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# Flexible navigation with neuromodulated cognitive maps

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## Abstract

2 Animals naturally form personalized cognitive maps to support efficient  
3 navigation and goal-directed behavior. In the brain, the CA1 subregion  
4 of the hippocampus plays a key role in this process, hosting spatially  
5 tuned neurons that adapt based on the behavioral context and internal  
6 states. Computational models of this ability include labeled graphs  
7 with locally specified spatial information, which avoid global metric  
8 structure, and deep neural networks trained on spatial tasks that exhibit  
9 emergent spatial tuning. However, these approaches often struggle to  
10 model one-shot adaptive mapping and typically rely on plasticity rules  
11 that lack biological plausibility.

12 We propose a neural architecture inspired by place-cell dynamics that  
13 enables rapid on-the-fly construction of cognitive maps during explo-  
14 ration of novel environments. The model relies on velocity inputs and  
15 grid cell modules to generate spatial representations and integrates neu-  
16 romodulatory signals responsive to boundaries and rewards. Learning  
17 combines synaptic plasticity, lateral inhibition, and modulatory gating  
18 of place-cell activity. For reward-driven navigation, the agent uses a  
19 modified Dijkstra algorithm to plan paths on the emergent cognitive  
20 map, treating place cells as nodes in a locally structured graph.

21 We compare our model with standard reinforcement learning (RL)  
22 agents and find that it achieves significantly higher sample efficiency,  
23 solving tasks in a single episode that RL agents require thousands of  
24 training steps to master. This performance advantage arises from biolog-  
25 ically inspired inductive biases embedded in the model architecture. In  
26 simulation, the agent adapts to dynamic reward locations and changes in  
27 the environment layout. Analysis of neuromodulated place cells reveals  
28 task-dependent changes in tuning field size and spatial density, aligning  
29 with experimental findings from hippocampal recordings. These results  
30 highlight the promise of biologically grounded computation and locally  
31 structured graph representations for flexible and data-efficient cognitive  
32 mapping.

33 

## 1 Introduction

34 Survival in complex environments demands efficient navigational strategies. From desert ants to  
35 humans, successful wayfinding—navigating toward goals out of sight—relies on internal spatial  
36 representations, or *cognitive maps* [1, 2]. These maps enable flexible planning and decision-making  
37 beyond simple stimulus-response associations.

38 Cognitive map theories propose multiple strategies for spatial navigation, ranging from simple route  
39 learning to survey-based and graph-based models. Route learning stores paths as action-  
40 position pairs but struggles with scalability and generalization at intersections [3, 4, 5]. Survey maps,  
41 grounded in Euclidean geometry, offer greater flexibility [4, 6] but sometimes contradict neural  
42 and behavioral data showing geometric distortions and topological biases [7, 8, 9, 10]. Labeled  
43 graphs strike a balance—encoding landmarks and transitions in a topological network that supports  
44 vector-like operations, planning, and prediction [11, 12, 13].

45 Neural substrates of spatial representations reside in the hippocampus (HP) and entorhinal cortex  
46 (EC), where specialized cells—including grid, border, speed, and place cells—encode geometric  
47 and contextual variables [14, 15, 16]. Place cells, particularly in CA1, anchor cognitive maps [17],  
48 integrating converging inputs from grid cells, CA3, and lateral EC [18, 19, 20, 21].

49 Neuromodulation plays a critical role in shaping this circuitry. Dopamine and other modulators  
50 adjust synaptic strength, tune place fields, and encode novelty and reward-prediction errors [22,  
51 23, 24]. These projections reshape spatial tuning [25, 26, 27, 28], support novelty detection [23],  
52 and transmit prediction errors, particularly via lateral EC inputs [29, 30]. These mechanisms echo  
53 principles of reinforcement learning (RL), highlighting the role of neuromodulation in adapting  
54 spatial representations to behavioral relevance [31, 24].

55 Computational models have captured individual components of this system. Early work proposed that  
56 the hippocampus encodes spatial position and direction [32], while topological models based on route  
57 learning highlight scalability challenges [5]. More recent approaches draw from predictive coding and  
58 reinforcement learning, including successor representations and the Tolman-Eichenbaum Machine,  
59 which generalize across spatial and relational tasks while mimicking biological activity patterns  
60 [33, 34, 35]. Path integration models trained on motion cues give rise to grid- and place-like tunings  
61 [36, 37, 38]. Others incorporate reward-driven Hebbian plasticity modulated by neuromodulators  
62 [39]. Yet, few architectures unify these ingredients into a biologically grounded system that learns  
63 online and adapts flexibly to novelty.

64 In this work, we introduce a biologically inspired model of cognitive map formation that integrates  
65 place cell representations, neuromodulatory signals, and graph-based spatial reasoning. The model  
66 constructs a topological map online, linking place cells along experienced trajectories and enriching  
67 them with scalar-valued modulatory signals. These modulators form analog fields across the map  
68 [40], drive local Hebbian plasticity in response to sensory prediction errors [41, 31, 42], and help  
69 maintain and adapt reward-based neural representations [43, 44, 45, 46, 34].

70 This architecture supports efficient goal-directed navigation without extensive offline training, lever-  
71 aging spatial priors, online plasticity, and modulatory feedback. We demonstrate how this system  
72 adapts to environmental changes and how neuromodulation influences place field allocation and  
73 remapping [47, 48], linking cognitive flexibility to underlying physiological mechanisms.

74 The remainder of the paper is organized as follows: Section 2 details the model and experimental  
75 setup; Section 3 presents results; Section 4 discusses broader implications and future directions.

