Scanning behavior in novel environments promotes *de novo* formation of hippocampal place fields in rats

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Introduction

The hippocampus is thought to play a critical role in episodic memory by incorporating the sensory input of an experience onto a spatial framework embodied by place cells. While the development of a new place field map has been shown to occur rapidly with experience [1], the interaction between discrete exploratory behaviors and the specific, immediate, and persistent modifications of neural representations required by episodic memory has not been established. We previously examined the relationship between place-field potentiation, a form of rate remapping, and head scanning behavior [2]. Here we investigate whether there is a similar interaction between head scanning and the formation of de novo place fields when the animals are first introduced to a completely novel environment. Place fields recorded in novel rooms [3] demonstrate both onset and, in some recordings, additional post-onset potentiation related to colocalized scanning activity on the prior lap. These results strongly suggest that, during the attentive behaviors that animals use to investigate their environments during exploration, place-cell activity mediates the one-trial encoding of ongoing experiences necessary for episodic memory.

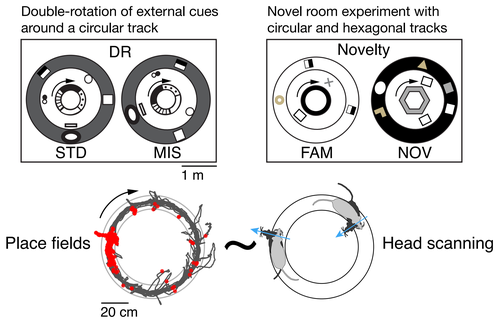


Fig. 1. To address the formation of new place fields in novel environments, we study tetrode recordings of place cells from a novel-room experiment [3] where rats (N = 10) navigated circular or hexagonal tracks in different rooms with distinct distal cues (top left). The rats were trained to familiarity in one room (FAM) and exposed to the novel room (NOV) for the first time during testing. Place fields were recorded on the tracks (bottom left) and examined in relation to place-cell activity during head-scanning events (bottom right).

Scans and field activation

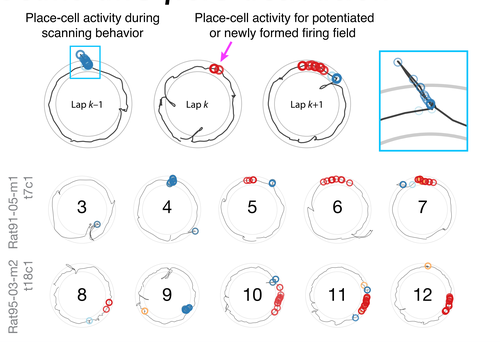


Fig. 2. Top row: illustration of place cell firing during a head-scan event (lap *k*–1, cyan box; inset) that is colocalized with a place field that first appears or is strongly potentiated on the next lap (lap *k*). Bottom rows: two examples from the DR experiment, for which scan–potentiation was previously demonstrated [2], showing 5 spike-trajectory laps centered on potentiation events (laps 5 (middle) and 10 (bottom), respectively). Red: running; blue: scanning; gold: pausing.

Head-scanning events

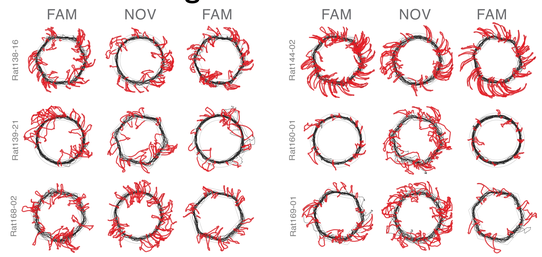


Fig. 3. Examples of detected head-scan events are shown as highlighted segments (red) of the trajectory (black) across the session. We show examples from different rats performing the 3 sessions of the novelty experiments: (from left to right) the first session in the familiar (FAM) room, the novel room (NOV) session, and a second session back in the FAM room.

Place-field potentiation events

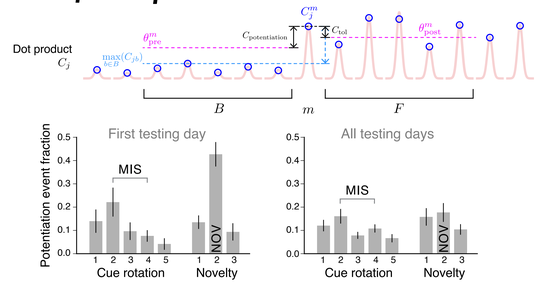


Fig. 4. Quantifying place-field potentiation on lap m relative to baseline laps (B). The amount of potentiation is assessed for at least 3 laps (F) after the event on lap m by using a normalized dot product (C_{jm}) of firing rate and comparing to the whole-session firing rate. The maximum threshold for detecting potentiation events (θ^m_{ev}) is adjusted so that early laps have lower potentiation requirements than late laps, to correct for whole-session averaging. A tolerance parameter is also included to allow for somewhat weaker potentiation on the laps after the potentiation event. Bottom: prevalence of potentiation events (789 total) among place fields (5,510 total) across the 5 (DR) or 3 (novelty) sessions.

