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Neurocomputing 32–33 (2000) 235–241

NEUROCOMPUTING

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Place cell firing shows an inertia-like process

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Accepted 11 January 2000

Abstract

Place cells were recorded from five animals performing a shuttle task on a linear track in which reward was only available at one end of the journey. Although place fields during the journey itself were directional, place fields at the turn-around point were bidirectional. Place fields that were directional on full-length journeys became locally bidirectional when the animal turned around in the middle of the place field. This suggests that place cells show an inertia-like process in which, once they begin firing, they continue firing whatever trajectory the animal takes. This process would be useful for storing routes and sequences. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Directional place cells; Hippocampus; Spatial reasoning; Cognitive maps

1. Introduction

Hippocampal pyramidal cells (*place cells*) fire in limited regions of an environment (the *place field* of the cell) [11]. On linear tracks, place cells show strong directionality [4,7,8], whereas during open-field foraging, place fields are non-directional [10]. In most linear track tasks, reward is given at each end, thus ensuring that the animal makes a complete journey. This reward distribution makes it difficult to determine whether there is a discrete or continuous representation shift at the turn-around point. This determination is critical for testing several models of the source of the directional tuning (see [14] for a review).

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Place cells were studied in a linear track task in which the rat shuttled between opposite ends, but was rewarded only at one end. In this task, the place field representation was continuous through the turn-around at the non-rewarded end. Surprisingly, even when rats turned around before reaching the end of the track, firing continued around the turn, becoming locally bidirectional for that trial. This inertia-like effect could play an important role in sequence learning.

2. Methods

2.1. *Subjects and training*

Five adult male, Fischer-344 rats were used. They were motivated by food deprivation (80% ad-lib feeding weight or higher). Water was freely available. All animals were pre-tested in the Morris water maze (see [1] for details). Animals were then trained to find food on a Figure-Eight maze, and finally trained to shuttle back and forth along a linear track. The track itself was 182 cm long and 16 cm wide. At one end of the track was a box, at the other a barrier. Rats were trained to leave the box, run along the track, and return, receiving food reward when they returned. Reward was never given at the barrier end of the track, but if the animal did not reach the barrier, he did not receive a food reward on returning to the box. The box and track were moved along the direction of travel for each lap, but the barrier remained fixed. These animals also received medial forebrain bundle stimulation reward under certain conditions.

2.2. *Surgery and recording*

Surgeries were conducted according to NIH guidelines for rodents. A hyperdrive (a microdrive allowing individual manipulations of 14 tetrodes) was implanted over the right dorsal CA3 and CA1 regions of the hippocampus. See [3,5] for detailed descriptions of surgical techniques.

Recordings were taken from the CA3 and CA1 regions of the hippocampus. We have not examined differences between these two areas. Spike timings and waveforms were recorded from the four channels of each electrode and clusters were separated subjectively using in-house software (XCLUST, M. Wilson, and MCLUST, A.D. Redish, see [9,18] for cluster separation details). Cells were classified as pyramidal cells or interneurons based on waveform shape, interspike interval histograms, and average firing rate. Only pyramidal cells were included in our analyses. All cells were required to have no interspike intervals less than 2 ms.

Each day, tetrodes were advanced until cleanly separable cells could be seen. The recording quality of the cells was assessed on a separate small platform or in a separate box. This means that the cells recorded were not biased by the expression of place fields in the environment.

EEG data were recorded from the hippocampal fissure by a reference electrode (a tetrode with all four wires connected to a single amplifier).