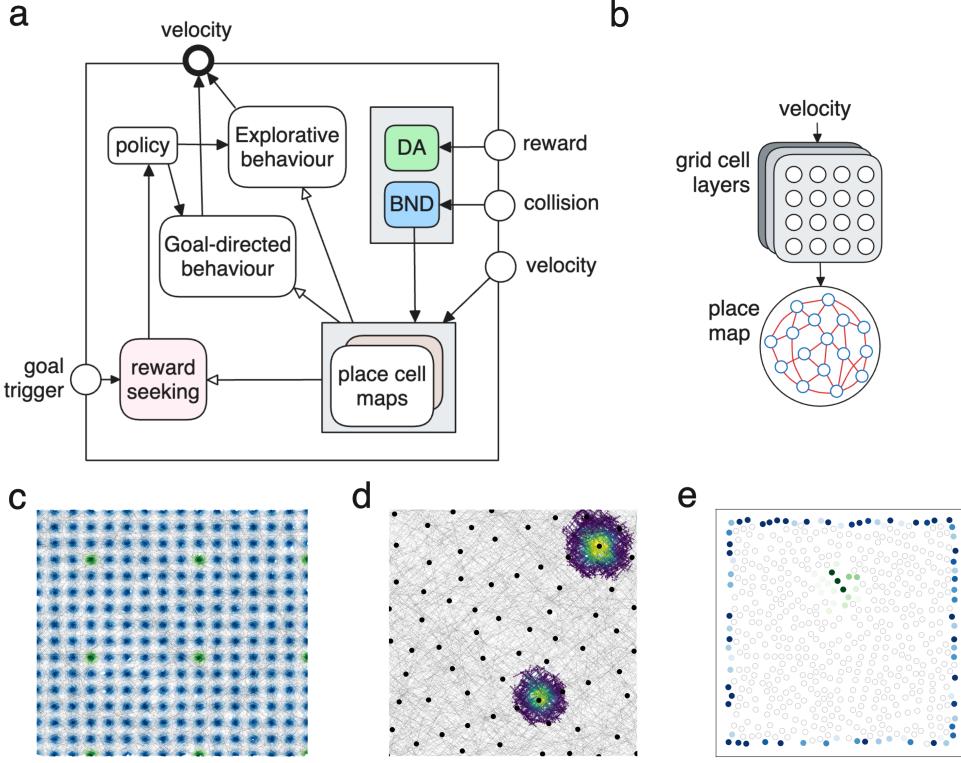
## 76 2 Methods

77 Our model focuses on cognitive map formation through an agent’s experiences within a closed  
78 environment, as illustrated in Figure 1a..

79 The architecture operates with minimal external information—just binary reward and collision signals.  
80 Instead, spatial representation emerges primarily from idiothetic information: the agent’s perception  
81 of self-motion [49]. Specifically, we use the factual velocity vector (the agent’s actual environmental  
82 displacement) as the primary navigational cue, which in biological systems emerges from integrated  
83 inertial and relative motion signals [50, 51].

84 **Place Cell Formation** Spatial representation begins with a stack of grid cell modules, each encoding  
85 a periodic tiling of space over a 2D torus  $T^2$  (Fig.1b,c). Grid cell activity vectors  $\mathbf{u}^{GC}$  project to two  
86 place cell layers with initially zeroed weights. When no place cells activate for the current input,  
87 a silent neuron is randomly selected and imprinted with the current activity. To ensure selectivity,  
88 imprinting is aborted if the new weight vector overlaps too strongly (via cosine similarity) with  
89 existing ones.

90 Each place cell's activation is given by a bounded activation function based on cosine similarity.  
 91 Details of lateral inhibition and recurrent connectivity are given in Appendix A.1.



**Figure 1: Model layout and spatial representations - a:** the full architecture of the model, consisting of three main sensory input, targeting the two modulators and the cognitive map module, and the executive components, represented by a policy module, two behavioral programs and a reward receiver. **b:** the cognitive map component, organized with a stack of grid cell modules receiving the velocity input and projecting to the layer of place cells. **c:** the neural activity of a grid cell module from a random trajectory; in blue the repeating activity of all cell, while in green the activity of only one, highlighting the periodicity in space. **d:** the distribution in space of the place cells centers, together with the activity of two cells showing the size of their place field. **e:** neuromodulation activity over the place cells map, with in blue the cells tagged by the collision modulation, and in green the ones targeted by reward modulation.

92 **Neuromodulation** Neuromodulators encode environmental salience. Two scalar modulators, one  
 93 for reward (DA) and one for boundary collisions (BND), are driven by binary inputs I and accumulate  
 94 over time via exponential decay.

95 Each modulator  $k$  updates synaptic weights to place cells through Hebbian plasticity:

$$\Delta \mathbf{W}^k = \eta^k v^k \mathbf{u}^{PC}$$

96 Weight vectors are constrained to remain non-negative. Reward modulation tags cells near rewarded  
 97 locations, while boundary modulation builds a representation of environmental edges. These scalar  
 98 fields form the core of the cognitive map (Fig. 1e). See Appendix A.2 for full learning rules and  
 99 parameter settings.

100 **Online Adaptation** To remain resilient to environmental changes (e.g., moving rewards), the  
 101 model uses a predictive mechanism to correct outdated internal representations. Before executing a  
 102 movement toward position  $\mathbf{x}_{t+1}$ , the system predicts the expected value  $\hat{v}^k$  of neuromodulator  $k$  at

103 that location. Then, a prediction error is computed and used to adjust the weights:

$$\Delta \mathbf{W}^k \leftarrow \Delta \mathbf{W}^k + \hat{\eta}^k (\hat{v}^k - v^k) \mathbf{u}^{PC}$$

104 The prediction learning rate  $\hat{\eta}^k < 1$  ensures that small errors are corrected gradually, while repeated  
105 mismatches lead to weight depression. This mechanism implements a simple form of predictive cod-  
106 ing and is inspired by temporal-difference learning [52], aligning with evidence that neuromodulatory  
107 systems signal prediction errors and update beliefs [53, 34, 54].

108 **Modulation of Place Fields** We further tested whether neuromodulators could directly alter spatial  
109 tuning. Place fields were dynamically shifted and resized based on recent salience signals.

110 Following a salient event (reward or collision), place field centers were displaced in grid cell space,  
111 with magnitude scaled by the neuromodulator  $v^k$  and proximity to the event:

$$\Delta \mathbf{W}_i^{GC,PC} = c^k v^k \varphi_{\sigma^k} (\mathbf{u}^{GC} - \mathbf{W}_i^{GC,PC})$$

112 Here,  $\varphi_\sigma$  is a Gaussian function, and  $c^k$  a scaling factor. This rule is inspired by BTSP plasticity  
113 [27, 47], which shifts CA1 place fields following salient experiences. Lateral inhibition prevents field  
114 overlap during remapping.

