independent codes for spatial and episodic memory in hippocampal neuronal ensembles. *Science* **309,** 619-623.

Liu, Z. X., Shen, K., Olsen, R. K. and Ryan, J. D. (2017) Visual Sampling Predicts Hippocampal Activity. *J. Neurosci.* **37,** 599-609.

Ludvig, N., Tang, H. M., Gohil, B. C. and Botero, J. M. (2004) Detecting location-specific neuronal firing rate increases in the hippocampus of freely-moving monkeys. *Brain Res.* **1014,** 97-109.

Macdonald, C. J., Lepage, K. Q., Eden, U. T. and Eichenbaum, H. (2011) Hippocampal "time cells" bridge the gap in memory for discontiguous events. *Neuron* **71,** 737-749.

Maguire, E. A. (2001) The retrosplenial contribution to human navigation: a review of lesion and neuroimaging findings. *Scand. J. Psychol.* **42,** 225-238.

Maguire, E. A. (2014) Memory consolidation in humans: new evidence and opportunities. *Exp. Physiol.* **99,** 471-486.

Maguire, E. A., Intraub, H. and Mullally, S. L. (2016) Scenes, spaces, and memory traces: what does the hippocampus do? *Neuroscientist* **22,** 432-439.

Malkova, L. and Mishkin, M. (2003) One-trial memory for object-place associations after separate lesions of hippocampus and posterior parahippocampal region in the monkey. *J. Neurosci.* **23,** 1956-1965.

Markus, E. J., Qin, Y. L., Leonard, B., Skaggs, W., McNaughton, B. L. and Barnes, C. A. (1995) Interactions between location and task affect the spatial and directional firing of hippocampal neurons. *J. Neurosci.* **15,** 7079-7094.

McClelland, J. L., McNaughton, B. L. and O'Reilly, R. C. (1995) Why there are complementary

learning systems in the hippocampus and neocortex: insights from the successes and failures of connectionist models of learning and memory. *Psychol. Rev.* **102,** 419-457.

McClelland, J. L. and Rumelhart, D. E. (1986) A distributed model of human learning and memory. In: *Parallel Distributed Processing*. pp. 170-215. Eds. J. L. McClelland, D. E. Rumelhart. MIT Press: Cambridge, Mass.

McNaughton, B. L., Barnes, C. A. and 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.

McNaughton, B. L., Chen, L. L. and Markus, E. J. (1991) "Dead reckoning", landmark learning, and the sense of direction: a neurophysiological and computational hypothesis. *J. Cogn. Neurosci.* **3,** 190-202.

Mehta, M. R., Quirk, M. C. and Wilson, M. A. (2000) Experience-dependent asymmetric shape of hippocampal receptive fields. *Neuron* **25,** 707-715.

Meister, M. L. and Buffalo, E. A. (2016) Getting directions from the hippocampus: The neural connection between looking and memory. *Neurobiol. Learn. Mem.* **134 Pt A,** 135-144.

Meister, M. L. R. and Buffalo, E. A. (2018) Neurons in primate entorhinal cortex represent gaze position in multiple spatial reference frames. *J. Neurosci.*

Miller, J. F., Neufang, M., Solway, A., Brandt, A., Trippel, M., Mader, I., Hefft, S., Merkow, M., Polyn, S. M., Jacobs, J., Kahana, M. J. and Schulze-Bonhage, A. (2013) Neural activity in human hippocampal formation reveals the spatial context of retrieved memories. *Science* **342,** 1111-1114.

Minderer, M., Harvey, C. D., Donato, F. and Moser, E. I. (2016) Neuroscience: Virtual reality explored. *Nature* **533,** 324-325.

Miyashita, Y., Rolls, E. T., Cahusac, P. M., Niki, H. and Feigenbaum, J. D. (1989) Activity of hippocampal formation neurons in the monkey related to a conditional spatial response task. *J. Neurophysiol.* **61,** 669-678.

Morris, R. G., Garrud, P., Rawlins, J. N. and O'Keefe, J. (1982) Place navigation impaired in rats with hippocampal lesions. *Nature* **297,** 681-683.