Scan–activation in the novel room

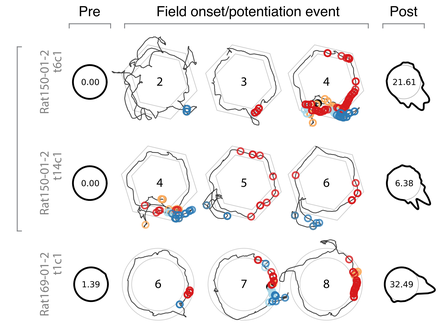


Fig. 5. Examples of potentiation events during initial exposure to the novel room. Each row ('Pre' polar firing-rate map with peak rate displayed at center, 3 spike-trajectory plots centered on the potentiation event, and 'Post' polar map) show onset and potentiation events recorded from 3 different animals, including two pairs of simultaneously recorded place cells (vertical brackets).

Simultaneous scan–activation of *de novo* place fields

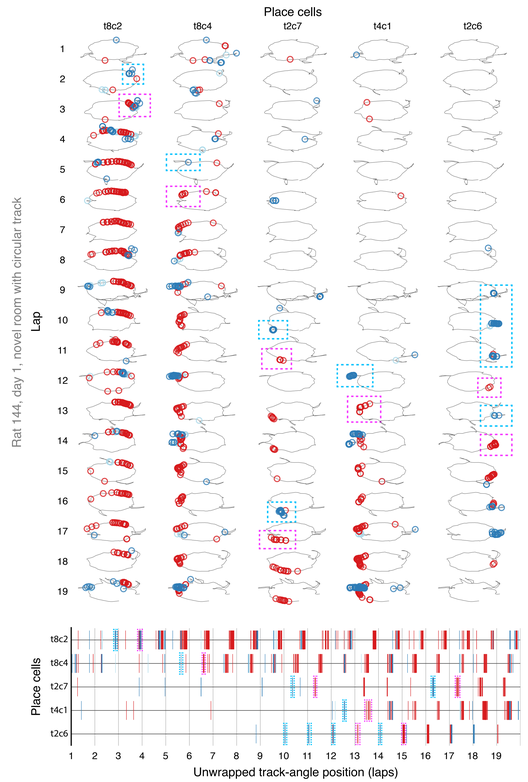
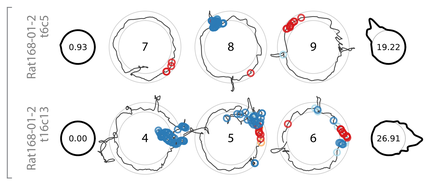
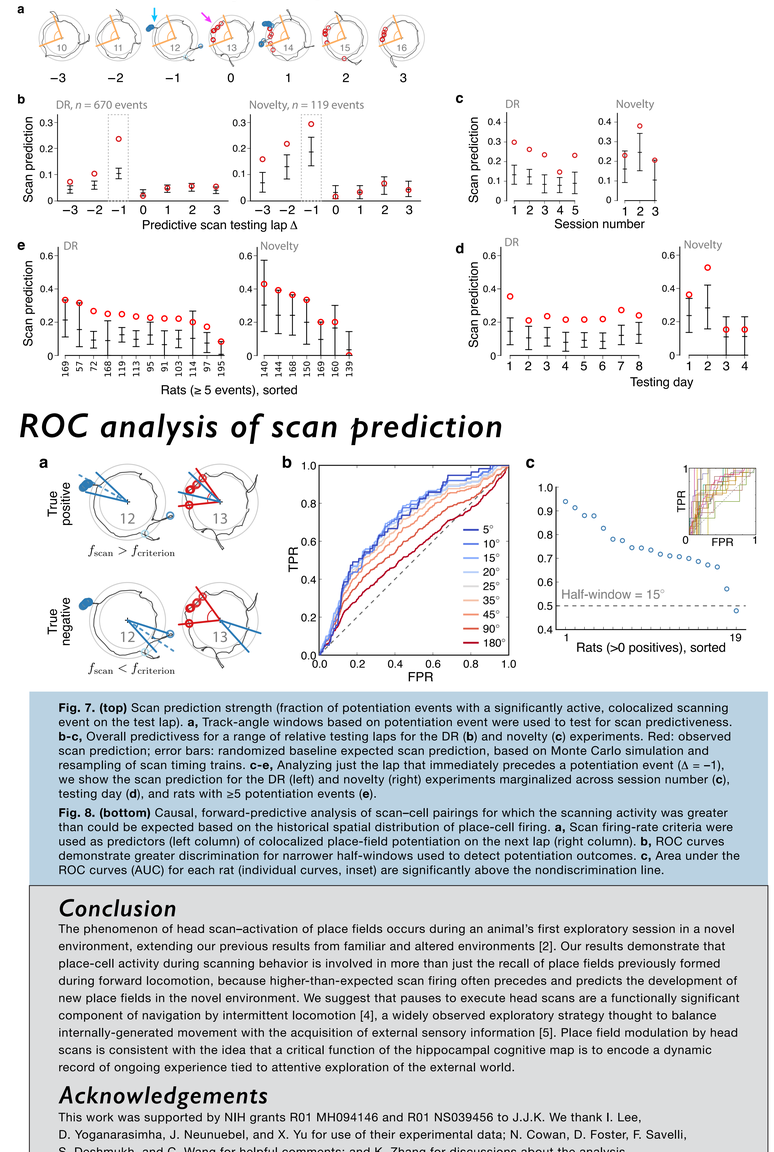


