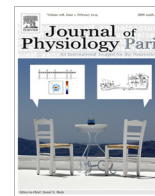


Contents lists available at [ScienceDirect](http://www.sciencedirect.com)

Journal of Physiology - Paris

journal homepage: www.elsevier.com/locate/jphysparis

A biologically inspired hierarchical goal directed navigation model



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ARTICLE INFO

Article history:

Available online 26 July 2013

Keywords:

Grid cell
Place cell
Hippocampus
Entorhinal cortex
Navigation

ABSTRACT

We propose an extended version of our previous goal directed navigation model based on forward planning of trajectories in a network of head direction cells, persistent spiking cells, grid cells, and place cells. In our original work the animat incrementally creates a place cell map by random exploration of a novel environment. After the exploration phase, the animat decides on its next movement direction towards a goal by probing linear look-ahead trajectories in several candidate directions while stationary and picking the one activating place cells representing the goal location. In this work we present several improvements over our previous model. We improve the range of linear look-ahead probes significantly by imposing a hierarchical structure on the place cell map consistent with the experimental findings of differences in the firing field size and spacing of grid cells recorded at different positions along the dorsal to ventral axis of entorhinal cortex. The new model represents the environment at different scales by populations of simulated hippocampal place cells with different firing field sizes. Among other advantages this model allows simultaneous constant duration linear look-ahead probes at different scales while significantly extending each probe range. The extension of the linear look-ahead probe range while keeping its duration constant also limits the degrading effects of noise accumulation in the network. We show the extended model's performance using an animat in a large open field environment.

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1. Introduction

One of the crucial features of many living organisms capable of locomotion is their ability to navigate from their current location to another one to perform a life critical task. For instance squirrels are surprisingly good at rediscovering locations of food they previously buried (Jacobs and Liman, 1991), rats can learn to revisit or to avoid previously visited food locations (Brown, 2011; Olton and Schlosberg, 1978). Many animals retreat to a previously visited shelter in the presence of an immediate threat, e.g., a rabbit running to the safety of its burrow when it detects a bird of prey in the skies, or of a long-term threat, e.g., a bear retreating to a cave for hibernation to conserve energy during a cold season. It is a plausible assumption that for the organisms to perform such navigation tasks they should possess a cognitive mechanism to represent their environment as a collection of critical regions, e.g., nest locations, food locations, etc., to recall these regions when the need arises, and means to exploit relations between such regions (O'Keefe and Nadel, 1978; Redish, 1999).

The entorhinal cortex and hippocampus play a role in goal-directed behavior towards recently learned spatial locations in an environment. Rats show impairments in finding the spatial

location of a hidden platform in the Morris water-maze after lesions of the hippocampus (Morris et al., 1982; Steele and Morris, 1999), postsubiculum (Taube et al., 1992) or entorhinal cortex (Steffenach et al., 2005). Recordings from these brain areas in behaving rats show neural spiking activity relevant to goal-directed spatial behavior, including grid cells in the entorhinal cortex that fire when the rat is in a repeating regular array of locations in the environment falling on the vertices of tightly packed equilateral triangles (Hafting et al., 2005; Moser and Moser, 2008). Experimental data also show place cells in the hippocampus that respond to mostly unique spatial locations (O'Keefe, 1976; McNaughton et al., 1983; O'Keefe and Burgess, 2005), head direction cells in the postsubiculum that respond to narrow ranges of allocentric head direction (Taube et al., 1990; Taube and Bassett, 2003), and cells that respond to translational speed of running (Sharp, 1996; O'Keefe et al., 1998).

In a previous work we proposed a goal-directed navigation model (Erdem and Hasselmo, 2012), inspired by experimental in vivo findings, using a network of simulated head direction cells, grid cells, and place cells. The model represents each salient spatial location with the firing field of a place cell as the simulated subject (animat) explores its environment. During navigation the model guides the animat from an arbitrary location towards a previsited goal location by sampling potential linear look-ahead trajectory probes and picking the one which activates the place cell representing the desired location, i.e., the goal place cell. In this model

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all place cell firing fields are the same size and thus they represent the environment at a single scale. However, the model has some shortcomings. The noise accumulation during each look-ahead trajectory scan (collection of probes during a single look-ahead session) limits the duration and range of each look-ahead trajectory probe. Hence there is no guarantee that any of the probes will reach the goal place cell's firing field. Furthermore, if the radial distribution of the probes is not dense enough the look-ahead trajectory scan might still fail to activate the goal place cell even if the goal place field is in the probe range.

In this paper we present a navigation model which has significant extensions and improvements over our previously reported navigation model in Erdem and Hasselmo (2012). The model presented here tackles the problem of noise accumulation during linear look-ahead scan phase by representing the environment in a hierarchy of multiple scales. The hierarchical approach indirectly helps limiting the critical noise accumulation during look-ahead scans to acceptable levels. The extended model achieves noise stabilization by keeping the duration of a linear look-ahead trajectory probe, a critical component of the navigation system, constant while extending its range arbitrarily. We also report several other improvements over our previous single scale model.

