Modeling the development of place cells in hippocampus

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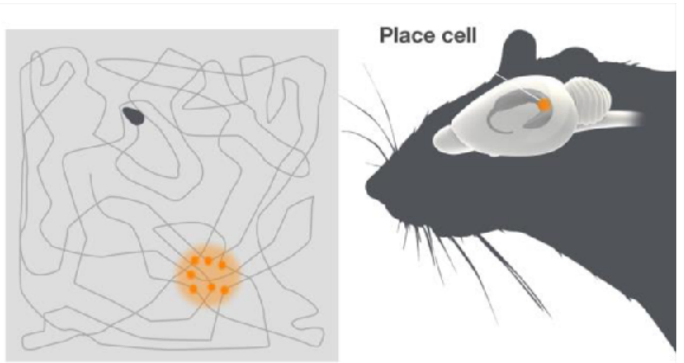
Introduction

In the 1st Whole Brain Architecture Initiative hackathon, we proposed two types of computational models for the representation of space inside our brain.

"Place cells" are located in hippocampus [1]. They fire when an animal moves into a specific location in an environment, and their activities allow an animal to form a spatial map in its brain.



So far, little has been known about how the firing patterns of place cells are formed, especially what external/internal information is sufficient for the formation. In this study, we took a computational approach to address this issue. To simulate the temporal firing patterns of place cells *in silico*, we used long short-term memory (LSTM), one of recurrent neural network (RNN) architectures, as the core of the models. The reasons for choosing LSTM are;

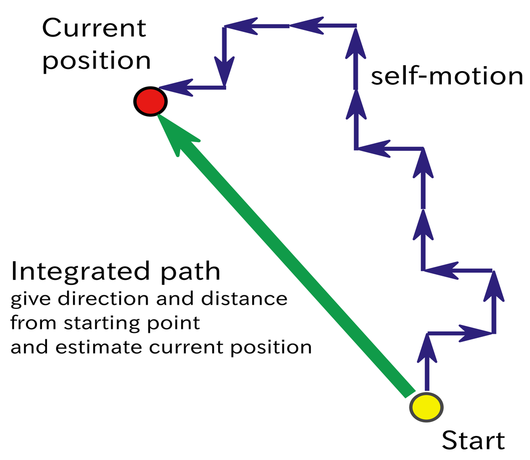
1. anatomy of hippocampal network is similar to RNN, especially in CA3 region
2. studies have shown that among RNN subtypes, LSTM generally works best in modeling temporal sequences.

Image: Kiehn, O., & Forssberg, H. (2014). Scientific background: the brain's navigational place and grid cell system. Retrieved November 1, 2015, from https://www.nobelprize.org/