Moser, M. B., Rowland, D. C. and Moser, E. I. (2015) Place cells, grid cells, and memory. *Cold Spring Harb. Perspect. Biol.* **7,** a021808.

Muller, R. U., Bostock, E., Taube, J. S. and Kubie, J. L. (1994) On the directional firing properties of hippocampal place cells. *J. Neurosci* **14,** 7235-7251.

Muller, R. U., Kubie, J. L., Bostock, E. M., Taube, J. S. and Quirk, G. J. (1991) Spatial firing correlates of neurons in the hippocampal formation of freely moving rats. In: *Brain and Space*. pp. 296-333. Ed. J. Paillard. Oxford University Press: Oxford.

Murray, E. A., Baxter, M. G. and Gaffan, D. (1998) Monkeys with rhinal cortex damage or neurotoxic hippocampal lesions are impaired on spatial scene learning and object reversals. *Behav. Neurosci.* **112,** 1291-1303.

Murray, E. A., Wise, S. P. and Graham, K. S. (2017) Representational specializations of the hippocampus in phylogenetic perspective. *Neurosci. Lett.,* 10.1016/j.neulet.2017.1004.1065.

Nadasdy, Z., Nguyen, T. P., Torok, A., Shen, J. Y., Briggs, D. E., Modur, P. N. and Buchanan, R. J. (2017) Context-dependent spatially periodic activity in the human entorhinal cortex. *Proc. Natl. Acad. Sci. U. S. A.* **114,** E3516-E3525.

Nasr, S., Liu, N., Devaney, K. J., Yue, X., Rajimehr, R., Ungerleider, L. G. and Tootell, R. B.

(2011) Scene-selective cortical regions in human and nonhuman primates. *J. Neurosci.* **31,** 13771-13785.

Nau, M., Navarro Schroder, T., Bellmund, J. L. S. and Doeller, C. F. (2018) Hexadirectional coding of visual space in human entorhinal cortex. *Nat. Neurosci.*

Navratilova, Z., Hoang, L. T., Schwindel, C. D., Tatsuno, M. and McNaughton, B. L. (2012) Experience-dependent firing rate remapping generates directional selectivity in hippocampal place cells. *Front Neural Circuits* **6,** 6.

Naya, Y. and Suzuki, W. A. (2009) Temporal dynamics of neuronal activity in macaque medial temporal lobe during a temporal-order-memory task. *Society for Neuroscience Abstracts* **192.4**.

Naya, Y., Yoshida, M. and Miyashita, Y. (2001) Backward spreading of memory-retrieval signal in the primate temporal cortex. *Science* **291,** 661-664.

Nowicka, A. and Ringo, J. L. (2000) Eye position-sensitive units in hippocampal formation and in inferotemporal cortex of the macaque monkey. *Eur. J. Neurosci.* **12,** 751-759.

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

O'Keefe, J. (1984) Spatial memory within and without the hippocampal system. In: *Neurobiology of the Hippocampus*. pp. 375-403. Ed. W. Seifert. Academic Press: London.

O'Keefe, J. (1991) The hippocampal cognitive map and navigational strategies. In: *Brain and Space*. pp. 273-295. Ed. J. Paillard. Oxford University Press: Oxford.

O'Keefe, J., Burgess, N., Donnett, J. G., Jeffery, K. J. and Maguire, E. A. (1998) Place cells, navigational accuracy, and the human hippocampus. *Philosophical Transactions of the Royal Society B* **353,** 1333-1340.

O'Mara, S. M., Rolls, E. T., Berthoz, A. and Kesner, R. P. (1994) Neurons responding to whole-body motion in the primate hippocampus. *J. Neurosci.* **14,** 6511-6523.

Olafsdottir, H. F., Barry, C., Saleem, A. B., Hassabis, D. and Spiers, H. J. (2015) Hippocampal place cells construct reward related sequences through unexplored space. *Elife* **4,** e06063.

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

Panzeri, S., Schultz, S. R., Treves, A. and Rolls, E. T. (1999) Correlations and the encoding of information in the nervous system. *Proceedings of the Royal Society of London B* **266,** 1001-1012.

