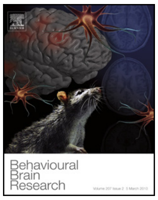
Behavioural Brain Research 256 (2013) 128–139

Contents lists available at ScienceDirect

Behavioural Brain Research

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



Research report

A cognitive map model based on spatial and goal-oriented mental exploration in rodents

Qing Zhu[a], Rubin Wang[a,b,*], Ziyin Wang[a]

[a] Institute for Cognitive Neurodynamics, School of Information Science and Engineering, East China University of Science and Technology, Shanghai 200237, China
[b] Department of Mathematics, School of Science, East China University of Science and Technology, Shanghai 200237, China

HIGHLIGHTS

- The spatial vector map and the goal-orient map are combined in this paper.
- A virtual plane chart is formed to reflect location information during the self-locating stage.
- The asymmetric synaptic connection is formed impermanently during the path exploration.
- Under the assumptions in this paper, path exploration effectively works with the virtual chart instead of actual movement.

ARTICLE INFO

Article history:
Received 4 December 2012
Received in revised form 24 May 2013
Accepted 27 May 2013
Available online 5 June 2013

Keywords:
Cognitive map
Mental exploration
Path finding
Place cell

ABSTRACT

The rodent hippocampus has been used to represent the spatial environment as a cognitive map. Classical theories suggest that the cognitive map is a consequence of assignment of different spatial regions to variant cell populations in the framework of rate coding. The current study constructs a novel computational neural model of the cognitive map based on firing rate coding, as widely appears in associative memory, thus providing an explanation for formation and function of the two types of cognitive maps: the spatial vector map, responsible for self localization and simultaneous updating of detailed information; and the goal-oriented vector map, important in route finding. A proposed intermediate between these two map types was constructed by combining the spatial vector and goal-orientation maps to form an effective and efficient path finding mechanism. Application of such novel cognitive map based path finding methods to a mental exploration model was explored. With adaptation as a driving force, the basic knowledge of the location relationships in the spatial cognitive map was reformed and sent to the goal-oriented cognitive map, thus solving a series of new path problems through mental exploration. This method allows for rapid identification of suitable paths under variant conditions, thus providing a simpler and safer resource for path finding. Additionally, this method also provides an improved basis for potential robotic path finding applications.

1. Introduction

The concept of the cognitive map was first proposed by Tolman in 1948 [1]. Tomlan suggested that the rat brain forms a map-like representation of its environment that can be applied to solve complex spatial problems. Using electrophysiological methods, O'Keefe and Dostrovsky [2] revealed the existence of place cells, a type of rapidly firing neurons located in the hippocampus. The response of these place cells is the basis for construction of modern cognitive maps.

When rodents are confined in relatively narrow spaces, isolated subgroups of pyramidal cells in the hippocampus exhibit an elevated firing rate that only appears when the animal is in a certain physical location. These special neurons, or place cells, are activated when the animal is in a specific location in its environment, known as the place field. Thus, certain types of hippocampal dysfunction may impact the ability of rats to perform spatial tasks. The development of place fields and corresponding place cell firing, or place coding, plays a vital role in spatial learning tasks associated with the rodent hippocampus. This is particularly apparent in abilities associated with spatial navigation in rats [3].

For centuries, scientists have explored how hippocampal cell activities relate to spatial location and the characteristics of these activities. Only recently, however, have researchers reported the existence of other specific cells involved in spatial orientation, such

---

* Corresponding author.
E-mail address: rbwang@163.com (R. Wang).

0166-4328/$ – see front matter. Crown Copyright © 2013 Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.bbr.2013.05.050

as head direction cells. These cells have specialized activities that are only apparent when the animal's head points in a specific direction relative to their environment [4]. Grid cells, which may be part of a self-motion based map of the spatial environment, have also recently been identified [5]. In order to simulate the coordination of various cells related to spatial tasks in rodents and elucidate the mechanisms by which animals perform these pathfinding problems, most scientists employ the path integration (PI) methods described by Darvin [6]. Such sophisticated mathematical methods coupled with modern computerization have allowed for rapid improvements in contemporary understanding of these mechanisms.

There are two primary theoretical models of cognitive maps that are associated with spatial navigation: spatial maps, which represent an animal's location relative to its environment; and goal-oriented maps, which indicate an animal's position relative to its goal. Spatial maps, which may involve no sensory signals, are functional maps that indicate the specific position and orientation of the animal in space. The neurological basis of spatial maps involves the interaction of closely arranged and interconnected place cells, promoting simultaneous firing. To the onlooker, this process may appear as a consistent population activity among place cells, an effect responsible for confusion in early research.