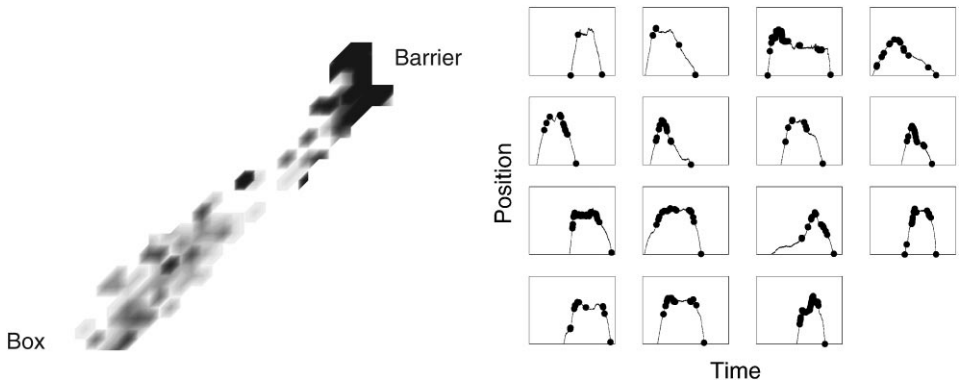


Fig. 1. (left) Place field of a cell with a field near the barrier end of the track; dark indicates high firing rate, grey low. (right) Each panel shows the trajectory of the animal near the end of the track, heavy dots indicate specific times at which the cell fired a spike.

3. Results

3.1. Representation at the end of the track

On most linear track tasks, animals are rewarded at each end of the linear track. The hippocampal EEG of animals in the process of eating tends to show large, irregular activity (LIA, [17]) punctuated by intermittent ripple complexes [2,12] rather than theta [17]. Place cell firing during LIA is not correlated with the current position of the animal [6]. In the present task, the animals did not have to stop at the end of the track; they just had to cross an invisible line near the end of the track (4" from the barrier). Thus, they typically did not wait at the end of the journey, but turned immediately around, and headed for the home box. The hippocampal theta rhythm continued uninterrupted throughout this journey, thus enabling the investigation of whether the firing pattern is continuous or discontinuous at the turn-around point, without the complication of an EEG state change.

1696 spike trains¹ were recorded from five animals. Fig. 1 shows the place field for a typical cell with a field at the barrier end of the track. Like most cells observed, this cell continued firing throughout the turn around.

Skaggs and McNaughton [15] defined the temporal correlation matrix (T) as the correlation of the ensemble representation at each moment in time: let $f_i(t)$ be the firing rate of cell i at time t , then the temporal correlation matrix T is the correlation of the state vector $F(t) = \{f_i(t), 1 \leq i \leq n_{\text{cells}}\}$ over all pairs of times t_1, t_2 . Fig. 2 (right) shows the average temporal correlation matrix over multiple trials in five animals. Note that there was no sharp pinch-point at the turn-around. Thus, there was a continuity of representation around the turn-around; the temporally contiguous population vectors were correlated, even around the turn-around.

¹ Since multiple sessions were recorded from each animal, some of these spike trains are likely to derive from the same cell.

3.2. Inertia at short turn-arounds

Is there something special about the end of the track? The animals clearly showed that they know the location of the invisible line at the end of the track; well-trained animals turned around so that the tracking LED on the head just crossed the line (without actually reaching the barrier). One can examine this question by looking at early turn-arounds. Sometimes, the animals did not go all the way to the end of the track. (They did not get rewarded if they did not go all the way, but sometimes they did not.)

When this happened inside a place field, a remarkable phenomenon was observed: the cell continued to fire as the animal turned around. Fig. 3 (top) shows a cell in which the animal turned around early within the field. Although the cell was very directional, with a strong preference for the outbound journey, when the animal turned around, the cell continued firing through the turn.

Directionality of a cell can be defined as $(S_0 - S_1)/(S_0 + S_1)$ where S_0 is the number of spikes fired in the outbound portion of the journey and S_1 , the number of spikes fired in the inbound portion. A cell with a strong outbound field will have a directionality close to 1.0, while a cell with a strong inbound field will have a directionality close to -1.0 . For strongly directional cells, directionality taken over the two seconds before and two seconds after the animal turned around within the field was smaller than the corresponding directionality over the entire journey. Fig. 3 (left) shows that this was a general property. Although there was no trend for cells with preferred firing on the inbound journey to change after turn-arounds within their field (single-factor ANOVA, $F = 0.40$, $df = (9,49)$, $P = 0.93$), cells that normally had a