Fig. 6. A simultaneously recorded ensemble of 5 place cells from the first day of testing in the novel room demonstrates formation of *de novo* place fields. We show the entire recording session (19 laps around the circular track) and every place cell for which we detected a potentiation event (out of 13 active place cells recorded during the session). Each detected potentiation event was significantly predicted (see 'Predictive analysis of scan–activation') by colocalized scanning activity on the prior lap. Dashed cyan boxes highlight the predictive scan for each event; dashed magenta boxes highlight the predicted events. Scan (blue), peri-scan (cyan), and forward-running (red) spikes are represented with circle markers (top) or tick marks (bottom). The session is shown both as series of trajectory plots for each cell (top) as well as raster plots across unwrapped track-angle distance from the starting position (bottom). This example demonstrates that scan–activation occurs for new fields that develop as the animal becomes familiar with a novel environment.



Predictive analysis of scan–activation



ROC analysis of scan prediction

Fig. 7. (top) Scan prediction strength (fraction of potentiation events with a significantly active, colocalized scanning event on the test lap). **a,** Track-angle windows based on potentiation event were used to test for scan predictiveness. **b-c,** Overall predictivess for a range of relative testing laps for the DR (**b**) and novelty (**c**) experiments. Red: observed scan prediction; error bars: randomized baseline expected scan prediction, based on Monte Carlo simulation and resampling of scan timing trains. **c-e,** Analyzing just the lap that immediately precedes a potentiation event ($\Delta = -1$), we show the scan prediction for the DR (left) and novelty (right) experiments marginalized across session number (**c**), testing day (**d**), and rats with ≥5 potentiation events (**e**).

Fig. 8. (bottom) Causal, forward-predictive analysis of scan–cell pairings for which the scanning activity was greater than could be expected based on the historical spatial distribution of place-cell firing. **a,** Scan firing-rate criteria were used as predictors (left column) of colocalized place-field potentiation on the next lap (right column). **b,** ROC curves demonstrate greater discrimination for narrower half-windows used to detect potentiation outcomes. **c,** Area under the ROC curves (AUC) for each rat (individual curves, inset) are significantly above the nondiscrimination line.

Conclusion

The phenomenon of head scan–activation of place fields occurs during an animal's first exploratory session in a novel environment, extending our previous results from familiar and altered environments [2]. Our results demonstrate that place-cell activity during scanning behavior is involved in more than just the recall of place fields previously formed during forward locomotion, because higher-than-expected scan firing often precedes and predicts the development of new place fields in the novel environment. We suggest that pauses to execute head scans are a functionally significant component of navigation by intermittent locomotion [4], a widely observed exploratory strategy thought to balance internally-generated movement with the acquisition of external sensory information [5]. Place field modulation by head scans is consistent with the idea that a critical function of the hippocampal cognitive map is to encode a dynamic record of ongoing experience tied to attentive exploration of the external world.

Acknowledgements

This work was supported by NIH grants R01 MH094146 and R01 NS039456 to J.J.K. We thank I. Lee, D. Yoganarasimha, J. Neunuebel, and X. Yu for use of their experimental data; N. Cowan, D. Foster, F. Savelli, S. Deshmukh, and C. Wang for helpful comments; and K. Zhang for discussions about the analysis.

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