Parkinson, J. K., Murray, E. A. and Mishkin, M. (1988) A selective mnemonic role for the hippocampus in monkeys: memory for the location of objects. *J. Neurosci.* **8,** 4059-4167.

Payne, H. L. and Raymond, J. L. (2017) Magnetic eye tracking in mice. *Elife* **6**.

Pfeiffer, B. E. and Foster, D. J. (2013) Hippocampal place-cell sequences depict future paths to remembered goals. *Nature* **497,** 74-79.

Pitkanen, A., Kelly, J. L. and Amaral, D. G. (2002) Projections from the lateral, basal, and accessory basal nuclei of the amygdala to the entorhinal cortex in the macaque monkey. *Hippocampus* **12,** 186-205.

Prusky, G. T. and Douglas, R. M. (2004) Characterization of mouse cortical spatial vision. *Vision Res.* **44,** 3411-3418.

Quirk, G. J., Muller, R. U. and Kubie, J. L. (1990) The firing of hippocampal place cells in the dark depends on the rat's recent experience. *J. Neurosci.* **10,** 2008-2017.

Quiroga, R. Q. (2012) Concept cells: the building blocks of declarative memory functions. *Nat. Rev. Neurosci.* **13,** 587-597.

Quiroga, R. Q., Reddy, L., Kreiman, G., Koch, C. and Fried, I. (2005) Invariant visual representation by single neurons in the human brain. *Nature* **435,** 1102-1107.

Ravassard, P., Kees, A., Willers, B., Ho, D., Aharoni, D. A., Cushman, J., Aghajan, Z. M. and Mehta, M. R. (2013) Multisensory control of hippocampal spatiotemporal selectivity. *Science* **340,** 1342-1346.

Rey, H. G., Ison, M. J., Pedreira, C., Valentin, A., Alarcon, G., Selway, R., Richardson, M. P. and Quian Quiroga, R. (2015) Single-cell recordings in the human medial temporal lobe. *J. Anat.* **227,** 394-408.

Ringo, J. L., Sobotka, S., Diltz, M. D. and Bunce, C. M. (1994) Eye movements modulate activity in hippocampal, parahippocampal, and inferotemporal neurons. *J. Neurophysiol.* **71,** 1285-1288.

Rivard, B., Li, Y., Lenck-Santini, P. P., Poucet, B. and Muller, R. U. (2004) Representation of objects in space by two classes of hippocampal pyramidal cells. *J. Gen. Physiol.* **124,** 9-25.

Robertson, R. G., Rolls, E. T. and Georges-François, P. (1998) Spatial view cells in the primate hippocampus: Effects of removal of view details. *J. Neurophysiol.* **79,** 1145-1156.

Robertson, R. G., Rolls, E. T., Georges-François, P. and Panzeri, S. (1999) Head direction cells in the primate pre-subiculum. *Hippocampus* **9,** 206-219.

Rolls, E. T. (1987) Information representation, processing and storage in the brain: analysis at the single neuron level. In: *The Neural and Molecular Bases of Learning*. pp. 503-540. Eds. J.-P. Changeux, M. Konishi. Wiley: Chichester.

Rolls, E. T. (1989) Functions of neuronal networks in the hippocampus and neocortex in memory. In: *Neural Models of Plasticity: Experimental and Theoretical Approaches*. pp. 240-265. Eds. J. H. Byrne, W. O. Berry. Academic Press: San Diego.

Rolls, E. T. (1990) Theoretical and neurophysiological analysis of the functions of the primate hippocampus in memory. *Cold Spring Harbor Symposia in Quantitative Biology* **55,** 995-1006.

Rolls, E. T. (1995) A model of the operation of the hippocampus and entorhinal cortex in memory. *Int. J. Neural Syst.* **6,** 51-70.

Rolls, E. T. (1996) A theory of hippocampal function in memory. *Hippocampus* **6,** 601-620.

Rolls, E. T. (2003) Consciousness absent and present: a neurophysiological exploration. *Prog. Brain Res.* **144,** 95-106.

Rolls, E. T. (2005) Head direction and spatial view cells in primates, and brain mechanisms for path integration and episodic memory. In: *Head Direction Cells and the Neural Mechanisms of Spatial Orientation*. pp. 299-318, Chapter 214. Eds. S. I. Wiener, J. S. Taube. MIT Press: Cambridge, MA.