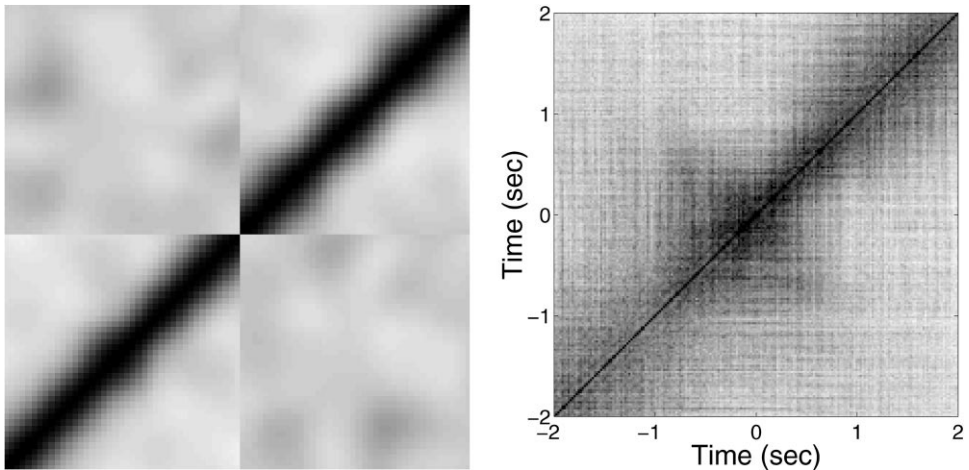


Fig. 2. The temporal correlation matrix. (left) Expected matrix if there were a break in the representation at the turn-around point. Note the sharp pinch-point in the middle. Simulation from Redish [14]. (right) Average correlation matrix, showing 2 s before and after each turn-around. Note the lack of a sharp pinch-point. This indicates a continuity of the representation around the turn-around point.