Wilson and McNaughton recently reported detailed recordings of place cell firing during spatial exploration, clearly demonstrating the representation of location on a two-dimensional plane using population coding of place cells [7]. This concentration of firing patterns surrounding the place code can be referred to as self-localization, a process that has been hypothesized to have a basis in the mutual connections among neighboring place cells [8]. Other experiments have shown that the population code is rearranged when the environment changes [9–11]. Furthermore, the same population coding pattern may spontaneously reappear when an animal is placed back into a previous environment [12].

In this framework, Muller et al. initially proposed that simultaneous place cell firing constitutes a network of strong synaptic connections between neighboring place fields [13,14]. Accordingly, place cells form an organized geometric network, simply referred to as a chart. The chart maps all environmental information, thus generating a detailed map of spatial relationships among place cells in which the strength of synaptic connections between place cell pairs correlates with distance between corresponding environmental locations. These symmetric interconnections are localized in the hippocampal CA3 region, the primary site of neural activity in environmental exploration in rodents. Using mutant mice with an ablated n-methyl-D-aspartate (NMDA) glutamate receptor gene affecting the CA3 region, Nakazawa et al. experimentally confirmed that recurrent connections between pyramidal cells form associative memories. Furthermore, this model effectively explains the mechanism by which mutual connections between place cells can represent an animal's position in space, even which subjected to environmental change. These proposed mechanisms, however, are not supported by experimental evidence demonstrating asymmetric synaptic plasticity. As a result, this mechanism fails to clarify how the animal can apply such spatial information to the problem-solving processes required for path determination.

An alternative and complementary model suggests that neural guides play a role in navigation toward a goal. Many different opinions and theories have been proposed regarding the exact mechanisms involved in this model [1,15–18]. Based on the assumption that place cells exist in the hippocampus, these theories primarily focus on the function of temporal asymmetry in the synaptic plasticity of hippocampal pyramidal cells. Burgess et al. firstly proposed that the cognitive map was constructed relative to the direction toward a single goal in the environment, potentially allowing for the development of improved paths by use of population vectors representing the animal's next movements. This model requires that goal-oriented vectors be encoded between place cells and goal cells, as opposed to previous models suggesting that these relationships existed chiefly among the place cells.

Subsequent iterations of this theory have been developed that apply asymmetric connections using Hebbian plasticity combined with an asymmetric time window [10,19,20]. These models provide a superior explanation of the contribution of asymmetric synaptic plasticity to specific cognitive functions, such as spatial navigation. These models, however, have limited applicability in spatial tasks with multiple goals. Notably, differences between reward locations may not always result in altered place cell activities. Because these theories are viable only in cases of single-goal, fixed-vector mapping, these models are unlikely to fully represent the fundamental properties of place cells.

Redish and Touretzky (1998) proposed an intermediate between the spatial and goal-oriented models of cognitive mapping by combining the spatial vector map and the goal-orientation map [3]. They hypothesized that symmetric connections between place cells of the spatial map are learned when a rat first explores a new area; however, the asymmetric property of goal-orientation is added to the network at later stages, allowing for the existence of multiple or changing goals. This model further demonstrates that asymmetric and symmetric connections can coexist within the framework of a single-goal, fixed-vector map.

While the intermediate model proposed by Redish and Touretzky had some merit, this model for path-finding was limited in practical application. Significant training was required to produce optimal goal-based vectors, making experiments both time and resource intensive. Animals were required to undergo significant periods of physical exploration of new spaces, ranging from several minutes to many hours. Ultimately, the model still only allowed for the development of a single path to a goal. In the case of multiple goals, experiments were replicated many times, representing a large time investment.

The shortcomings of this model can be overcome by considering a model of mental exploration characterized by virtual exploration of a new space. Upon initial examination, the results of this simulation may seem similar to the traditional model; however, a principal difference exists. Using this modified technique, a stationary simulation of animal exploration results in the formation of a representative virtual plane in the hippocampal CA3 region, thus simulating the process of real area exploration over the course of only a few seconds. Because of the rapid and responsive process involved, the mental exploration model may fulfill particular cognitive functions related to goal finding and path determination in practical settings.

The concept of mental exploration was initially proposed by Hopfield [16] as a hypothetical method for solving spatial problems. On an abstract level, imagining multiple possible futures, planning a chain of actions to achieve a novel goal, and many other aspects of what is commonly referred to as thinking actually involves mental exploration. These processes are all based on the first cognitive map; however, within a fraction of a section to several minutes, mental exploration produces a modified alternative cognitive map, often occurring through protracted evolution of neural activity in stationary animals. The logical outcome of such mental exploration and subsequent cognitive map generation is behavioral actions directly related to the activity at hand. When circumstances permit its use, mental exploration can be faster, more energy-efficient, and safer than physical exploration for spatial problem-solving.

Mental exploration also has the added benefit of producing temporary, goal-oriented cognitive maps that are separate from the original spatial knowledge generated by real exploration. Thus, when an animal starts another mission, the original spatial information can be used, producing no unnecessary interference in the