115 In addition to dislocation, field size was modulated by scaling the gain of recently active neurons.  
116 The gain  $\beta_i$  of each cell was adjusted via a trace variable  $m_i$ . This provides a mechanism for  
117 neuromodulators to transiently enhance or suppress spatial sensitivity.

118 **Policy and Behavior** To evaluate the model’s utility in navigation, we implemented a simple policy  
119 toggling between exploration and goal-seeking behavior, depending on an external goal flag and the  
120 internal map.

121 Exploration consisted of a stochastic walk with persistence, plus periodic plans to visit random known  
122 locations to avoid stagnation. Goal-directed navigation was triggered when a reward representation  
123 was present and executed via shortest-path planning on the place cell graph.

124 The graph was defined by place cells as nodes and synaptic links as edges. The agent selected targets  
125 either randomly or based on cells with high dopaminergic weight, echoing hippocampal replay and  
126 value-based navigation [55, 56, 57]. Planning was achieved via Dijkstra’s algorithm with a cost  
127 function that penalized proximity to boundaries.

Table 1: Comparison of neural network models for spatial navigation and representation

Model	Architecture	Training method	Ext. C.
Banino et al. [36]	LSTM + linear layers + CNN	BPTT and deep RL, supervised	Yes
Cueva et al. [38]	RNN + linear layers	Hessian-free algorithm with regularization	Yes
Sorcher et al. [37]	RNN + linear layers	Backpropagation with regularization	Yes
Whittington et al. [35]	Attractor network and deep networks	Backpropagation and Hebbian learning	No
de-Cothi et al. [34]	Successor representation	TD-learning + eligibility traces	Yes
Brozsko et al. [58]	Spike Response Model	Online modulated Hebbian plasticity	Yes
<b>Ours</b>	Rate layers	Online neuromodulated plasticity	No

Model	Task	Input	Output
Banino et al.	Path integration, goal navigation	Velocity, visual input, reward	PC, HDC
Cueva et al.	Path integration	Velocity	Position
Sorcher et al.	Path integration	Velocity	PC
Whittington et al.	Relational graph knowledge	Observation and action	Observation
de-Cothi et al.	Planned navigation	Observation	–
Brozsko et al.	Goal navigation	Position, reward	Action
<b>Ours</b>	Goal navigation	Velocity, reward, collision	Action

Note: PC = Place Cells, HDC = Head Direction Cells, Ext. C. = External Spatial Coordinates

128 **Comparison with previous architectures** Several previous computational models show structural  
 129 and conceptual similarities with the present work. A prominent category among them employs deep  
 130 neural networks—often with recurrent components—and relies on gradient-based learning strategies  
 131 such as backpropagation through time. These models typically require multiple training episodes or  
 132 large datasets for convergence. In contrast, our model adopts biologically inspired, synaptically local  
 133 plasticity rules, and requires only a single training episode for adaptation.

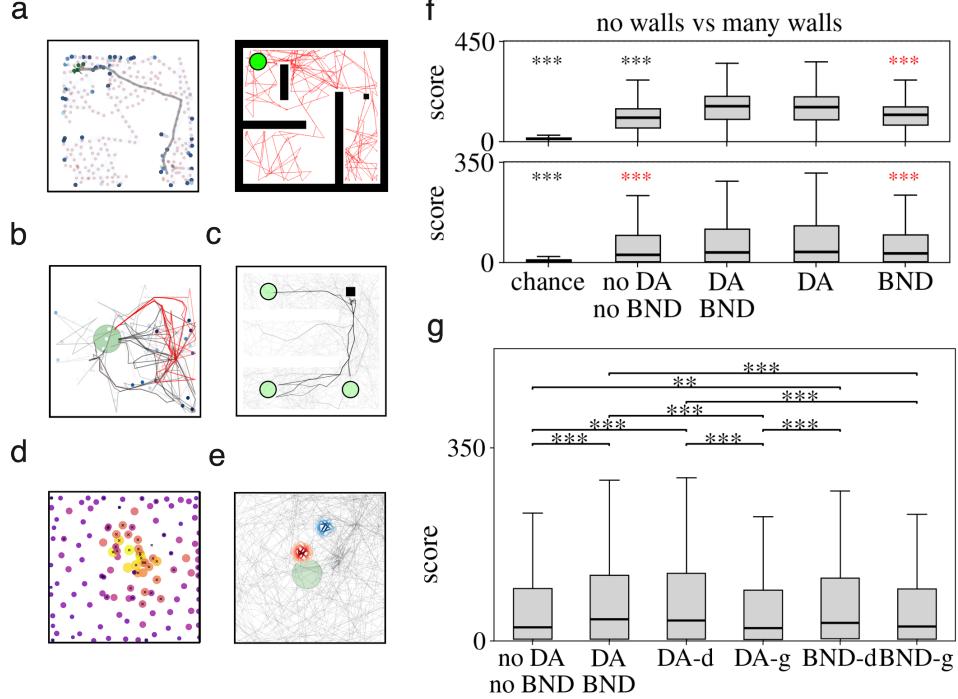
134 Other models utilize spiking neurons [58] or explicit neural representations [34], and incorporate  
 135 online learning rules more closely aligned with ours. These models also focus more directly on  
 136 goal-directed navigation, in contrast to purely path integration tasks. However, both of these rely on  
 137 external spatial coordinates to represent current position. Our model instead constructs an internal  
 138 coordinate system by integrating its own velocity output, enabling endogenous spatial tracking.

139 **Naturalistic task** The model was evaluated on a biologically inspired navigation benchmark  
 140 involving exploration and goal-seeking behavior in closed environments. Performance was measured  
 141 as the total number of rewards collected over multiple trials.

142 Optimization of the model parameters was carried out using the evolutionary Covariance-Matrix  
 143 Adaptation strategy (CMA-ES) [59] with a population of 128 individuals for 100 generations.