Rolls, E. T. (2012) Invariant visual object and face recognition: neural and computational bases, and a model, VisNet. *Front. Comput. Neurosci.* **6, 35,** 1-70.

Rolls, E. T. (2013) The mechanisms for pattern completion and pattern separation in the hippocampus. *Front. Syst. Neurosci.* **7,** 74.

Rolls, E. T. (2014) *Emotion and Decision-Making Explained*. Oxford University Press: Oxford.

Rolls, E. T. (2015) Limbic systems for emotion and for memory, but no single limbic system. *Cortex* **62,** 119-157.

Rolls, E. T. (2016a) *Cerebral Cortex: Principles of Operation*. Oxford University Press: Oxford.

Rolls, E. T. (2016b) A non-reward attractor theory of depression. *Neurosci. Biobehav. Rev.* **68,** 47-58.

Rolls, E. T. (2017a) The orbitofrontal cortex and emotion in health and disease, including depression. *Neuropsychologia* doi: 10.1016/j.neuropsychologia.2017.1009.1021.

Rolls, E. T. (2017b) A scientific theory of ars memoriae: spatial view cells in a continuous attractor network with linked items. *Hippocampus* **27,** 570-579.

Rolls, E. T. (2018a) *The Brain, Emotion, and Depression*. Oxford University Press: Oxford.

Rolls, E. T. (2018b) The storage and recall of memories in the hippocampo-cortical system. *Cell Tissue Res.* **373,** 577-604.

Rolls, E. T., Aggelopoulos, N. C. and Zheng, F. (2003) The receptive fields of inferior temporal cortex neurons in natural scenes. *J. Neurosci.* **23,** 339-348.

Rolls, E. T., Cheng, W., Gilson, M., Qiu, J., Hu, Z., Ruan, H., Li, Y., Huang, C. C., Yang, A. C., Tsai, S. J., Zhang, X., Zhuang, K., Lin, C. P., Deco, G., Xie, P. and Feng, J. (2018) Effective Connectivity in Depression. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging* **3,** 187-197.

Rolls, E. T. and Deco, G. (2002) *Computational Neuroscience of Vision*. Oxford University Press: Oxford.

Rolls, E. T., Judge, S. J. and Sanghera, M. (1977) Activity of neurones in the inferotemporal cortex of the alert monkey. *Brain Res.* **130,** 229-238.

Rolls, E. T. and Kesner, R. P. (2006) A computational theory of hippocampal function, and empirical tests of the theory. *Prog. Neurobiol.* **79,** 1-48.

Rolls, E. T., Miyashita, Y., Cahusac, P. M. B., Kesner, R. P., Niki, H., Feigenbaum, J. and 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, E. T. and O'Mara, S. (1993) Neurophysiological and theoretical analysis of how the primate hippocampus functions in memory. In: *Brain Mechanisms of Perception and Memory: from Neuron to Behavior*. pp. 276-300. Eds. T. Ono, L. R. Squire, M. E. Raichle, D. I. Perrett, M. Fukuda. Oxford University Press: New York.

Rolls, E. T. and O'Mara, S. M. (1995) View-responsive neurons in the primate hippocampal complex. *Hippocampus* **5,** 409-424.

Rolls, E. T., Robertson, R. G. and Georges-François, P. (1997a) Spatial view cells in the primate hippocampus. *Eur. J. Neurosci.* **9,** 1789-1794.

Rolls, E. T., Robertson, R. G. and Georges-François, P. (1997b) Spatial view cells in the primate hippocampus: effect of removal of view details. *Society for Neuroscience Abstracts* **23,** 765.

Rolls, E. T. and Stringer, S. M. (2005) Spatial view cells in the hippocampus, and their idiothetic update based on place and head direction. *Neural Netw.* **18,** 1229-1241.

Rolls, E. T., Stringer, S. M. and Elliot, T. (2006) Entorhinal cortex grid cells can map to hippocampal place cells by competitive learning. *Network: Computation in Neural Systems* **17,** 447-465.

