

Novelty Assessment Report

Paper: From movement to cognitive maps: recurrent neural networks reveal how locomotor development shapes hippocampal spatial coding

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Abstract

The hippocampus contains neurons whose firing correlates with an animal's location and orientation in space. Collectively, these neurons are held to support a cognitive map of the environment, enabling the recall of and navigation to specific locations. Although recent studies have characterised the timelines of spatial neuron development, no unifying mechanistic model has yet been proposed. Moreover, the processes driving the emergence of spatial representations in the hippocampus remain unclear (Tan et al., 2017). Here, we combine computational analysis of postnatal locomotor development with a recurrent neural network (RNN) model of hippocampal function to demonstrate how changes in movement statistics -- and the resulting sensory experiences -- shape the formation of spatial tuning. First, we identify distinct developmental stages in rat locomotion during open-field exploration using published experimental data. Then, we train shallow RNNs to predict upcoming visual stimuli from concurrent visual and vestibular inputs, exposing them to trajectories that reflect progressively maturing locomotor patterns. Our findings reveal that these changing movement statistics drive the sequential emergence of spatially tuned units, mirroring the developmental timeline observed in rats. The models generate testable predictions about how spatial tuning properties mature -- predictions we confirm through analysis of hippocampal recordings. Critically, we demonstrate that replicating the specific statistics of developmental locomotion -- rather than merely accelerating sensory change -- is essential for the emergence of an allocentric spatial representation. These results establish a mechanistic link between embodied sensorimotor experience and the ontogeny of hippocampal spatial neurons, with significant implications for neurodevelopmental research and predictive models of navigational brain circuits.

Disclaimer

This report is **AI-GENERATED** using Large Language Models and WisPaper (a scholar search engine). It analyzes academic papers' tasks and contributions against retrieved prior work. While this system identifies **POTENTIAL** overlaps and novel directions, **ITS COVERAGE IS NOT EXHAUSTIVE AND JUDGMENTS ARE APPROXIMATE**. These results are intended to assist human reviewers and **SHOULD NOT** be relied upon as a definitive verdict on novelty.

Note that some papers exist in multiple, slightly different versions (e.g., with different titles or URLs). The system may retrieve several versions of the same underlying work. The current automated pipeline does not reliably align or distinguish these cases, so human reviewers will need to disambiguate them manually.

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Core Task Landscape

This paper addresses: **Developmental Emergence of Hippocampal Spatial Representations from Locomotor Experience**

A total of **28 papers** were analyzed and organized into a taxonomy with **19 categories**.

Taxonomy Overview

The research landscape has been organized into the following main categories:

- **Computational and Mechanistic Models of Spatial Representation Development**
- **Empirical Developmental Trajectories of Spatial Neurons and Behavior**
- **Self-Motion Signals and Vestibular Contributions to Spatial Coding**
- **Learning-Dependent Plasticity and Task-Specific Spatial Representations**
- **Subcortical and Cortical Network Interactions in Spatial Navigation**
- **Comparative and Cross-Species Spatial Coding Studies**
- **Methodological and Theoretical Frameworks for Spatial Coding Research**

Complete Taxonomy Tree

- Developmental Emergence of Hippocampal Spatial Representations from Locomotor Experience Survey Taxonomy
- Computational and Mechanistic Models of Spatial Representation Development
 - Recurrent Neural Network Models of Spatial Tuning Emergence ★ (1 papers)
 - [0] From movement to cognitive maps: recurrent neural networks reveal how locomotor development shapes hippocampal spatial coding (Anon et al., 2026) [View paper](#)
 - Experience-Dependent Sculpting of Hippocampal Circuits (2 papers)
 - [1] How development sculpts hippocampal circuits and function (Rosa Cossart, 2021) [View paper](#)
 - [3] Experience of Euclidean geometry sculpts the development and dynamics of rodent hippocampal sequential cell assemblies (Usman Farooq, 2024) [View paper](#)
- Empirical Developmental Trajectories of Spatial Neurons and Behavior
 - Postnatal Emergence and Maturation of Spatial Cell Types (3 papers)
 - [6] Developmental perspectives on spatial navigation: sensory development, experience, and neuronal heterogeneity (Xiaojing Chen, 2025) [View paper](#)
 - [7] Development of the hippocampal cognitive map in preweanling rats (Thomas J. Wills, 2010) [View paper](#)
 - [11] The development of spatial behaviour and the hippocampal neural representation of space (Thomas J. Wills, 2014) [View paper](#)
 - Spatial Behavior Ontogeny and Hippocampal Function (3 papers)
 - [12] Building hippocampal circuits to learn and remember: insights into the development of human memory (Pierre Lavenex, 2013) [View paper](#)
 - [14] The ontogeny of hippocampal memory: Bridging behavioural and neuronal development (Bevandic, 2025) [View paper](#)
 - [19] Emergence of spatial behavioral function and associated mossy fiber connectivity and c-Fos labeling patterns in the hippocampus of rats (Rachel Comba, 2015) [View paper](#)
 - Early Spatial Coding and Memory Development in Humans (2 papers)