### 144 3 Results

145 **Performance in wayfinding** Our primary aim was to evaluate the formation of the cognitive map  
 146 through neuromodulation in terms of the performance of the goal navigation in different environments.



**Figure 2: Cognitive maps and performance results - a:** the plot on the left represent a cognitive map over a space, together with the plan (grey line) to reach a target location from a starting position. The plot on the right is a view of the same environment but with highlighted walls (black thick lines) the reward (green circle), trajectory (red line), agent position (black square). - **b:** plot of trajectories before (black) and after (red) the insertion of a wall between the starting and goal positions, the wall can be spotted from the boundary cells in blue - **c:** trajectories for multiple trials with the agent starting at the same position (black square) but with the reward location (green circles) periodically moving - **d:** place cells centers with size and color proportional to its node degree (number of neighbors); further, it notable is the correlation with the distance from the reward (in the center) - **e:** place fields of the same cell before and after several relocation of its center following reward events - **f:** performance comparison with same environmental conditions for five different models: one baseline as chance level (plasticity disabled, except for place cells generation), and four variants with different ablations of DA and BND modulations of place fields density and size. Results in terms of reward count and Bonferroni-corrected pairwise t-test, black stars stand for statistical difference with respect to all other groups, red starts only to the DA and DA+BND. - **g:** ablation performance comparison similar to c, and over the same environment for model variants with different active modulatory mechanisms: no DA and BND place field modulation, full DA and BND, DA-d for PC density, DA-g activation gain, BND-d for PC density, BND-g for activation gain.

147 The best model resulting from evolution reached solid navigation and adaptation skills. The agent  
 148 was able to visit a significant portion of the environment during exploration and use neuromodulation  
 149 to produce useful spatial representations.

150 The left panel of plot 2a displays place cells associated with collisions and reward events, signaling  
 151 boundaries (in blue) and reward (in green) locations. The overlap of these two representations and  
 152 the place cells (in pink) is what we refer to as a cognitive map, since these are the main sources of  
 153 spatial and contextual information used during planned navigation, whose path is depicted as a gray  
 154 line. The right panel instead portrays the actual environment with walls (black), reward location  
 155 (green), and multiple trajectories (red). During exploration, the main areas were visited until the  
 156 reward position was located and the goal-directed navigation dominated, as highlighted by the density  
 157 of the path lines. Considering the position of the walls and corners, the layout of this environment  
 158 does not always make the target locations visible, as it is a non-convex area and therefore can be  
 159 classified as wayfinding [60]. The challenge of not being able to use straight lines is overcome by the  
 160 graph approach using local data and the consideration of boundary place cells, allowing the agent to

161 plan accordingly. In addition, by construction the path also minimized the length of the path, within  
162 the part of the space covered by the cognitive map.

163 In general, this result confirms the ability of the model to focus on navigation and obstacle avoidance.  
164 However, it is worth nothing that not all simulations resulted in a reward being found in the first place,  
165 due to the randomness of the exploratory process; this was more pronounced in complex environment.

166 **Detour task** The planning ability and the plastic nature of the cognitive map should provide re-  
167 silience against unexpected changes in the environment layout. In order to verify this we implemented  
168 a detour experiment. Initially, the agent was familiarized with a square environment with the reward  
169 in the middle and starting always from the same position. Then, a wall was placed in between the  
170 starting position and the reward, therefore forcing new trajectory for reaching it. As expected, the  
171 agent was able to form a representation of the new obstacle and calculating new paths around it,  
172 succeeding the task. In plot 2b they are shown the trajectories before and after the wall placement,  
173 and it is manifested the ability of detour in the new layout.

174 **Adaptive goal representation through prediction error** Then, we tested the adaptability to  
175 environmental changes. In this scenario, the reward object was moved after being fetched a fixed  
176 number of times. Here, the difficulty was to unlearning previous locations and discovering new ones,  
177 in a protocol similar to [39]. In plot 2c is reported the set of trajectories over many trials with the  
178 reward displaced in three possible locations. The agent was capable of planning behavior, as earlier,  
179 but also exploring and finding the new rewards, as shown by the density of lines. Whenever a goal  
180 path resulted in a failed prediction, the DA-based sensory error weakened the association between the  
181 place cells and the reward signal, leading to an extinction of its representation at that location.

182 This result validates the resilience of the model to changing sensory expectations, in this case the  
183 reward position.

184 **Modulation of spatial resolution affects performance** Lastly, we investigated the effect of  
185 modulating the density of place cells and the size of the field. The goal position was fixed, but the  
186 agent was randomly relocated after fetching; performance was defined as the total number of reward  
187 counts within a time window.

188 Our working hypothesis is that these experience-driven neuronal changes would improve the quality  
189 of the cognitive map and be reflected in navigational abilities. The assessment of this claim was  
190 conducted by comparing variants of the model, obtained by progressively ablating the reward (DA)  
191 and collision (BND) modulation of density and field size, but a cognitive map was still possible as  
192 their representations of goals and boundaries were preserved. We also defined a chance level by  
193 instead blocking all modulation-based plasticity and allowing only place cells to form. All models  
194 were run in two different environments differing by number of internal walls, in total 2048 simulations  
195 were done for each case.

196 Plot 2d showcases the distribution of place cells with the circle size and color represent the node  
197 degree, which aligns discretely with the reward position and the density. Further, in plot 2e the  
198 place field of one cell is shown, before and after several reward occurrences and consequent center  
199 relocation.

200 The statistical results are shown in plot 2f. The top reports the scores in the setting without internal  
201 walls. All models performed above chance, but the main finding is the affirmation of the importance  
202 of neuronal modulation, as revealed by the statistical difference between those endowed with it and  
203 the one not. Furthermore, possession of DA modulation resulted in a significantly higher score than  
204 BND modulation alone (red stars). In fact, in a situation with a convex region such as this, once the  
205 reward has been located, the boundary information has limited utility.

206 A similar pattern emerged when more internal walls were introduced, as shown by the results at the  
207 bottom. In this environment, scores were overall lower as navigation became more difficult, and  
208 the difference among groups thinner, although noticeable. Here, the sole presence of the boundary  
209 modulation of place cells did not result in better performance than the baseline. This outcome  
210 highlights how the main improvements are brought by reward-driven neuronal modulation (DA).