Rolls, E. T., Stringer, S. M. and Trappenberg, T. P. (2002) A unified model of spatial and episodic memory. *Proceedings of the Royal Society of London B* **269,** 1087-1093.

Rolls, E. T. and Tovee, M. J. (1994) Processing speed in the cerebral cortex and the neurophysiology of visual masking. *Proceedings of the Royal Society of London B* **257,** 9-15.

Rolls, E. T. and Treves, A. (1998) *Neural Networks and Brain Function*. Oxford University Press: Oxford.

Rolls, E. T. and Treves, A. (2011) The neuronal encoding of information in the brain. *Prog. Neurobiol.* **95,** 448-490.

Rolls, E. T., Treves, A., Robertson, R. G., Georges-François, P. and Panzeri, S. (1998) Information about spatial view in an ensemble of primate hippocampal cells. *J. Neurophysiol.* **79,** 1797-1813.

Rolls, E. T. and Webb, T. J. (2014) Finding and recognising objects in natural scenes: complementary computations in the dorsal and ventral visual systems. *Front. Comput. Neurosci.* **8,** 85.

Rolls, E. T. and Xiang, J.-Z. (2005) Reward-spatial view representations and learning in the hippocampus. *J. Neurosci.* **25,** 6167– 6174.

Rolls, E. T. and Xiang, J.-Z. (2006) Spatial view cells in the primate hippocampus, and memory recall. *Rev. Neurosci.* **17,** 175-200.

Rolls, E. T., Xiang, J.-Z. and Franco, L. (2005) Object, space and object-space representations in the primate hippocampus. *J. Neurophysiol.* **94,** 833-844.

Rueckemann, J. W. and Buffalo, E. A. (2017) Spatial responses, immediate experience, and memory in the monkey hippocampus. *Current Opinion in Behavioral Sciences* **17,** 155-160.

Sakon, J. J., Naya, Y., Wirth, S. and Suzuki, W. A. (2014) Context-dependent incremental timing cells in the primate hippocampus. *Proc. Natl. Acad. Sci. U. S. A.* **111,** 18351-18356.

Sato, N., Sakata, H., Tanaka, Y. and Taira, M. (2004) Navigation in virtual environment by the macaque monkey. *Behav. Brain Res.* **153,** 287-291.

Schultz, S. and Rolls, E. T. (1999) Analysis of information transmission in the Schaffer collaterals. *Hippocampus* **9,** 582-598.

Shapiro, M. L., Tanila, H. and Eichenbaum, H. (1997) Cues that hippocampal place cells encode: dynamic and hierarchical representation of local and distal stimuli. *Hippocampus* **7,** 624-642.

Shen, K., Bezgin, G., Selvam, R., McIntosh, A. R. and Ryan, J. D. (2016) An Anatomical Interface between Memory and Oculomotor Systems. *J. Cogn. Neurosci.* **28,** 1772-1783.

Sidhu, M. K., Stretton, J., Winston, G. P., Bonelli, S., Centeno, M., Vollmar, C., Symms, M., Thompson, P. J., Koepp, M. J. and Duncan, J. S. (2013) A functional magnetic resonance imaging study mapping the episodic memory encoding network in temporal lobe epilepsy. *Brain* **136,** 1868-1888.

Singer, A. C. and Frank, L. M. (2009) Rewarded outcomes enhance reactivation of experience in the hippocampus. *Neuron* **64,** 910-921.

Sliwa, J., Plante, A., Duhamel, J. R. and Wirth, S. (2016) Independent neuronal representation of facial and vocal identity in the monkey hippocampus and inferotemporal cortex. *Cereb. Cortex* **26,** 950-966.

Smith, M. L. and Milner, B. (1981) The role of the right hippocampus in the recall of spatial location. *Neuropsychologia* **19,** 781-793.

Sobotka, S., Nowicka, A. and Ringo, J. L. (1997) Activity linked to externally cued saccades in single units recorded from hippocampal, parahippocampal, and inferotemporal areas of macaques.

J. Neurophysiol. **78,** 2156-2163.

Sobotka, S. and Ringo, J. L. (1997) Saccadic eye movements, even in darkness, generate event-related potentials recorded in medial sputum and medial temporal cortex. *Brain Res.* **756,** 168-173.

