

RAPID COMMUNICATION

Dissociation of the Geometric and Contextual Influences on Place Cells

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*Department of Psychology, University College London, London, United Kingdom***KEY WORDS:** hippocampus; cognitive map; place cells; context; remapping; spatial learning

INTRODUCTION

It is well established that changing a rat's environment changes the spatial firing properties of hippocampal place cells (Muller and Kubie, 1987; Bostock et al., 1991; Kentros et al., 1998), a phenomenon known as remapping. The question as to how place cells localize their firing in a particular environment is still debated, but one class of model proposes that the cells use geometric information about the rat's distance from the walls (O'Keefe and Burgess, 1996). According to this view, remapping in a new environment could occur because the walls change either their size and shape, or their surface characteristics (e.g., color, odor), or both. This suggests a model of, for example, color-induced remapping in which place cells respond not simply to walls, but to walls of a specific color (Burgess and Hartley, 2002).

If this model is correct, a spatial shift of the firing location of place cells should occur only after changes to those aspects of the environment that convey spatially localizing information to the cells, namely, the walls. We tested this by recording place cells in a box in which the floor was changed from black to white independent of the walls. We predicted that remapping would occur only when the walls were changed, since it is these that localize the fields. However, we found that, in fact, changing the floor alone frequently induced the same remapping as changing the whole box, indicating that the trigger for remapping had a different source from the spatial determinants of place field location.

Four rats were implanted with tetrodes controlled by microdrives, using standard procedures described previously (Jeffery et al., 2003). Recordings took place in a square wooden recording box constructed from walls that were 70 cm long and 50 cm high. One side of the walls was painted black and the other white, so that the walls facing the rat could be changed in "color"

(as we refer to black and white, for simplicity) by reversing them. The floor was composed of black or white foam board. The walls were interchanged and the floor rotated at regular intervals to prevent local odor cues from gaining control of place fields (Save et al., 2000).

Beginning at least 1 week after implantation, each rat was screened for place cells on a holding platform located to one side of the laboratory room. When place cells were isolated, the rat was lifted from the holding platform into the recording box, where it foraged for cooked honey-flavored rice, thrown into the recording box at intervals by the experimenter, for the duration of the 2- or 4-min trial. Recordings were made with the box configured as all-black, all-white, white walls with black floor or black walls with white floor.

We first recorded four 2-min trials in the all-black box and four two-min trials in the all-white box, to see how the cell fired in the two conditions. Usually these blocks of trials were repeated, to check that both patterns could be reestablished freely. This procedure generated a prototypical "black pattern" and "white pattern" of firing for each cell. A single 4-min trial was then recorded in each of the hybrid boxes to see whether a given cell fired in its black pattern, its white pattern or in some other way. To prevent confounding by sequence effects, sometimes the walls were changed first and sometimes the floor, and sometimes the manipulations, were interspersed with further all-black or all-white trials.

Place cells were accepted into the analysis if, in at least one of the two baseline box conditions, they showed stable, spatially localized firing with a field size that was less than 75% of the box area, a mean peak rate of >1 Hz, a mean number of spikes per trial of >20 , and a mean within-condition correlation (a measure of spatial stability; see below) of >0.4 . We then looked at the specific firing patterns in the different box conditions. First, we generated firing rate maps using a smoothing procedure as described previously (Jeffery et al., 2003). Next, we established whether the change of the box from all-black to all-white induced remapping by comparing the firing rate maps from a given place cell in each of the boxes, using a two-step procedure. First, if the cell's firing rate in

Grant sponsor: Wellcome Trust; Grant number: 060062/JHW/KM/JAT.

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Accepted for publication 6 March 2003

DOI 10.1002/hipo.10162

TABLE 1.