211 Then, in order to enquiry which particular modulatory action was mostly relevant, we conducted a  
212 similar test on the same environment but ablating not only specific neuromodulators, but also whether

213 they affected the place cells density or the activation gain parameter. In plot 2g are reported the  
214 comparisons among different variants. The general trend matched the previous results 2c, in that DA  
215 is the best neuromodulator in terms of correlation with performance. The additional finding was that  
216 density modulation is significantly the primary action behind the behavioural improvements, and  
217 alone does not perform worse than the model with all actions together.

218 Taken together, these findings support the hypothesis of practical utility of direct modulation of  
219 place-field structure for active navigation, even in these simple settings.

## 220 4 Discussion

221 Exploration and planning in known and past environment are essential behaviors of animals, directly  
222 affecting their success in world understanding and goal reaching.

223 An important element behind these abilities is the formation of a map of their surroundings as they  
224 make new experiences, known as a cognitive map. Numerous speculations have been made about the  
225 shape and neural foundations of such an object, varying in the types of modeling assumptions and  
226 experimental support.

227 The contribution of the present work was to propose a rate network model, inspired by the CA1  
228 hippocampal region [17]. We used grid cells together with synaptic plasticity as a mechanism to  
229 develop information-rich representations based on place cells updated through experience, grouped  
230 with common perspectives on cognitive maps [61]. In the spirit of minimizing the geometric  
231 assumptions in the neural space, we treated the generated place network as a topological graph, with  
232 sensory information added locally through the action of neuromodulators. This idea aligned with the  
233 concept of a *labeled graph* [62, 8], however, it is also true that no metric violations were actually  
234 possible in these settings.

235 The tasks we applied the agent consisted of an exploratory and exploratory phase, in which it was  
236 prompted to plan and reach reward positions. For simplicity, the first stage relied on a random walk  
237 process, as it was outside the scope of this work. This choice had the side effect that the reward was  
238 not always discovered, leading to the formation of incomplete maps, and thus impairing performance.  
239 However, this issue was limited in frequency.

240 The simulation results validated the model, showing the expected emergence of cognitive maps and  
241 their encoding of information collected during the experience. The online nature of the formation  
242 of the locations on the map aligns with the idea of using only idiothetic velocity input, as in path  
243 integration [6, 63, 64]. Previous work followed a similar direction using recurrent networks, but  
244 required extensive gradient-based training [65, 38, 51]. Another important difference is that our  
245 resulting neural network was composed solely of place cells, although neuromodulated, and no other  
246 types of neuron were present. This distinction is justified by the partially different task structure, which  
247 did not involve supervised learning and did not receive visual information as in [36]. Furthermore,  
248 our model relied on predefined grid cells layers, which constituted a strong and sufficient inductive  
249 bias, and did not have to be learned from scratch.

250 An additional relevant aspect is also the consideration of the place cell layer as an explicit graph data  
251 structure, on which the path-planning and decision-making algorithm was applied. The adoption of  
252 this level of description lead to robustness and flexibility, enabling effective navigation in all tested  
253 environments, which varying in layout complexity. Nevertheless, this approach did act as another  
254 clear inductive bias, which lifted the need to learn an approximation of it through network dynamics  
255 and even more differently tuned neurons.

256 Adaptability was tested by occasionally moving the reward position, leading to the generation of  
257 an internal prediction error that was used to update its representation on the map. The agent was  
258 proved capable of unlearning previous associations, returning to exploration, and memorizing new  
259 reward locations. This behavioral protocol is similar to previous work [58], in which dopaminergic  
260 and cholinergic activity was utilized within a Hebbian plasticity rule to strengthen or weaken reward-  
261 associated spatial representations. However, alternatively to exploiting neuromodulators with opposite  
262 valence, we followed a predictive coding framework, a direction linked to hippocampal representations  
263 [34, 66] and explored various computational approaches [67, 68, 69]. This choice departed from our  
264 focus on using operations on the cognitive map itself by simulating future sensory experiences and

265 learning from feedback. In fact, neuromodulation has been long associated with this functionality  
266 [40], especially dopamine [25, 43, 46, 31].

267 Lastly, the hypothesis of relevance of the active modulation of the neuronal properties of place cells  
268 was corroborated by simulating ablation experiments. These tests reported a significant impact of  
269 altering the place cells density on the total count of collected rewards. In general, these results are  
270 consistent with the experimental observations of alteration of place cells following reward events  
271 [27, 70], in particular in terms of increased clustering of cells [71, 72], reminiscent of changes in  
272 firing rate after contextual changes [73, 74].

273 Concerning the modulation of place fields, there is significant experimental evidence of their alter-  
274 nation during reward events [75, 76, 77], some reporting shrinkage near reward objects [78], and  
275 boundaries [79]. The coupling with higher local density could be explained by better optimization of  
276 the cell distribution for goal representation and planning [80]. However, in our settings, the fields  
277 become enlarged, especially in the direction of the target, although the performance improvements  
278 were not tested significant. A possible explanation can be the simplicity of our reward, which was  
279 solely defined as an area of space. The lack of rich non-spatial features thus did not require the place  
280 cells to code for smaller spatial variation. Therefore, enlargement might have improved the stability  
281 of the representation, marking the nodes associated with rewards more solidly, given the stochasticity  
282 of its delivery. Further, the graph-path algorithm utilized the strength of the DA-modulated connec-  
283 tions for determining the goal representation, stronger fields inherently developed stronger weights,  
284 making planning more reliable planning. Although these findings are limited within the limit of our  
285 simulation protocol, there have been experimental observations of elongation of place fields along  
286 trajectories over meaningful experiences [81, 82].

287 In conclusion, this work showed a possible architecture for coupling emergent spatial representations  
288 with neuromodulated plasticity to achieve an experience-driven cognitive map. The reliance of few  
289 spatial and algorithmic inductive biases, grid cells and planning algorithm, supports the idea of label  
290 graph for goal navigation. Future work can investigate the application to other spatial domains,  
291 such as motor control and three-dimensional navigation. In addition, a richer input feature can be  
292 added, such as visual information [83], as well as new neuromodulators that encode different sensory  
293 dimensions or internally generated signals.