Spiers, H. J. and Maguire, E. A. (2006) Thoughts, behaviour, and brain dynamics during navigation in the real world. *Neuroimage* **31,** 1826-1840.

Stefanacci, L., Suzuki, W. A. and Amaral, D. G. (1996) Organization of connections between the amygdaloid complex and the perirhinal and parahippocampal cortices in macaque monkeys. *J. Comp. Neurol.* **375,** 552-582.

Steward, O. (1976) Topographic organization of the projections from the entorhinal area to the hippocampal formation of the rat. *J. Comp. Neurol.* **167,** 285-314.

Strange, B. A., Witter, M. P., Lein, E. S. and Moser, E. I. (2014) Functional organization of the hippocampal longitudinal axis. *Nat. Rev. Neurosci.* **15,** 655-669.

Stringer, S. M. and Rolls, E. T. (2008) Learning transform invariant object recognition in the visual system with multiple stimuli present during training. *Neural Netw.* **21,** 888-903.

Stringer, S. M., Rolls, E. T. and Trappenberg, T. P. (2005) Self-organizing continuous attractor network models of hippocampal spatial view cells. *Neurobiol. Learn. Mem.* **83,** 79-92.

Stringer, S. M., Rolls, E. T. and Tromans, J. (2007) Invariant object recognition with trace learning and multiple stimuli present during training. *Network: Computation in Neural Systems* **18,** 161-187.

Suzuki, W. A. and Amaral, D. G. (1994a) Perirhinal and parahippocampal cortices of the macaque monkey - cortical afferents. *J. Comp. Neurol.* **350,** 497-533.

Suzuki, W. A. and Amaral, D. G. (1994b) Topographic organization of the reciprocal connections between the monkey entorhinal cortex and the perirhinal and parahippocampal cortices. *J. Neurosci.* **14,** 1856-1877.

Tabuchi, E., Mulder, A. B. and Wiener, S. I. (2003) Reward value invariant place responses and reward site associated activity in hippocampal neurons of behaving rats. *Hippocampus* **13,** 117-132.

Takahashi, N., Kawamura, M., Shiota, J., Kasahata, N. and Hirayama, K. (1997) Pure topographic disorientation due to right retrosplenial lesion. *Neurology* **49,** 464-469.

Takeuchi, T., Duszkiewicz, A. J. and Morris, R. G. (2014) The synaptic plasticity and memory hypothesis: encoding, storage and persistence. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **369,** 20130288.

Taube, J. S., Goodridge, J. P., Golob, E. J., Dudchenko, P. A. and Stackman, R. W. (1996) Processing the head direction signal: A review and commentary. *Brain Res. Bull.* **40,** 477-486.

Taube, J. S., Muller, R. U. and Ranck, J. B. J. (1990) Head-direction cells recorded from the postsubiculum in freely moving rats 1: Description and quantitative analysis. *J. Neurosci.* **10,** 420-435.

Teng, E. and Squire, L. R. (1999) Memory for places learned long ago is intact after hippocampal damage. *Nature* **400,** 675-677.

Terrazas, A., Krause, M., Lipa, P., Gothard, K. M., Barnes, C. A. and McNaughton, B. L. (2005) Self-motion and the hippocampal spatial metric. *J. Neurosci.* **25,** 8085-8096.

Thome, A., Marrone, D. F., Ellmore, T. M., Chawla, M. K., Lipa, P., Ramirez-Amaya, V.,

Lisanby, S. H., McNaughton, B. L. and Barnes, C. A. (2017) Evidence for an Evolutionarily Conserved Memory Coding Scheme in the Mammalian Hippocampus. *J. Neurosci.* **37,** 2795-2801.

Treves, A. and Rolls, E. T. (1991) What determines the capacity of autoassociative memories in the brain? *Network* **2,** 371-397.

Treves, A. and Rolls, E. T. (1992) Computational constraints suggest the need for two distinct input systems to the hippocampal CA3 network. *Hippocampus* **2,** 189-199.