- [10] The development of spatial location coding: Place learning and dead reckoning in the second and third years (Nora S. Newcombe, 1998) [View paper](#)
- [24] Mechanisms of change: A cognitive neuroscience approach to declarative memory development (J Richmond, 2008) [View paper](#)
- Self-Motion Signals and Vestibular Contributions to Spatial Coding
 - Vestibular and Otolith Contributions to Place Field Stability (1 papers)
 - [17] Linear self-motion cues support the spatial distribution and stability of hippocampal place cells (Ryan E. Harvey, 2018) [View paper](#)
 - Locomotor Modulation of Hippocampal Spatial Coding (3 papers)
 - [4] Self-motion and the hippocampal spatial metric (Alejandro Terrazas, 2005) [View paper](#)
 - [21] DISTINCT NEURAL SIGNATURES OF HIPPOCAMPAL POPULATION DYNAMICS DURING LOCOMOTION-IN-PLACE (Samsoun Inayat, 2025) [View paper](#)
 - [27] Effects of self-locomotion on the activity of place cells in the hippocampus of a freely behaving monkey. (Yutaro Hazama, 2020) [View paper](#)
 - Action Sequences and Multidimensional Movement Encoding (1 papers)
 - [5] Locomotor action sequences impact the scale of representation in hippocampus and posterior parietal cortex (Laura E Shelley, 2021) [View paper](#)
- Learning-Dependent Plasticity and Task-Specific Spatial Representations
 - Orthogonalization and State-Dependent Coding During Spatial Learning (1 papers)
 - [2] Emergence of orthogonal hippocampal representations during spatial learning. (Verner P. Bingman, 2025) [View paper](#)
 - Grid Scale and Upstream Inputs Regulating Place Map Properties (1 papers)
 - [18] Grid scale drives the scale and long-term stability of place maps (Caitlin S. Mallory, 2018) [View paper](#)
- Subcortical and Cortical Network Interactions in Spatial Navigation
 - Cerebellar Contributions to Spatial Coding and Foraging Strategy (1 papers)
 - [22] The cerebellum promotes sequential foraging strategies and contributes to the directional modulation of hippocampal place cells (Lu Zhang, 2023) [View paper](#)
 - Supramammillary and Hypothalamic Regulation of Locomotion and Hippocampal Activity (1 papers)
 - [26] Supramammillary regulation of locomotion and hippocampal activity (Jordan S. Farrell, 2021) [View paper](#)
 - Hippocampal-Cortical Network Interactions and Movement (1 papers)
 - [16] The Hippocampus and Cortical Networks (Biesalski, 2025) [View paper](#)
- Comparative and Cross-Species Spatial Coding Studies
 - Primate Hippocampal Spatial Encoding During Free Navigation (1 papers)
 - [8] Spatial encoding in primate hippocampus during free navigation (Hristos S. Courellis, 2019) [View paper](#)
- Methodological and Theoretical Frameworks for Spatial Coding Research
 - Neural Activity Patterns and Population Dynamics Underlying Spatial Coding (2 papers)
 - [13] A manifold of spatial maps in the brain (D. Derdikman, 2010) [View paper](#)
 - [20] Neural Activity Patterns Underlying Spatial Coding in the Hippocampus. (Marielena Sosa, 2018) [View paper](#)
 - Methodological Advances in Cellular Identification and Recording (1 papers)
 - [23] Author response: Juxtacellular opto-tagging of hippocampal CA1 neurons in freely moving mice (Lingjun Ding, 2021) [View paper](#)
 - Theoretical Perspectives on Hippocampal Spatial Maps and Memory (2 papers)
 - [9] The hippocampus and space revisited (Lynn Nadel, 1991) [View paper](#)
 - [28] Common to Development and Learning? (E BIENENSTOCK, 1998) [View paper](#)
 - Egocentric and Allocentric Spatial Representation Frameworks (1 papers)
 - [25] Roles of egocentric and allocentric spatial representations in locomotion and reorientation. (Weimin Mou, 2007) [View paper](#)
 - Object-Tracking and Dynamic Spatial Coding (1 papers)
 - [15] Hippocampal place cell activity during chasing of a moving object associated with reward in rats (S. A. Ho, 2008) [View paper](#)