Remapping Properties of Individual Cells

Cell	Baseline remapping ^a	Pattern in W walls, floor	Pattern in B walls, W floor	Cell's remapping determinant ^c	Cell's B field determinant ^b	Cell's W field determinant ^b
103121	Shifted	Black	Black	Complex	Either	Both
110121	Shifted	Black	White	Floor	Floor	Floor
110122	Shifted	Black	Neither	Floor	Floor	Both
226111	Off (B)	Neither	Neither	Complex	—	Both
226112	Shifted	White	White	Complex	Both	Either
209123	Off (W)	White ^d	Black	Walls	Walls	—
214121	Off (W)	White ^d	Black	Walls	Walls	—
413121	Shifted	Black	White	Floor	Floor	Floor
413122	Off (W)	Black	Black	Complex	Either	—
423111	Shifted	Black	White	Floor	Floor	Floor
423112	Off (W)	Black	White ^d	Floor	Floor	—
423114	Unstable (W)	Black	White ^d	Floor	Floor	—
423115	Off (B)	Neither	White	Floor	—	Floor
423116	Off (B)	Black ^d	White	Floor	—	Floor
423117	Off (B)	Black ^d	White	Floor	—	Floor
423118	Shifted	Neither	White	Floor	Both	Floor
424111	Shifted	Intermediate	White	Complex	Floor	Either
424112	Shifted	Black	White	Floor	Floor	Floor
429111	Shifted	Intermediate	White	Complex	Floor	Either
429112	Off (W)	White ^d	White ^d	Complex	Both	—
429113	Unstable (W)	Black	White ^d	Floor	Floor	—
429114	Off (B)	Black ^d	White	Floor	—	Floor
429115	Shifted	Black	White	Floor	Floor	Floor
429116	Shifted	Intermediate	Intermediate	Complex	Either	Either
406122	Off (B)	White	White	Complex	—	Either
406123	Shifted	Neither	White	Floor	Both	Floor
601121	Off (W)	Black	Black	Complex	Either	—
601123	Shifted	Black	Black	Complex	Either	Both

—, Absent or unstable.

B, black; W, white.

^aShifted, the cell shifted its field when the box changed color; off, the cell switched off in black (B) or white (W); unstable, the cell fired in that condition but did not produce a stable field.

^bThe data are broken down according to individual fields and indicate which environmental feature switched that particular field on or off.

^cAspects of the environment that needed to be changed in order to induce remapping. Complex, the cell responded to some combination of change to the walls and floor.

^dIf absence or instability of a field occurred in one of the baseline conditions, a similar absence or instability in one of the hybrid boxes is assumed to reflect establishment of that baseline pattern.

one of the box conditions dropped below a mean peak rate of 1 Hz or a mean number of spikes of 20 per trial in one of the conditions, it was considered to have remapped by switching off. If the cell fired in both boxes, the firing rate maps were next compared by correlating the two maps on a pixel-by-pixel basis, excluding pixels with no firing in either map.

Comparison of the firing rate maps from recordings made in the same box condition produced within-condition correlations, and those produced by comparing maps between the black and white boxes produced between-condition correlations. The within-con-

dition and between-condition correlations were then compared using a one-tailed *t*-test. If these were significantly different, the cell was said to have remapped between conditions; if they were not, the cell would be said not to have remapped (although this did not, in fact, occur). This procedure produced results that agreed with the experimenters' by-eye assessment of remapping in all cases (see also Jeffery et al., 2003).

The place cell map in each hybrid condition (black-walled box with white floor or white-walled box with black floor) was then compared with the maps produced in the all-black box and the