Treves, A. and Rolls, E. T. (1994) A computational analysis of the role of the hippocampus in memory. *Hippocampus* **4,** 374-391.

Van Hoesen, G. W. (1982) The parahippocampal gyrus. New observations regarding its cortical connections in the monkey. *Trends in Neuroscience* **5,** 345-350.

van Strien, N. M., Cappaert, N. L. and Witter, M. P. (2009) The anatomy of memory: an interactive overview of the parahippocampal-hippocampal network. *Nat. Rev. Neurosci.* **10,** 272-282.

Vann, S. D., Aggleton, J. P. and Maguire, E. A. (2009) What does the retrosplenial cortex do? *Nat. Rev. Neurosci.* **10,** 792-802.

Vedder, L. C., Miller, A. M., Harrison, M. B. and Smith, D. M. (2016) Retrosplenial cortical neurons encode navigational cues, trajectories and reward locations during goal directed navigation. *Cereb. Cortex*.

Vogt, B. A. and Laureys, S. (2009) The primate posterior cingulate gyrus: connections, sensorimotor orientation, gateway to limbic processing. In: *Cingulate Neurobiology and Disease*. pp. 275-308. Ed. B. A. Vogt. Oxford University Press: Oxford.

Vogt, B. A. and Pandya, D. N. (1987) Cingulate cortex of the rhesus monkey: II. Cortical afferents. *J. Comp. Neurol.* **262,** 271-289.

Wallace, D. J., Greenberg, D. S., Sawinski, J., Rulla, S., Notaro, G. and Kerr, J. N. (2013) Rats maintain an overhead binocular field at the expense of constant fusion. *Nature* **498,** 65-69.

Washburn, D. A. and Astur, R. S. (2003) Exploration of virtual mazes by rhesus monkeys (Macaca mulatta). *Anim. Cogn.* **6,** 161-168.

Whitlock, J. R. (2017) Posterior parietal cortex. *Curr. Biol.* **27,** R691-R695.

Wilson, M. A. and McNaughton, B. L. (1993) Dynamics of the hippocampal ensemble code for space. *Science* **261,** 1055-1058.

Wilson, M. A. and McNaughton, B. L. (1994) Reactivation of hippocampal ensemble memories during sleep. *Science* **265,** 676-679.

Wirth, S., Avsar, E., Chiu, C. C., Sharma, V., Smith, A. C., Brown, E. and Suzuki, W. A. (2009) Trial outcome and associative learning signals in the monkey hippocampus. *Neuron* **61,** 930-940.

Wirth, S. and Baraduc, P. (2018) [Spatial orientation in the primate: I see, there I am]. *Med. Sci. (Paris)* **34,** 33-36.

Wirth, S., Baraduc, P., Plante, A., Pinede, S. and Duhamel, J. R. (2017) Gaze-informed, task-situated representation of space in primate hippocampus during virtual navigation. *PLoS Biol.* **15,** e2001045.

Wirth, S., Yanike, M., Frank, L. M., Smith, A. C., Brown, E. N. and Suzuki, W. A. (2003) Single neurons in the monkeys hippocampus and learning of new associations. *Science* **300,** 1578-1581.

Wood, E. R., Dudchenko, P. A. and Eichenbaum, H. (1999) The global record of memory in hippocampal neuronal activity. *Nature* **397,** 613-616.

Wood, E. R., Dudchenko, P. A., Robitsek, R. J. and Eichenbaum, H. (2000) Hippocampal neurons encode information about different types of memory episodes occurring in the same location. *Neuron* **27,** 623-633.

Yanike, M., Wirth, S., Smith, A. C., Brown, E. N. and Suzuki, W. A. (2009) Comparison of associative learning-related signals in the macaque perirhinal cortex and hippocampus. *Cereb. Cortex* **19,** 1064-1078.

Youngstrom, I. A. and Strowbridge, B. W. (2012) Visual landmarks facilitate rodent spatial navigation in virtual reality environments. *Learn. Mem.* **19,** 84-90.

Zeidman, P. and Maguire, E. A. (2016) Anterior hippocampus: the anatomy of perception, imagination and episodic memory. *Nat. Rev. Neurosci.* **17,** 173-182.