Narrative

Core task: developmental emergence of hippocampal spatial representations from locomotor experience. The field investigates how spatial coding in the hippocampus arises through experience and maturation, spanning computational modeling, empirical developmental studies, and mechanistic analyses of sensory and network contributions. Computational and mechanistic models explore how recurrent neural networks and self-organizing principles can generate place cells and grid cells from movement statistics, with works like Euclidean Geometry Sculpt[3] and Self-motion Spatial Metric[4] emphasizing geometric constraints and self-motion signals. Empirical developmental trajectories track the maturation of spatial neurons and navigation behavior across postnatal development, as seen in studies such as Development Sculpt[1] and Prewaning Cognitive Map[7]. Additional branches examine vestibular and self-motion inputs, learning-dependent plasticity in task-specific contexts, subcortical-cortical network interactions, cross-species comparisons including primate work like Primate Free Navigation[8], and methodological frameworks for recording and analyzing spatial coding.

Particularly active lines of work contrast bottom-up sensory-driven models with top-down network-level accounts of spatial tuning emergence. Some studies focus on how locomotor action sequences and movement statistics directly shape hippocampal representations, as in Locomotor Action Sequences[5], while others emphasize the role of cortical and subcortical circuits in sculpting these codes through recurrent dynamics and plasticity. Movement to Cognitive Maps[0] sits within the computational modeling branch, specifically addressing how recurrent neural network architectures can learn spatial tuning from locomotor experience. Its emphasis on mechanistic emergence from movement statistics aligns closely with Self-motion Spatial Metric[4] and Euclidean Geometry Sculpt[3], which similarly propose that geometric and kinematic features of exploration drive the formation of cognitive maps. Compared to purely empirical developmental studies like Development Sculpt[1], Movement to Cognitive Maps[0] offers a normative computational account of the principles underlying observed maturational trajectories.

Related Works in Same Category

No sibling papers were found in the same taxonomy leaf. A taxonomy-subtopic-level comparison will be produced instead.

Taxonomy-Level Summary

Both subtopics address how experience shapes hippocampal spatial representations during development, but from complementary perspectives. The original leaf focuses on computational RNN models that simulate the mechanistic process of spatial tuning emergence from locomotor statistics, while the sibling examines empirical studies of how actual environmental and geometric experience sculpt

hippocampal circuits. Together they represent the modeling versus experimental approaches to understanding experience-dependent spatial development.

Similarities: - Both emphasize experience-dependent (rather than purely innate) mechanisms in spatial representation development - Both focus on developmental emergence rather than mature circuit function - Both consider how locomotor or environmental experience drives hippocampal spatial neuron properties - Both exclude purely innate developmental programs that operate without experience

Differences: - Original leaf uses computational RNN models as the primary methodology; sibling uses empirical circuit-level studies - Original leaf specifically focuses on locomotor statistics and sensory experience as inputs; sibling emphasizes geometric and environmental features - Original leaf requires RNN architecture as a modeling constraint; sibling is agnostic to computational approaches - Original leaf simulates mechanistic processes; sibling examines actual biological circuit sculpting - Sibling explicitly addresses circuit-level changes; original leaf focuses on emergent spatial tuning properties

Suggested Search Directions: - Hybrid studies that combine RNN modeling with empirical circuit manipulation to validate computational predictions - Studies comparing locomotor statistics across different environmental geometries to bridge the two perspectives - Research on how specific circuit connectivity patterns (from sibling) could be implemented in RNN architectures (from original)

Sibling Subtopics

- **Experience-Dependent Sculpting of Hippocampal Circuits** (leaves: 1, papers: 2)
- Scope: Studies examining how geometric or environmental experience shapes hippocampal circuit development and spatial representations.
- Exclude: Studies on innate developmental programs without experience manipulation belong under intrinsic developmental programs.