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295

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297 The authors declare no competing interests.  
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## 536 5 Appendix

### 537 5.1 Grid cell module

538 Unlike other approaches to generate grid fields [84, 85], we defined a correspondence between the  
539 global environment in which the agent moves, a two-dimensional Euclidean space  $\mathbf{R}^2$ , and a bounded  
540 local space of a grid module, corresponding to the torus.

541 The global velocity  $\mathbf{v} = \{x, y\}$  is then mapped to a local velocity, scaled by a speed scalar  $s_l^{gc}$  specific  
542 to the grid cell module  $l$ , which determines its periodicity in space. This approach has been used in  
543 previous works [20].

544 The choice of a toroidal space is motivated by consolidated experimental evidence of the neural space  
545 of grid cells, which are organized in modules of different sizes spanning the animal’s environment.  
546 However, the shape of their firing pattern is known to be hexagonal, which corresponds to the optimal  
547 tiling of a two-dimensional plane, giving rise to a neural space lying on a twisted torus. In this work,  
548 for simplicity, we consider a square tiling and thus a square torus, without much loss of generality  
549 except for the slight increase of grid cells required for a sufficiently cover.

550 A grid cell module  $l$  of size  $N^{gc}$  is identified by a set of positions defined over a square centered  
 551 on the origin and size of 2, such that  $\{(x_i, y_i) \mid i \in N^{gc} \wedge x_i, y_i \in (-1, 1)\}$ . This local square  
 552 space has boundary conditions for each dimension, such that, for instance, when  $x_t + s_l^{gc} \cdot v_x > 2$   
 553 the position update is taken to the other side  $x_{t+1} = x_t + s_l^{gc} \cdot v_x - 2$ , where  $s_l^{gc}$  is the scale of the  
 554 velocity in the local space of the module  $l$  with respect to the real global agent velocity  $v = \{v_x, v_y\}$ .  
 555 When the module is initialized, the starting positions of its cells are uniformly distributed over the  
 556 square forming a lattice. When the agent is reset in a new position at the beginning of new trial, a  
 557 displacement vector is applied to the last cells positions such that the mapping between the module  
 558 local space and the global environment is preserved.

559 The firing rate vector of each cell is determined with respect to a 2D Gaussian tuning curve centered  
 560 at the origin at  $(0, 0)$ , and it is calculated as

$$561 r_i = \exp\left(-\frac{x_i^2+y_i^2}{\sigma_l^{gc}}\right), \text{ where } \sigma_l^{gc} \text{ is the width of the tuning curve for module } l.$$

562 The final population vector of the grid cell network GC is the concatenated and flattened firing rate  
 563 vector of all modules  $\mathbf{u}^{GC}$ .

564  
 565 In our model, each grid cell had a tuning width of 0.04. They were defined as 8 modules of size 36,  
 566 and the relative speed scales were  
 567  $\{1., 0.8, 0.7, 0.5, 0.4, 0.3, 0.2, 0.1, 0.07\}$ .

## 568 5.2 Place cells

569 **Tuning formation** The tuning of a new place cell is simply defined as the current GC population  
 570 vector  $\mathbf{u}_i^{GC}$ , and its index is that of the first silent cell, which is added to the forward weight matrix  
 571  $\mathbf{W}_i^{GCtoPC} \leftarrow \mathbf{u}^{GC}$ .

572 In order to avoid overlapping of place fields, the tuning process is aborted in case the cosine similarity  
 573 of the new pattern and the old ones is greater than a threshold  $\theta_{rep}^{PC}$ .

574 Each cell represents a position in the GC activity space, which can be considered a node within a  
 575 graph of place cells (PC). Although it is totally possible to only use the  $N^{GC}$ -dimensional tuning  
 576 patterns and be agnostic about the dimensionality of the space in which the agent lives, to simplify  
 577 the calculations, we mapped each pattern to 2D positions in a vector space. Then, the PC recurrent  
 578 connectivity matrix is calculated with a nearest neighbors algorithm, which instead of a fixed number  
 579 K of neighbors uses a distance threshold  $\theta_{rec}^{PC}$ .

580 **Activity** The current firing rate of the PC population is determined by the cosine similarity between  
 581 the GC input and the forward weight matrix, then passed through a generalized sigmoid  $\phi(z) =$   
 582  $[1 + \exp(-\beta(z - \alpha))]^{-1}$ . The parameter  $\alpha$  represents the activation threshold, or horizontal offset,  
 583 while  $\beta$  the gain, or steepness.

$$u_i^{PC} = \phi\left(\cos\left(\mathbf{u}^{GC}, \mathbf{W}_i^{GC,PC}\right)\right)$$

584 It is also defined as an activity trace, which has an upper value of 1 and decays exponentially:

$$m_i = -m_i/\tau^{PC} + u_i$$

585 It is used as a proxy for a memory trace.

586  
 587 In the model, a PC population is defined by its average place field size, determining the granularity of  
 588 the representation of the place.

589 Below, a table of the parameters specific to the two PC populations is reported.

	$\beta$	$\alpha$	$\theta_{\text{rep}}^{\text{PC}}$	$\theta_{\text{rec}}^{\text{PC}}$	$\tau^{\text{PC}}$
pc	33.0	1.0	0.86	43	140

Table 2: PC layer parameters

### 590 5.3 Modulation

591 Neuromodulation is defined in terms of a leaky variable  $v$  whose state is perturbed by an external  
 592 input  $x$ , whose qualitative meaning differs for each neuromodulator  $k$ .

$$\begin{aligned} v_k &= -v_k/\tau_k + x_k \\ v_k &= \max(v_k, 0) \end{aligned} \quad (1)$$

593 **Learning rule** The connection weights  $W^k$  are updated according to a plasticity rule composed of  
 594 an Hebbian term, involving the leaky variable and the place cells above a certain threshold  $\theta^k$ , and a  
 595 prediction error.

