Efficient Spatial Learning in the Hippocampus via Left-Right Theta Sweeps in the Entorhinal Cortex

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Abstract

Recent findings show that grid cells in the medial entorhinal cortex (MEC) generate an internal positional signal that sweeps outward from the animal's current location into the surrounding environment. These sweeps alternate stereotypically between leftward and rightward directions across successive theta cycles, suggesting an intrinsic mechanism for spatial sampling. Here, we propose that left-right sweeps in grid cells support efficient spatial learning of recurrent connectivity between place cells in hippocampal region CA3. We extend a recent model that produces left-right sweeps in grid cells to show that: (1) synchronised left-right sweeps across grid modules drive coherent sweeps in downstream hippocampal place cells; (2) such sweeps accelerate the learning of place cell connectivity, facilitating rapid spatial map formation; and (3) disruption of theta oscillations abolishes sweep dynamics and impairs map formation. These findings suggest that grid cell theta sweeps provide an intrinsic scaffold for efficient spatial learning in the hippocampus. The model also generates testable predictions for how circuit-level disruptions—such as those arising during normal ageing or in the early stages of Alzheimer's disease—may lead to spatial deficits.

Keywords: left-right theta sweeps; grid cells; place cells; head direction cells; spatial learning

Results

A parasubiculum-entorhinal-hippocampal microcircuit for generating theta sweeps

Theta sweeps—the forward-sweeping, position-related activity of place and grid cells during each theta cycle as rodents run on linear tracks—were recently observed as left-right alternating sweeps in grid cells when rodents navigate open fields (Fig. 1a; Vollan et al., 2025). These alternations originate from bidirectional sweeps in theta-modulated head direction cells in the parasubiculum, upstream of the entorhinal grid cells. Notably, grid cell sweeps precede those in place cells by tens of milliseconds, suggesting that place cell sweeps are inherited from grid cells (Vollan et al., 2025). These results point to a parasubiculum–entorhinal–hippocampal microcircuit that orchestrates theta sweeps in the hippocampal formation (Fig. 1b). We propose that this mechanism supports efficient spatial map learning in the hippocampus, as theta sweeps allow animals to mentally simulate unvisited locations without physical exploration, thereby activating place cells with firing fields along the imagined path.

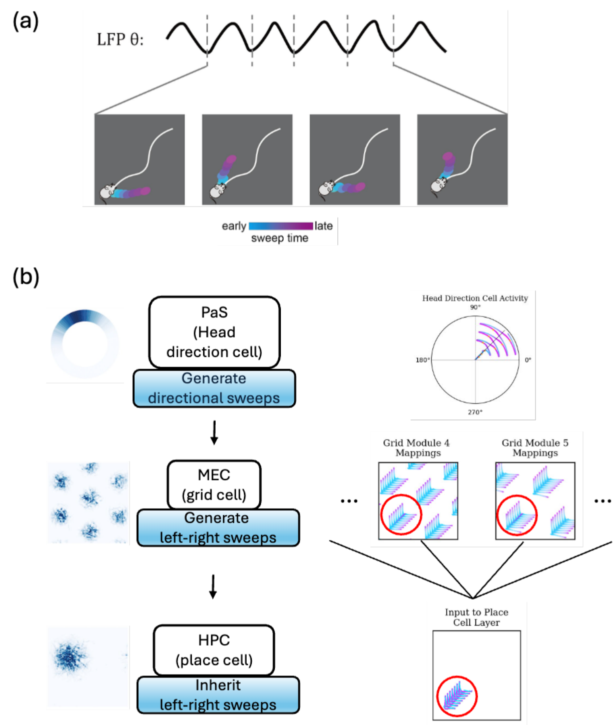

Figure 1: Schematic of left-right theta sweeps in grid cells and the proposed systems model. (a)left-right theta sweeps across four successive local field potential (LFP) theta cycles. (b) the proposed systems model in producing coordinated theta sweeps in parasubiculum–entorhinal–hippocampal microcircuit

Left-right theta sweeps significantly accelerate rapid spatial map formation in the hippocampus

To investigate this, we extend a recent model based on continuous attractor dynamics that generates left-right sweeps in grid cells from bidirectional sweeps in upstream head direction cells (Ji et al., 2025). Head direction cells (HDCs), positioned at the top of the extended model, form a ring attractor:

$$\tau_h \frac{\partial h}{\partial t} = -h + \sum J_h f(h) - a_h + I_h, \qquad (1)$$

This simplified dynamic omits many details. Here, h is the presynaptic input to an HDC, and $f(h)$ is its firing rate. The term a_h represents firing rate adaptation, and I_h represents directional input modulated by theta oscillations (Tsanov et al., 2011). Under the influence of a_h and I_h, the directional information encoded in the ring attractor sweeps from side to side along the head axis (Fig. 1b).

