International Congress Series 1301 (2007) 294 – 297

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Simple dynamical system model of selective cue responding cell development

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Abstract. In a recent experimental paper, Foster and Wilson [D.A. Foster, M.A. Wilson, Nature 440 (2006) 680–683] reported reverse replay of recent behavioural sequences in rat hippocampal place cells during the awake state immediately after spatial experience at the reward location. A simple dynamical system firing rate neuron model, illustrating how such replay can generate a map of the environment, selectively linking the replay location with other functionally relevant locations, is presented. Numerical simulations show the rapid development of a cell with receptive field corresponding to the reward location and only one of two cues in a cued T-maze task. © 2007 Published by Elsevier B.V.

Keywords: Hippocampus; Replay; Remapping; Reward; Dynamics

1. Introduction

Research into brain function can provide insights into novel information processing systems and can be applied to the design of computers that perform 'brain-style' information processing. Understanding how the hippocampus performs its task of forming a cognitive map of the animal's spatial environment [2] would provide such insight. The main functional entities in the formation of an environmental map are *place cells*, which are pyramidal neurons located in the CA1 and CA3 regions of the hippocampus, whose firing is strongly correlated with the location of the freely moving rat. A related phenomenon is referred to as *remapping* [3], whereby the location specific firing of these place cells changes markedly. Circumstances that trigger a remapping include changing shape of apparatus, changing colour of a cue card or changing the orientation of the apparatus

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0531-5131/ © 2007 Published by Elsevier B.V.
doi:10.1016/j.ics.2006.12.100

relative to background cues. The remapping phenomenon illustrates an important method of how the brain processes information.

In a recent experimental paper, D.J. Foster and M.A. Wilson [1] reported reverse replay of recent behavioural sequences in hippocampal place cells during the awake state immediately after spatial experience, which occurred even after the first lap on a new track at the reward point. They suggest that this replay may play a role in the evaluation of event sequences, as in reinforcement learning models. I propose a very minimal model of how such replay can be used for rapid cue and novelty detection, remapping, and for the formation of a functional cognitive map associating reward locations with behaviourally meaningful locations and signals such as cues. Although the model is simple, I expect the principles to be relevant to real biological networks and also to provide insight into how to realize brain-style information processing based on sequence replay. I illustrate the idea by application to a rat forced run in a cued T-Maze task.

2. Model and results

The model is based on simplified hippocampal structure composed of an input layer (entorhinal cortex (EC)) and an association layer (CA3) (see Fig. 1A). In this highly simplified description the EC projects in a one-to-one fashion to CA3. CA3 is described as an all-to-all associative network, modelling its known dense excitatory recurrent connections. Cells are described by activities, which can be considered as membrane potentials or firing rates. The EC layer is composed of N cells with receptive fields which respond to environmental cues, or landmarks, activated as the rat runs through them. The association layer CA3 activities, a_i, of number N are given by,

$$\begin{aligned} \frac{da_i}{dt} &= -a_i + p_i(x(t)) + g(\Sigma(w_{ij} - k_1)a_j)R(t) \\ \frac{dw_{ij}}{dt} &= k_2 a_i + k_3 a_j + k_4 a_i a_j - k_5(w_{ij} - k_1) \end{aligned} \tag{1}$$

Here, the w_{ij} are weights modifiable by competitive Hebbian learning and $g(x)$ is the sigmoidal function. p_i is the one-to-one input from the input layer and depends on the rat position $x(t)$. The parameter $k_1 = 10$ is the fixed point of the weights equation in the absence of activities in the association layer; it is included only to avoid negative weights and is not

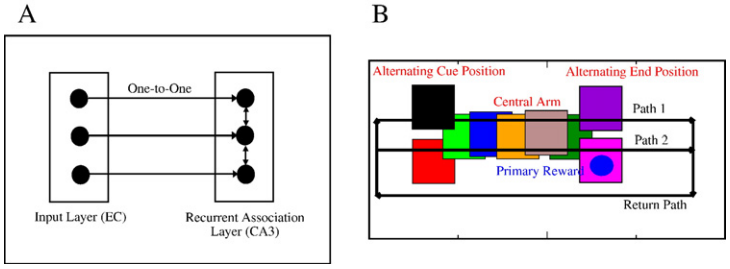

Fig. 1. (A) Model description. (B) Alternation task described in text.