596 A prediction  $p$  is calculated before each time-step and signifies the expected neuromodulation  
 597 activation for a given place cell  $\hat{v}_i^k = W_i^k \hat{u}_i^{\text{PC}}$ , where  $\hat{u}_i^{\text{PC}}$  is the PC population vector obtained by  
 598 simulating the planned action. A prediction error is computed as the difference between the prediction  
 599 and the current modulated place activation.

600 The full connection update then becomes:

$$\Delta W_i^k = \eta^k v_i^k u_i^{\text{PC}} - \eta_{\text{pred}}^k (\hat{v}_i^k - v_i^k) u_i^{\text{PC}}$$

601 where  $\eta^k$ ,  $\eta_{\text{pred}}^k$  are the learning rates, interpretable as the weight contribution of the Hebbian coupling  
 602 and prediction accuracy respectively. Additionally, connections values are kept non-negative and, in  
 603 order to speed up the extinction of past place-reward associations, if a non-zero prediction error is  
 604 below a 0.5 then it is set to 0.5.

605 **Active neuronal modulation** Neuromodulation acts on the neuronal profile of the place cells by  
 606 affecting the value of the activation gain and relocate the center of their tuning.

607 Gain modulation is implemented using the activity traces and a constant reference gain value  $\bar{\beta}$ :

$$\beta_i = c_a^k m_i \bar{\beta} + (1 - m_i) \bar{\beta}$$

608 where  $c_a^k$  is a scaling gain parameter, and if it is 1 then no modulation takes place.

609 Concerning center relocation, it is applied to recently active neurons with non-zero trace  $m_i$ . For a  
 610 place cell  $i$  with position  $x_i$  (in the vector space), it is calculated a displacement vector  $q_i$  with respect  
 611 to the current position  $x_j$ , identified as the most active place cell  $j$ .

$$q_i = c_b^k v^k \exp \left( -\frac{\|x_i - x_j\|}{\sigma^k} \right)$$

612 where  $c_b^k$  is a scaling relocation parameter, while  $\sigma^k$  the width of the Gaussian distance. This  
 613 displacement is used to move in GC activity space and get the new GC population vector to use as  
 614 tuning pattern.

615 Also in this case, it is ensured that the new place field center is at a minimum distance  $\theta_{\min}^{\text{PC}}$  from the  
 616 others; here Euclidean distance is used.

### 617 5.4 Decision making

#### 618 Behaviour selection logic

619 The possible behaviours are *exploration* and *exploitation*, and an action is defined as a 2D velocity

620 vector. For exploration, an action can be generated either as random navigation, using a polar vector  
 621 of fixed magnitude (the speed) and angle sampled from a uniform distribution, or as a step within  
 622 a goal-directed navigation plan to reach a random destination, which corresponds to a randomly  
 623 sampled existing place cells. In the goal-directed navigation the magnitude of the velocity vector  
 624 is less or equal than a fixed speed value, depending on the distance from the next target position in  
 625 the plan. Instead, for the exploitation behaviour, the action is a step within a goal-directed navigation  
 626 towards the reward location. The behaviour selection process depends on the experience of collision,  
 627 the presence of a plan, and the success in the navigation planning. A diagram of this logic is reported  
 628 in Figure 3.

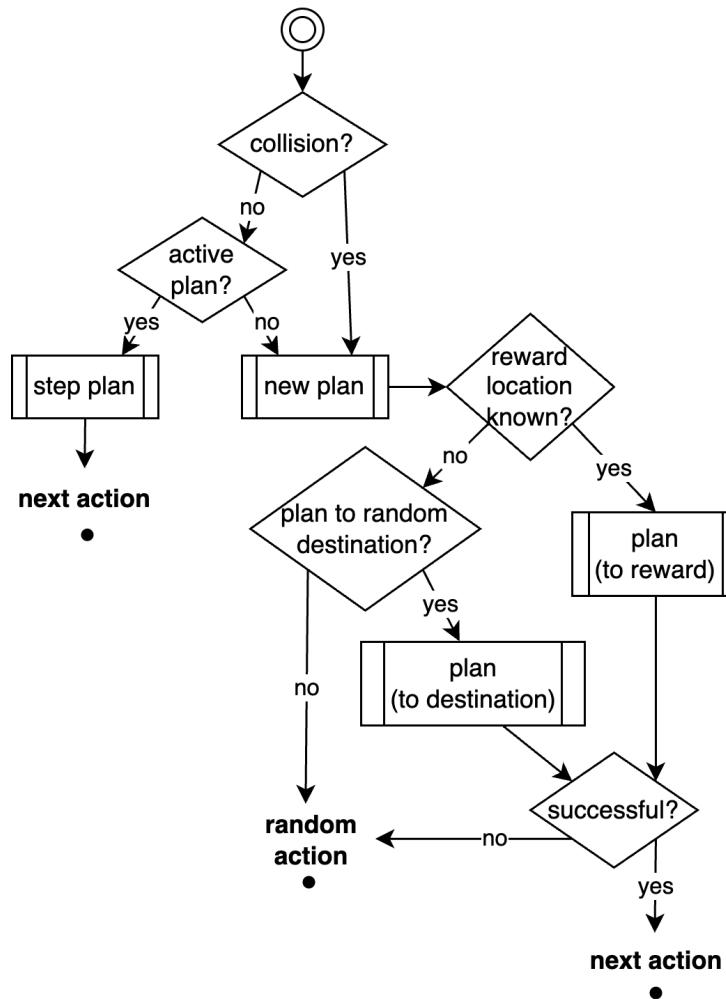


Figure 3: Diagram of the behaviour selection process

629 Path-planning algorithm  
 630

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**Algorithm 1** Modified Dijkstra algorithm

---

**Require:** Connectivity matrix  $\mathbf{C} \in \{0, 1\}^{N^{PC} \times N^{PC}}$ , Node coordinates  $\mathbf{x} \in \mathbb{R}^{N^{PC} \times 2}$ , Node weights  $\tilde{\mathbf{W}} \in \mathbb{R}^{N^{PC}}$ , Start node s, End node t