The hierarchical approach to represent the environment in multiple scales is also supported by experimental in vivo recordings. Differences in the firing field size and spacing of grid cells along the dorsal to ventral axis of entorhinal cortex have been reported in previous studies (Hafting et al., 2005; Sargolini et al., 2006; Giocomo et al., 2011). Grid cell firing field size and separation grows larger as the anatomical location of the cell slides from dorsal to ventral border of entorhinal cortex. Also, CA3 place cell firing fields ranging from <1 m to 10 m along the dorsal to ventral pole have been previously recorded (Kjelstrup et al., 2008; Jung and Wiener, 1994; Maurer et al., 2005). Both findings encourage the idea of hierarchical multi-scale representation of space in rats.

Our model of goal directed navigation based on spatial behavior of grid cells is also suited as a biologically-inspired model for SLAM (Simultaneous Localization And Mapping) in robotic navigation (Milford et al., 2004; Eustice et al., 2006; Guanella et al., 2007; Milford, 2008; Fibla et al., 2010; Duff et al., 2011). However, none of the cited previous work exploits the advantages of a hierarchical approach.

2. Material and methods

In this section we present the main ideas and constructs used to extend our previous goal-directed navigation model of linear look-ahead trajectories. We start by briefly explaining our original navigation model involving a network of the head direction cells, grid cells, and place cells as shown in Fig. 1. We show how this network is able to cognitively represent an explored environment as a place cell map. We continue by showing how linear look-ahead trajectory scans can be used to discover the best heading from the current location of the animat towards a predefined goal location. We then introduce our new model extending the previous one by using a hierarchical approach. This extended model represents a given environment using multiple place cell maps at different resolutions.

2.1. Notation

We show scalar parameters by italic lowercase characters, e.g., a . Vectors are shown by bold lowercase characters, e.g., \mathbf{a} . Vectors are row-wise unless specified otherwise. Matrices are shown by uppercase bold letter, e.g., \mathbf{A} . We show an item's position index in a collection with subscripts, e.g., a_i . Superscript is reserved for

power operations with the exception of the transpose operation, e.g., \mathbf{a}^T . We show collections such as sets and populations by uppercase italic letters, e.g., \mathbf{A} . Lowercase italic bold characters represent the class of the item they refer to, e.g., place cell \mathbf{p} or grid cell \mathbf{g} .

2.2. Single level place cell map

In our previous work we proposed a single scale model to solve the goal directed navigation task using a network of simulated head-direction cells tuned towards specific allocentric orientations using cosine tuning, entorhinal persistent spiking cells, entorhinal grid cells, hippocampal place cells, and pre-frontal cortical columns. Our original model works as explained briefly next.

2.2.1. Head direction cells

A head direction cell is a type of neuron tuned to increase its firing rate whenever the head direction (heading) of the animat gets closer to the cell's preferred angle (Taube et al., 1990). Extensive experimental data describe head direction cells in the deep layers of the entorhinal cortex (Sargolini et al., 2006) and in other areas including the postsubiculum (Taube et al., 1990). Previous work has also shown that usually a population of head direction cells are anchored to a salient landmark cue. In light of these, assuming that the firing rate of a head direction cell is cosine tuned and velocity modulated, we can represent its firing rate as follows:

$$\mathbf{D} = \begin{bmatrix} \cos(\theta_1 + \theta_0) & \dots & \cos(\theta_m + \theta_0) \\ \sin(\theta_1 + \theta_0) & \dots & \sin(\theta_m + \theta_0) \end{bmatrix} \quad (1a)$$

$$\mathbf{d}(t) = \mathbf{v}(t) \cdot \mathbf{D} = [d_1(t), \dots, d_m(t)] \quad (1b)$$

where θ_i is the i th cell's preferred angle, θ_0 is the heading angle of the anchor cue, \mathbf{D} is the tuning kernel, $\mathbf{d}(t)$ is the vector of head direction firing rates at time t , $\mathbf{v}(t)$ is the animat's velocity vector at time t , and m is the total number of head direction cells in the model. All angles are allocentric, i.e., in the global coordinate system.

2.2.2. Grid cells

A grid cell is a type of neuron tuned to fire whenever the animat's spatial position falls into regions of space, or *firing fields*, forming a periodic hexagonal grid pattern. Previous work have shown existence of grid cells showing firing fields with different inter-field spacing and firing field diameters (Hafting et al., 2005; Sargolini et al., 2006; Giocomo et al., 2011). Several computational models have previously been proposed to explain the grid cell mechanism. In our work we chose to use the *persistent spiking cell model* which falls into the category of *phase interference models* (Burgess et al., 2007; Burgess, 2008; Hasselmo, 2008). In standard slice preparations, most cortical neurons generate spikes during depolarizing input, but will not continue firing after stimulation ends. However, in the presence of cholinergic or metabotropic glutamate agonists, pyramidal cells in medial entorhinal cortex commonly show persistent firing (Klink and Alonso, 1997; Egorov et al., 2002; Fransén et al., 2006; Tahvildari et al., 2007; Yoshida et al., 2008) even when all synaptic input is blocked. The mechanisms of intrinsic persistent firing in single neurons could contribute to persistent spiking shown with unit recording during the delay period of delayed matching to sample tasks in awake, behaving rats (Young et al., 1997) and monkeys (Suzuki et al., 1997). Persistent spiking could also underlie persistent fMRI activation appearing during delay periods in human memory tasks, which can be reduced by muscarinic cholinergic blockade (Schon et al., 2004; Schon et al., 2005; Hasselmo and Stern, 2006). More detailed treatment of the grid cell model based on the interaction of persistent

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