Grid cells (GCs), situated in the middle layer of the model, form a toroidal attractor (Gardner et al., 2022):

$$\tau_g \frac{\partial g}{\partial t} = -g + \sum J_g f(g) - a_g + I_g(h). \qquad (2)$$

This is again a simplified dynamic. Here, g denotes the presynaptic input to a grid cell, which receives recurrent input from other grid cells on the torus and is driven by upstream HDC activity $I_g(h)$. Due to the influence of HDCs, GCs exhibit left-right sweeps (Fig.1b).

Place cells (PCs), in the bottom layer of the model, follow recurrent dynamics:

$$\tau_p \frac{\partial p}{\partial t} = -p + \sum J_p f(p) - a_p + I_p(g_{1-5}). \qquad (3)$$

Here, $I_p(g_{1-5})$ represents input from five grid modules with different grid spacings. Multiple modules are used because grid cells fire at multiple locations within an environment, making the location information from a single module ambiguous. Input from multiple grid modules significantly reduces this ambiguity (McNaughton et al., 2006), enabling robust activation of place cells with firing fields centred near the animal's actual position in a theta-sweep manner (Fig. 1b).

Notably, place cells are initially connected by a random synaptic weight matrix J_p (Fig. 2b). We introduced a rate approximation for additive spike-timing-dependent plasticity (STDP) to allow synaptic connections between place cells to be modified as the animal explores the environment (Gütig et al., 2003). When two place cells are activated in close temporal proximity, their synaptic connection is strengthened. Without theta sweeps, only connections between place cells whose firing fields overlap with the animal's physical path are updated (Fig. 2a&b). In contrast, theta sweeps also update connections between place cells with firing fields along the "virtual path" represented by the sweep. As a result, synaptic connectivity is learned more rapidly in the presence of theta sweeps (Fig. 2b). We quantified the speed of spatial map formation by measuring the correlation between synaptic strength and the distance between place field centres. An ideal spatial map after learning exhibits a continuous attractor structure in which cells encoding nearby (vs. distant) locations have stronger (vs. weaker) connections. Our results show that map formation proceeds more quickly when theta sweeps are present than when they are absent (Fig. 2c).

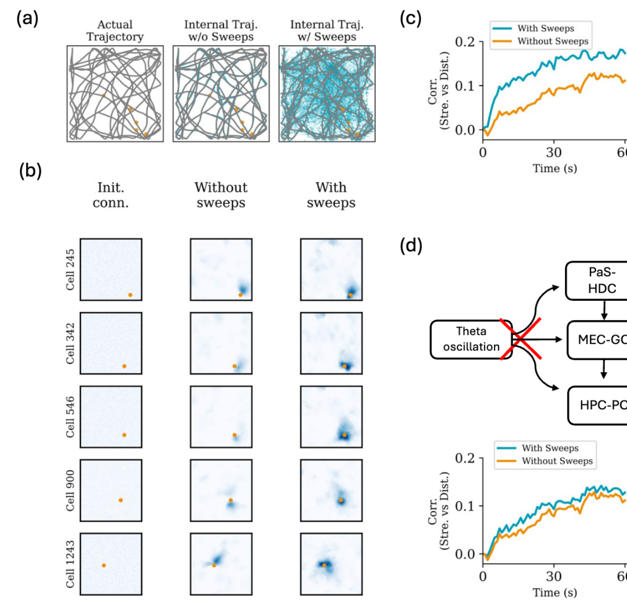

Figure 2: Left-right sweeps in grid cells facilitate spatial learning in downstream place cells in the hippocampus. (a) Comparison of actual agent movement trajectories and internal location trajectories in place cell network without and with theta sweeps. (b) Connection profiles of selected place cells before and after simulation with or without left-right sweeps. (c) Average weight-distance correlation (Spearman) during learning with (blue) and without (orange) sweeps. (d) Disrupted weight-distance correlation in absence of theta oscillation.

Disruption of theta modulation impairs spatial learning in the hippocampus

These results suggest that left-right theta sweeps, generated upstream in the entorhinal cortex, may play a critical role in supporting spatial learning in the hippocampus. To test this, we disrupted theta oscillations throughout the circuit and observed a marked impairment in spatial learning (Fig. 2d). This finding provides a mechanistic basis for understanding spatial deficits observed in normal ageing and in the early stages of Alzheimer's disease (Musaeus et al., 2018).

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