**Ensure:** Shortest path from  $t_0$  to T

```

1: distances  $\leftarrow [\infty, \infty, \dots, \infty]$                                  $\triangleright$  Initialize distances
2: distances[ $t_0$ ]  $\leftarrow 0$ 
3: parent  $\leftarrow [-1, -1, \dots, -1]$                                           $\triangleright$  Parent pointers
4: finalized  $\leftarrow [\text{false}, \text{false}, \dots, \text{false}]$                        $\triangleright$  Set of finalized nodes
5: PQ  $\leftarrow \emptyset$                                                         $\triangleright$  Priority queue
6: PQ.push((0,  $t_0$ ))                                                  $\triangleright$  Insert start node with priority 0
7: while PQ  $\neq \emptyset$  do
8:   (dist, j)  $\leftarrow$  PQ.extractMin()
9:   if finalized[j] or dist > distances[j] then
10:    continue
11:   end if
12:   finalized[j]  $\leftarrow$  true
13:   if j = T then
14:     break                                                                $\triangleright$  Destination reached
15:   end if
16:   for each node i where  $\mathbf{C}_{i,j} = 1$  and not finalized[i] do
17:     if  $\tilde{\mathbf{W}}[i] < -1000$  then
18:       continue                                                        $\triangleright$  Skip nodes with high negative weights
19:     end if
20:      $\Delta x \leftarrow \mathbf{x}_{j,0} - \mathbf{x}_{i,0}$ 
21:      $\Delta y \leftarrow \mathbf{x}_{j,1} - \mathbf{x}_{i,1}$ 
22:     edge_dist  $\leftarrow \sqrt{\Delta x^2 + \Delta y^2}$                           $\triangleright$  Euclidean distance
23:     new_dist  $\leftarrow d[j] + \text{edge\_dist}$ 
24:     if new_dist < d[i] then
25:       d[i]  $\leftarrow$  new_dist
26:       parent[i]  $\leftarrow$  u
27:       PQ.push((new_dist, i))
28:     end if
29:   end for
30: end while
31: path  $\leftarrow []$ 
32: if d[T] =  $\infty$  then                                                  $\triangleright$  No path exists
33:   return  $\emptyset$ 
34: end if
35: curr  $\leftarrow t$ 
36: while curr  $\neq -1$  do
37:   path.append(curr)
38:   curr  $\leftarrow$  parent[curr]
39: end while
40: path.reverse()
41: if path is empty or path[0]  $\neq s$  then
42:   return  $\emptyset$ 
43: end if
return path

```

---

631 The planning of a new route is implemented as a modified Dijkstra algorithm over the place cell  
 632 graph, provided as connectivity matrix C. Its particularity is the use of a weighting  $\tilde{\mathbf{W}}$  of the nodes  
 633 according to the neuromodulation map. A description is reported in algorithm 5.4.

634 **5.5 Environments**

635 The game in which test the model has been developed with the python library Pygame, used under  
 636 license GNU LGPL version 2.1 and available at <https://github.com/pygame/pygame>. The  
 637 environment layout consisting in a customizable arrangement of vertical and horizontal hard walls  
 638 with variable length and fixed width. Below in Figure 4 some samples are shown.

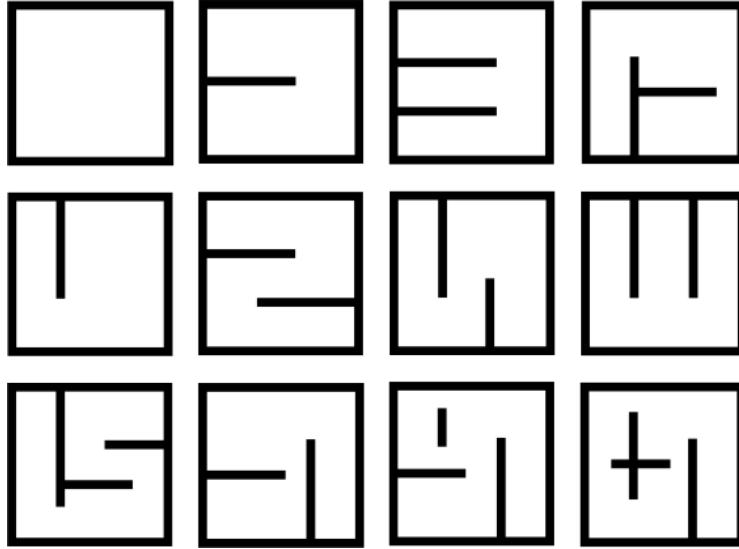


Figure 4: Sample of generated environments

639 The reward object is defined as a circle with size the 5% of the total environment area. When the  
 640 agent position is within its boundary, it is provided a binary signal  $R \sim \mathcal{B}(p_r)$  drawn from a Bernoulli  
 641 with probability  $p_r = 0.6$ . The duration of the reward fetching is set to 2 time steps.

642 The agent object is defined as a square with size the 3.3% of the total environment area.

643 The testing protocol was inspired by the behavior of animals that venture into new territories in search  
 644 of food. It was divided into two parts:

- 645 • **exploration phase:** the agent was placed in a random location within the environment for  
 646 10'000 time steps. In this phase the reward is not present. Further, in order to force greater  
 647 exploration of the environment, every 3'000 steps it was teleported to another random  
 648 location. This external intervention was meant to mitigate the randomness in the exploratory  
 649 behavioural strategy of the agent.
- 650 • **reward phase:** a reward is insert in a random location, and it is available to be discovered.  
 651 When it is encountered, the agent is teleported to a random location within the environement,  
 652 and after a fixed about 100 time step it is enabled its reward-seeking behaviour, in the form  
 653 of goal-directed navigation. The total duration of this phase is set to 20'000 time steps.

654 An episode is defined as a continuous trajectory during the reward phase, namely a set of time steps  
 655 starting from when the agent is place in a position until either it finds the reward or the simulation  
 656 ends.

657 **Detour experiment** The protocol is modified such that after a fixed number of episodes the layout  
 658 of the environment is changed, *e.g.* a wall is inserted. This experiment is meant to test the ability  
 659 to reach the reward location by using the same cognitive map, and possibly update it with the new  
 660 sensory information, such as the detection of the new boundaries.

661 **Changing reward experiment** During the reward phase, the reward location is changed after a  
 662 fixed number of fetches.

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