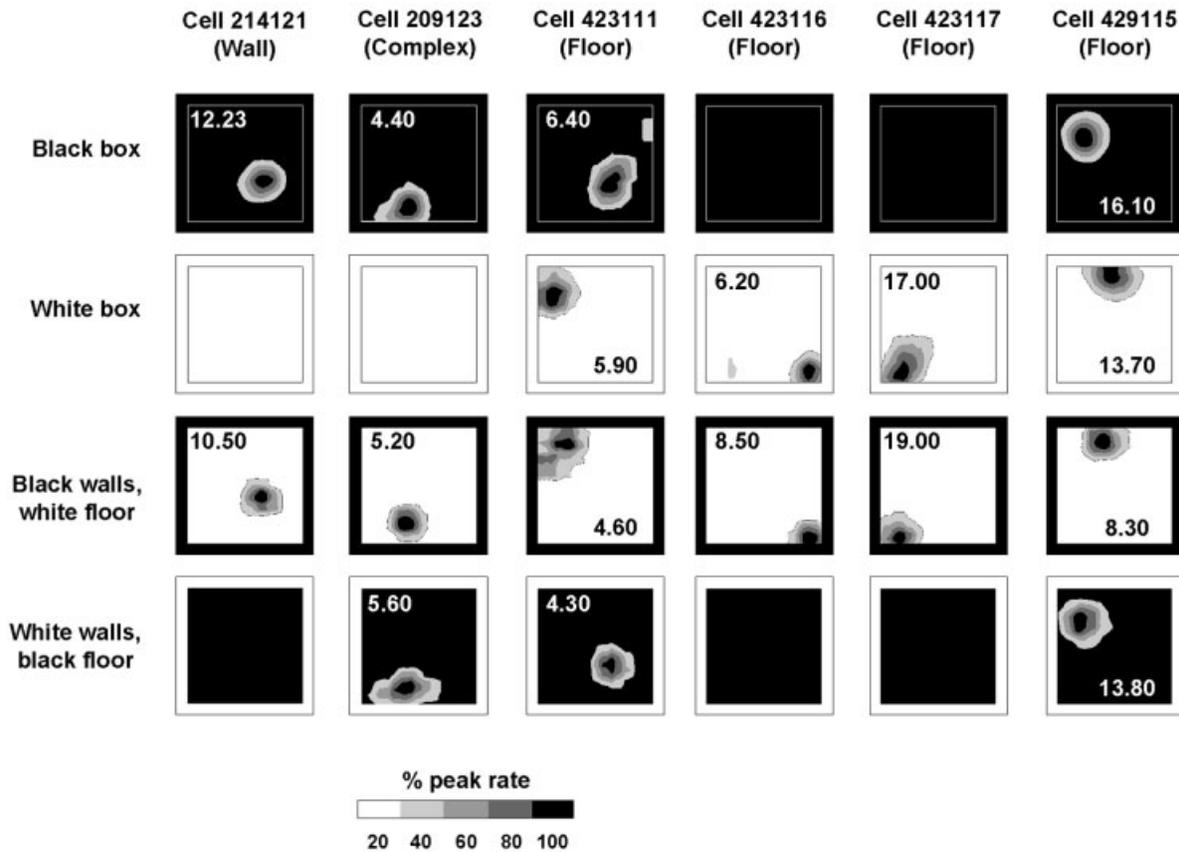


FIGURE 1. Types of remapping elicited by a recording box configured as all-black, all-white, white walls and black floor or black walls and white floor. The firing location of each cell is indicated by the contour plot. The peak rate of the field is shown in Hz. The cell in the leftmost column showed a firing pattern (“wall”) that depended on the color of the walls and was independent of the floor. The next

cell (“complex”) fired in the same way if the box was all black or had only black walls or a black floor. The remaining columns show the most common pattern observed, in which the firing pattern depended on the color of the floor alone (“floor”) and was independent of the walls. This shows that the spatially localizing information (the walls) can be dissociated from the cues triggering remapping (the floor).

all-white boxes, in the same ways as described above (first by rate analysis and then by field location analysis). If the cell switched off in the hybrid condition and had also switched off in one of the baseline conditions, the cell was assumed to have adopted the pattern of the corresponding box color. If the cell fired in the hybrid box, a correlation analysis was performed to see whether it resembled the “black” or the “white” pattern. If the between-condition correlations generated by comparing a hybrid box field with each of the black box trials did not differ significantly from the within-condition correlations generated by those trials, then the cell was said to have adopted a “black” firing pattern, and similarly for the white-box comparisons. If the between-condition hybrid-box correlations differed from both black and white within-condition correlations the cell was said to have adopted a “new” pattern, and if it differed from neither it was said to have adopted an “intermediate” pattern (these latter situations occurred only rarely; Table 1).