Contributions Analysis

Overall novelty summary. The paper proposes a computational framework linking postnatal locomotor development to hippocampal spatial tuning emergence via recurrent neural networks trained on predictive coding. It occupies the 'Recurrent Neural Network Models of Spatial Tuning Emergence' leaf, which currently contains only this work among 28 papers across the taxonomy. This leaf sits within the broader 'Computational and Mechanistic Models' branch, which includes two leaves total. The sparse population of this specific modeling approach suggests the paper addresses a relatively underexplored mechanistic niche within the developmental spatial coding literature.

The taxonomy reveals substantial empirical work on developmental trajectories (three leaves covering postnatal emergence, spatial behavior ontogeny, and human infant studies) and diverse mechanistic branches examining self-motion signals, learning-dependent plasticity, and subcortical regulation. The paper's closest conceptual neighbors appear in 'Experience-Dependent Sculpting of Hippocampal Circuits' (two papers) and 'Vestibular and Otolith Contributions' (one paper), both emphasizing sensorimotor experience. However, the RNN-based predictive coding approach distinguishes this work from geometric constraint models or empirical developmental characterizations, positioning it at the intersection of computational neuroscience and developmental systems.

Among 16 candidates examined across three contributions, the analysis identified one refutable pair for the directional selectivity prediction (6 candidates examined, 1 refutable). The locomotor development classification contribution showed no refutations across 10 candidates, while the core RNN modeling contribution was not matched against any candidates. The limited search scope (top-K semantic retrieval) means these statistics reflect a focused sample rather than exhaustive coverage. The directional selectivity finding appears to have some prior empirical grounding, whereas the computational classification of locomotor stages and the RNN framework itself show less direct overlap within the examined literature.

Given the restricted search scale and the paper's position in a sparsely populated taxonomy leaf, the work appears to occupy a distinctive methodological space combining developmental locomotor analysis with predictive RNN modeling. The analysis does not cover potential overlaps in broader machine learning or theoretical neuroscience literatures outside the hippocampal spatial coding domain. The contribution-level statistics suggest varying degrees of novelty, with the core modeling framework showing minimal direct precedent among examined candidates.

This paper presents **3 main contributions**, each analyzed against relevant prior work:

Contribution 1: Computational classification of postnatal locomotor development stages in rats

Description: The authors introduce a computational method to identify distinct developmental stages in rat locomotion (crawl, walk, run) by analyzing movement statistics from experimental data. This classification provides the foundation for generating synthetic trajectories used to train RNNs at each developmental stage.

This contribution was assessed against **10 related papers** from the literature. Papers with potential prior art are analyzed in detail with textual evidence; others receive brief assessments.

1. Open-source software for automated rodent behavioral analysis

URL: [View paper](#)

Brief Assessment

Automated Rodent Analysis[35] focuses on software tools for general rodent behavioral analysis across various paradigms, not specifically on computational classification of postnatal locomotor development stages. The candidate paper reviews existing open-source software capabilities rather than proposing novel developmental stage classification methods.

2. Repetitive motor behavior: further characterization of development and temporal dynamics

URL: [View paper](#)

Brief Assessment

Repetitive Motor Behavior[41] focuses on stereotyped motor behaviors in deer mice using trajectory modeling, not computational classification of locomotor development stages in rats during open-field exploration.

3. Quantification of early learning and movement sub-structure predictive of motor performance

URL: [View paper](#)

Brief Assessment

Early Learning Quantification[40] focuses on quantifying motor learning sub-structure in rotarod tasks, not on classifying developmental locomotor stages in rodents through computational analysis of movement statistics.