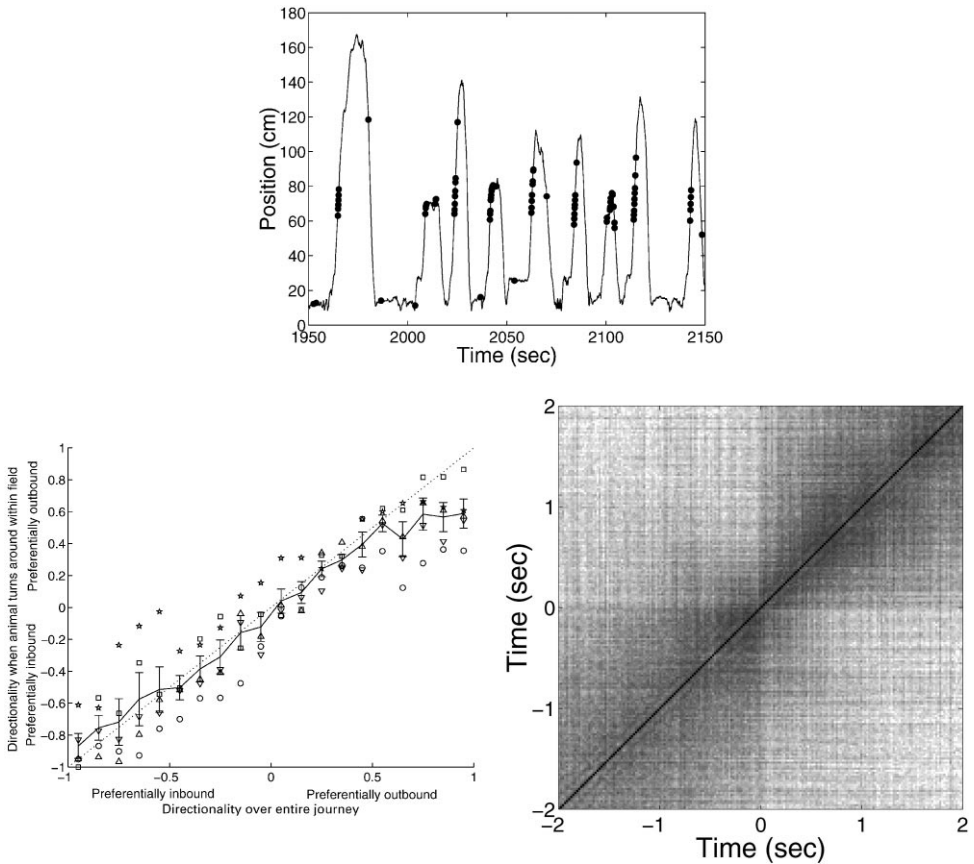


Fig. 3. (top) Trajectory of an animal through part of the task. Time along the x -axis, position along the y -axis. The animal was running out and back. Spikes fired by the single cell in question are indicated by heavy dots. Note that the cell had a very directional field, but continued firing as the animal turned around prematurely (such as on the seventh lap shown). (left) Change in directionality across short turn-arounds. Each dot indicates the average of all cells with a certain directionality for an animal. While inbound cells did not change, outbound cells lost their directionality when the animal turned around within the field. (right) Temporal correlation matrix across short turn-arounds. Although the outbound representations were spread across into the inbound spaces, there was still a sharp boundary where the inbound cells began firing.

preferred firing on the outbound journey lost their directionality when the animal turned around within the field (single-factor ANOVA, $F = 3.24$, $df = (9,49)$, $P = 0.005$).

An important question is whether the outbound and inbound representations mix or whether the inbound representation does not appear until the outbound representation is complete. The lack of change of inbound cells in Fig. 3 (left) suggests that the inbound cells did not wait until the firing of the outbound cells ceased to begin firing. This can be measured directly by looking at the temporal correlation matrix

around the short turn-around points (Fig. 3 (right)). Note that while the outbound representations fade across the boundary, there was still a sharp beginning to the inbound representations. This is an additional indication that the inbound cells began firing as soon as the animal turned around, even though the outbound cells continued firing.

4. Discussion

The evidence presented here suggests a sort of inertia term to place cell firing, a sort of burst effect. Clearly, the initial stimulus for the cell is correlated with the animal's spatial location (because cells do show spatial fields) and at least partially trajectory-dependent (because cells on linear tracks have a directional dependence), but once the cell begins to fire, it has a tendency to continue to fire no matter what trajectory the animal takes.

An apparently similar effect was observed in a two-dimensional environment by Gothard et al. [3]. They trained animals to find food relative to a pair of local landmarks in a large environment. Their animals also began from a small box and returned to that box after the trial. They report cells which fired in sequence after the animal left the box (box-out cells), independent of either the location of the box or the trajectory of the animal as it left the box.

This inertia effect also relates closely to the effect of phase precession and suggests a possible explanation of it. Phase precession is a well-studied effect of the correlation of hippocampal place cell firing to the theta EEG rhythm. Initial firing of a place cell when the animal is in a place field occurs at a phase of approximately 90° – 120° relative to the peak excitability of the pyramidal cell population [16], and subsequent firing occurs at earlier and earlier phases of theta [13,16].

A number of hypotheses have been proposed to explain this effect (see [14] for a review), but none have held up to all of the data. One proposal, made by O'Keefe and Recce [13] is that place cells have an intrinsic rhythm at a frequency slightly higher than 7 Hz, so that, when the cell was firing, beats between the two rhythms would lead to a phase precession of cell discharge. This theory, however, does not explain why the cells start firing at a constant phase of theta and stop after a short time. This theory can be modified by including an initial stimulus, followed by an inertia-like process. Such an inertial effect could be accounted for by the general property of attractor networks to resist a change in state.

The observation that the continued firing of outbound cells mixes with the onset of firing of inbound cells rules out any simple explanation, such as the propagation time of input from sensory systems to the hippocampus.

This inertia effect would be particularly useful for learning routes. The hippocampus has been hypothesized to store and replay sequences in general and routes in particular by a number of authors (see Ref. [14] for a review). In a sense, what the inertia effect does is to take a point in space and stretch it forward in time, thus enabling associations across time.

Acknowledgements

We thank Joe Bohanick, Sam Dedios, Kim Hardesty, Nathan Insel, Jeri Meltzer, Karen Weaver-Sommers, and Joyce Yuan for help in running the experiments and Jason Gerrard and Ephron Rosenzweig for helpful discussions and help with the experiments. This work was supported by NIH grants AG15085, AG12609, MH01565, MH01227, and NS20331.

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