Twenty-eight place cells were analyzed in detail from the four rats. The behavior of the firing of these cells in response to the various box manipulations is presented in Table 1. The mean (\pm SEM) within-condition correlation was 0.68 ± 0.02 . Changing the box from black to white induced immediate remapping of all of

the cells, as indicated by the drop of the correlation value to 0.30 ± 0.07 . Twelve cells remapped by switching on or off, 14 remapped by shifting their fields and two remapped by developing unstable fields in one of the box conditions. Of the cells that switched off in one of the conditions, the lowest mean peak rate seen in the other condition was 5.35 Hz, so switching off was a robust phenomenon.

We then introduced the hybrid box condition, in which the walls and floor of the box were changed independently. Figure 1 shows the behavior of a subset of cells from the all-black trials, the all-white trials, and the two kinds of hybrid trial. We expected that when the walls and floor were changed independently, the place fields would adopt the pattern appropriate to the color of the walls rather than the floor, and indeed this did happen in two cells, both from the same rat (e.g., Fig. 1, left-hand column). However, and somewhat surprisingly, place fields more often adopted the pattern corresponding to the floor, regardless of the color of the walls (Fig. 1, right-hand four columns). For some other cells, the fields responded to some combination of the walls and the floor. The relative behaviors of individual cells in the four rats are shown in Table 1. In all, two cells remapped when the walls alone were changed, 15 cells remapped when the floor alone was changed and 11 cells showed a complex response where remapping depended on

some combination of a change of walls and floor. The latter pattern is described in more detail below. Note that despite the variation of remapping responses between rats, there was a tendency for cells from a given rat (indicated by the same first digit in the cell's identity code) to display similar behavior (Table 1). This was not invariable, however, suggesting a slight degree of partial remapping, something reported previously (Shapiro et al., 1997; Tanila et al., 1997). Note also that we never saw both a black and a white pattern simultaneously active.

The finding that remapping to color could occur when the floor alone was changed indicates that the remapping signal was not inextricably "bound" to the walls. We tested this further by hybridizing the boxes even more, by changing only two of the walls, or by changing only half the floor, to try and determine whether the context signal is truly non-local. One cell (not shown) adopted a "black" firing pattern, a field along the south wall of the box, even when all of the box was white except the north half of the floor. Thus, this small part of the box was sufficient to activate the cell's "black" pattern even when the field itself was located elsewhere, and surrounded by white. Interestingly, remapping was also sometimes provoked by changing the boxes in the dark, suggesting that the influence of "color" may have been at least partly due to olfaction rather than (or as well as) vision.

The nonlocality of the remapping trigger implies that the spatial information (telling a cell where to fire) is modulated by color information (telling the cell which of its spatial inputs to respond to). We propose the following simple model to explain the dissociation between spatial and nonspatial influences on place cell activity. In this model (Fig. 2), each place cell receives one or more sets of context-free spatial inputs, which we follow Burgess and Hartley (2002) in calling boundary inputs. Each set of boundary inputs specifies a particular place field and is weakly activated by the walls when the rat enters the area of the environment corresponding to that field. Each set of boundary inputs is supplemented (switched on or facilitated) by a set of context inputs, such as the box color manipulated in this experiment. These context inputs effectively tell the place cells which environment the rat is in, and they function by determining which boundary inputs drive the place cell above firing threshold. In the present experiment, the hybrid-box results can be explained by assuming that the novel box condition happens to activate (by some process of generalization) one of the preexisting (black or white) context inputs, an activation that may vary from rat to rat. Because we never saw both patterns occur simultaneously in the same cell, even in the mixed-color boxes, we assume some kind of inhibitory mechanism, either at the level of the context inputs or the boundary inputs, that allows only one set of inputs to be active in a given environment.