4. A role for motor neurons in the development and function of the spinal circuitry governing locomotion

URL: [View paper](#)

Brief Assessment

Motor Neurons Locomotion[44] focuses on spinal cord motor circuitry development and motor neuron specification, not computational classification of locomotor stages. The candidate uses experimental recording methods rather than computational clustering approaches to analyze developmental locomotion.

5. Validation of a new system for the automatic registration of behaviour in mice and rats

URL: [View paper](#)

Brief Assessment

Automatic Registration System[38] focuses on automated detection of general laboratory behaviors in mice and rats, not on computational classification of developmental locomotor stages or postnatal development trajectories.

6. Detecting ataxia using an automated analysis of motor coordination and balance of mice on the balance beam

URL: [View paper](#)

Brief Assessment

Detecting Ataxia Automatically[42] focuses on automated classification of motor coordination deficits (missteps, stops) in ataxia mouse models using balance beam assays, not on identifying developmental stages in normal rodent locomotion.

7. Reinforcement learning deficits exhibited by postnatal PCP-treated rats enable deep neural network classification

URL: [View paper](#)

Brief Assessment

Deep Neural Classification[36] focuses on using deep neural networks to classify reinforcement learning deficits in PCP-treated rats, not on computational classification of developmental locomotor stages in normal rodent development.

8. An artificial neural network for automated behavioral state classification in rats

URL: [View paper](#)

Brief Assessment

Automated Behavioral Classification[37] focuses on classifying behavioral states (wake, sleep stages) using electrophysiological signals in adult rats, not on identifying developmental stages of locomotion in postnatal rats through movement statistics analysis.

9. Unsupervised classification of neocortical activity patterns in neonatal and pre-juvenile rodents

URL: [View paper](#)

Brief Assessment

Unsupervised Neocortical Classification[43] focuses on classifying neocortical oscillatory activity patterns (spindle bursts, nested gamma) in rodents, not locomotor development stages. The candidate paper analyzes neural network oscillations using features like amplitude, frequency, and cross-frequency coupling, whereas the original paper classifies movement statistics (speed, rotational speed, spatial transitions) to identify crawl/walk/run stages.

10. An automated behavior analysis system for freely moving rodents using depth image

URL: [View paper](#)

Brief Assessment

Depth Image Analysis[39] focuses on automated behavior classification using depth imaging techniques for freely moving rodents, not on computational classification of postnatal locomotor development stages or the identification of distinct developmental stages (crawl, walk, run) through movement statistics analysis.

Contribution 2: RNN model demonstrating how locomotor development drives spatial cell emergence

Description: The authors develop a recurrent neural network trained on visual prediction tasks using trajectories corresponding to developmental locomotion stages. The model recapitulates the sequential emergence of spatially tuned units mirroring biological developmental timelines observed in rats.

This contribution was assessed against **0 related papers** from the literature. Papers with potential prior art are analyzed in detail with textual evidence; others receive brief assessments.

Contribution 3: Novel prediction of directional selectivity emergence in place cells validated experimentally

Description: The model predicts that directional selectivity in hippocampus emerges primarily through conjunctive place-direction coding rather than pure head direction cells. The authors confirm this previously unreported developmental increase in conjunctive cells through analysis of CA1 recordings.

This contribution was assessed against **6 related papers** from the literature. Papers with potential prior art are analyzed in detail with textual evidence; others receive brief assessments.

1. Neural mechanisms of self-location

URL: [View paper](#)

Brief Assessment

Neural Self-Location[32] appears to focus on boundary-responsive cells and early place cell development mechanisms, not on the developmental trajectory of conjunctive place-direction coding that the original paper predicts and validates.

2. Altered hippocampal place cell representation and theta rhythmicity following moderate prenatal alcohol exposure

URL: [View paper](#)

Brief Assessment

Prenatal Alcohol Exposure[31] examines directional selectivity deficits in adult rats following prenatal alcohol exposure, not the developmental emergence of directional selectivity in healthy animals. The candidate focuses on pathological disruption rather than normal developmental mechanisms.

3. Development of spatial firing in the hippocampus of young rats

URL: [View paper](#)

Prior Art Analysis

Spatial Firing Development[34] demonstrates that directional selectivity in hippocampal neurons was already experimentally observed and characterized during development, predating the original paper's claim of novelty. The candidate paper directly reports empirical findings showing that head directional firing appears around day 30 and is essentially identical to adult animals, while place cell activity

develops more slowly. This establishes prior experimental evidence for the developmental emergence of directional coding in the hippocampus, which the original paper claims as a novel prediction from their model that they subsequently validated.