Using this model, our results can be reconsidered at the level not of the whole cell, but of the individual fields (Table 1). Thus, of the 42 fields recorded (22 in the black box and 20 in the white box), two were present if the walls were a particular color (regardless of the floor), 22 were present if the floor was a particular color (regardless of the walls), 10 were present if either the floor or the walls were a particular color and 8 were only present if both the walls and the floor were a particular color. A χ^2 test comparing walls and floor showed that the place cells were more strongly influenced by

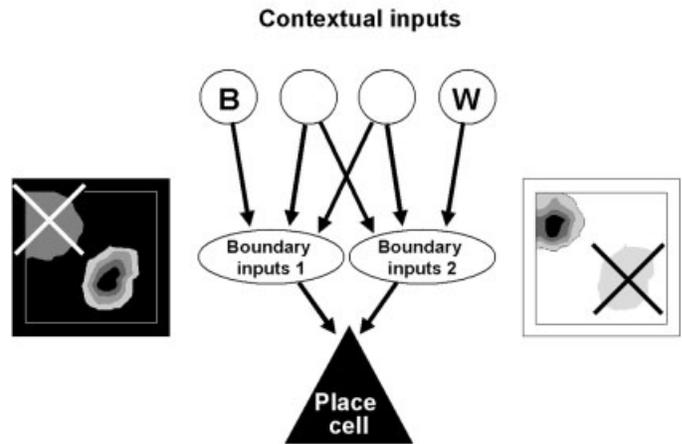


FIGURE 2. Model showing how context cues such as color might control the spatial firing of place cells. The two firing rate plots show how the place cell has a different place field when the box is black than when it is white. The silent field in each box is shown faintly and crossed out. We assume that each field is generated by a set of boundary inputs, carrying information emanating from the walls of the box that tell the cell where to fire within the box. Each set of boundary inputs is, in turn, controlled (perhaps directly driven by, or presynaptically facilitated by) its own particular set of context inputs. Thus, when the rat is in the black box, the black inputs activate one boundary input set and generate the "black" field and, when it is in the white box, the white inputs activate the other boundary input set and generate the "white" field. We explain the hybrid-box remapping pattern by assuming that for a given rat, the hybrid box activates one of the existing context inputs, so that the cell produces a "black" field or a "white" field.

the floor ($\chi^2 = 15.0$; $df = 1$; $P < 0.0005$), perhaps because the rat has greater contact with it.

Nothing about our model precludes the possibility that the contextual inputs might themselves originate from the geometry of the environment. For example, Lever et al. (2002) recently reported that place cells can acquire the ability to distinguish a square from a circular environment. If this remapping were being governed by the geometric properties of the environment then the fields should have shown subtle changes—stretching, splitting, and small shifts in location—of the type seen by O'Keefe and Burgess (1996). In fact, the remapping pattern seen in their experiment is more reminiscent of a "contextual" remapping of the type seen in the present study, suggesting that something about the squareness or circularity of the environment (such as, perhaps, the presence or absence of corners) controlled the spatial firing of the cells in the same way that color does. By this view, the same set of walls could act both as a geometric cue (controlling the location of the fields) and a contextual one (controlling whether a given field is expressed or not).

In conclusion, our results provide the first clear demonstration that, of the environmental determinants of place cell firing, the information telling place cells where to fire can emanate from a different location in space from the information telling them whether to fire at that place. This constrains models of how place fields are formed. We propose that the location of the field is specified by purely geometric inputs ("boundary inputs"), and that whether a cell responds to a given set of these inputs depends on

which context inputs (“context” in the present experiment meaning “color”) are currently active. By this model, contextual remapping can be understood as the recruitment of different sets of boundary inputs by different context cues.

Acknowledgments

This work was supported by The Wellcome Trust, Project grant 060062/JHW/KM/JAT (to K.J.).

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