Evidence

Evidence 1 - **Rationale:** Spatial Firing Development[34] already reported experimental observations of head directional firing development in young rats (around day 30), demonstrating that directional selectivity emergence in hippocampal regions was empirically characterized before the original paper's claimed novel prediction. The candidate shows directional coding appears early while place cell specificity develops later, establishing prior knowledge of directional selectivity development. - **Original:** a particularly novel prediction arising from our model is that directional selectivity in the hippocampus emerges primarily through conjunctive place-direction coding rather than in pure head direction cells. we investigated this prediction in ca1 recordings and confirmed a significant developmental... - **Candidate:** however, preliminary results indicate that head directional firing recorded around day 30 is essentially identical to that seen in adult animals. therefore, the development of reliable, spatially specific place cell activity parallels the developmental time course of spatial navigational ability, bu...

4. Experience-dependent firing rate remapping generates directional selectivity in hippocampal place cells

URL: [View paper](#)

Brief Assessment

Experience-dependent Firing Remapping[30] studies directional selectivity development through experience-dependent plasticity in adult rats on tracks, not developmental emergence during postnatal maturation as claimed by the original paper.

5. Orientation selectivity enhances context generalization and generative predictive coding in the hippocampus

URL: [View paper](#)

Brief Assessment

Orientation Selectivity Enhancement[33] focuses on orientation selectivity in visual processing contexts, not directional selectivity in hippocampal place cells during development. The minimal context provided does not address hippocampal spatial coding or developmental emergence of conjunctive place-direction cells.

6. Sequential Development of Task Representation from Hippocampus to Prefrontal Cortex Supports Goal-Directed Spatial Navigation

URL: [View paper](#)

Brief Assessment

Sequential Task Representation[29] focuses on directional tuning in hippocampal-prefrontal networks during adult spatial navigation learning in 2D VR, not on developmental emergence of directional selectivity in place cells during postnatal maturation as studied in the original paper.

Appendix: Text Similarity Detection

No high-similarity text segments were detected across any compared papers.

References

- [0] From movement to cognitive maps: recurrent neural networks reveal how locomotor development shapes hippocampal spatial coding [View paper](#)
- [1] How development sculpts hippocampal circuits and function [View paper](#)
- [2] Emergence of orthogonal hippocampal representations during spatial learning. [View paper](#)
- [3] Experience of Euclidean geometry sculpts the development and dynamics of rodent hippocampal sequential cell assemblies [View paper](#)
- [4] Self-motion and the hippocampal spatial metric [View paper](#)
- [5] Locomotor action sequences impact the scale of representation in hippocampus and posterior parietal cortex [View paper](#)
- [6] Developmental perspectives on spatial navigation: sensory development, experience, and neuronal heterogeneity [View paper](#)
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- [28] Common to Development and Learning? [View paper](#)
- [29] Sequential Development of Task Representation from Hippocampus to Prefrontal Cortex Supports Goal-Directed Spatial Navigation [View paper](#)
- [30] Experience-dependent firing rate remapping generates directional selectivity in hippocampal place cells [View paper](#)
- [31] Altered hippocampal place cell representation and theta rhythmicity following moderate prenatal alcohol exposure [View paper](#)

- [32] Neural mechanisms of self-location [View paper](#)
- [33] Orientation selectivity enhances context generalization and generative predictive coding in the hippocampus [View paper](#)
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- [39] An automated behavior analysis system for freely moving rodents using depth image [View paper](#)
- [40] Quantification of early learning and movement sub-structure predictive of motor performance [View paper](#)
- [41] Repetitive motor behavior: further characterization of development and temporal dynamics [View paper](#)
- [42] Detecting ataxia using an automated analysis of motor coordination and balance of mice on the balance beam [View paper](#)
- [43] Unsupervised classification of neocortical activity patterns in neonatal and pre-juvenile rodents [View paper](#)
- [44] A role for motor neurons in the development and function of the spinal circuitry governing locomotion [View paper](#)