Path-integrating place cell

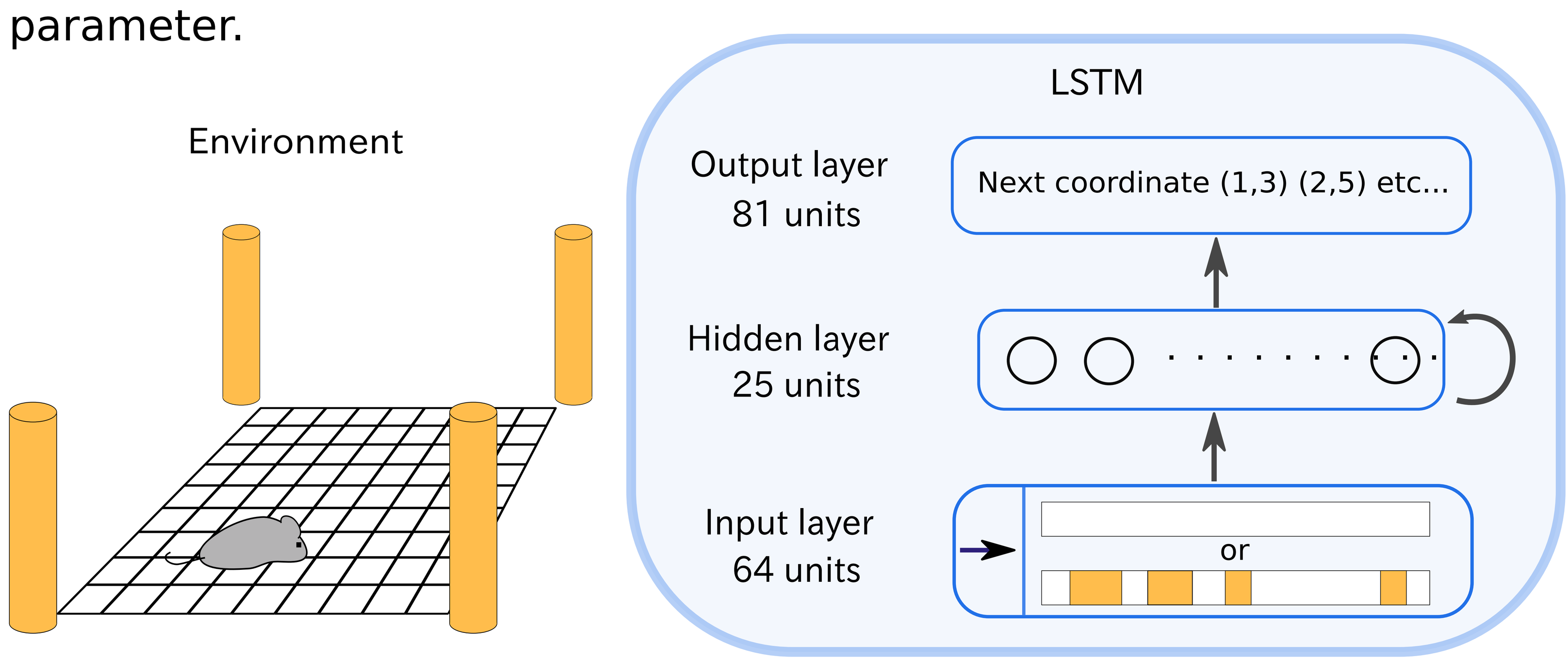
Path integration theory

Place cells can encode relative spatial location by the integration of linear and angular self-motion [2]. The accumulated error is corrected by the sensory cue (e.g. visual stimulus).

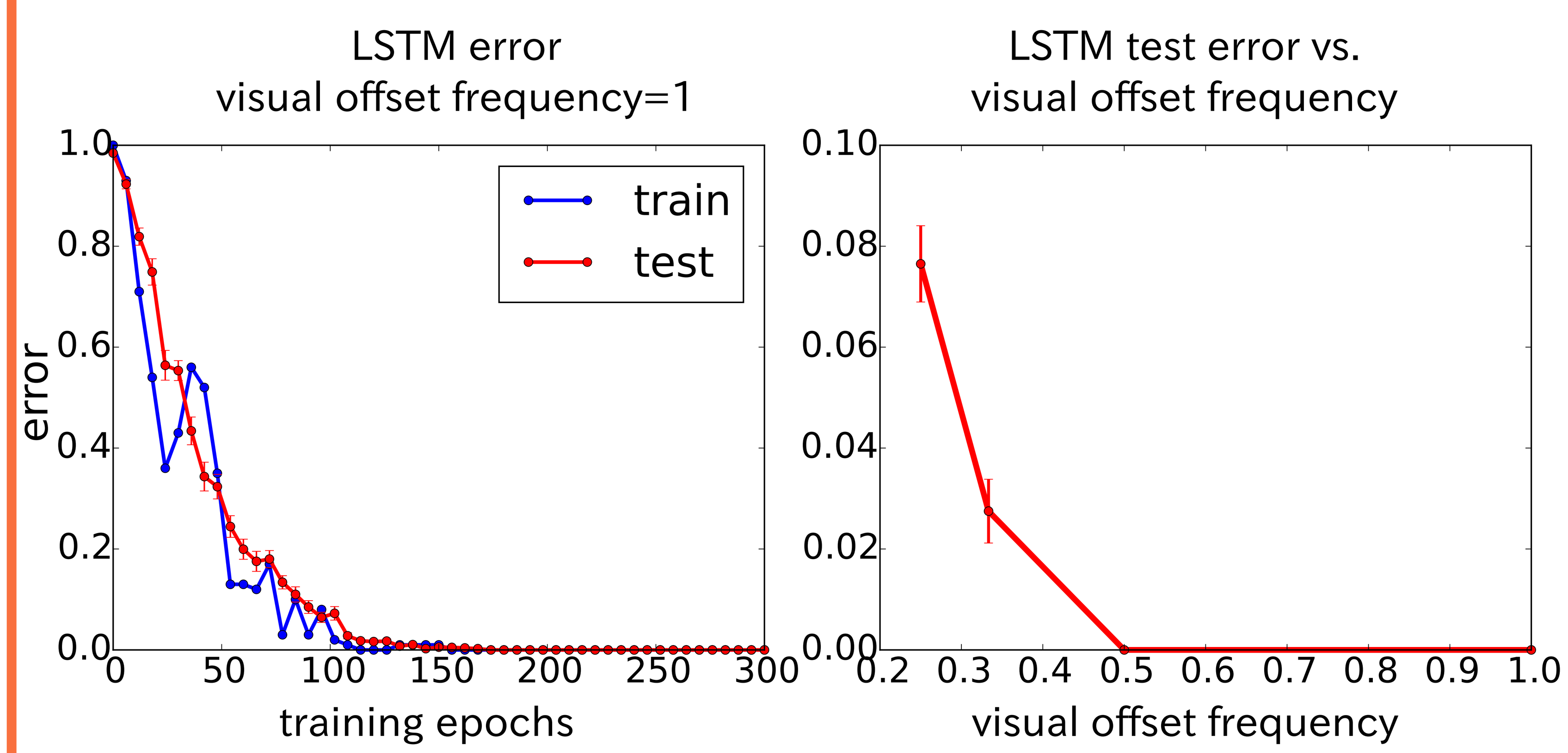


Implementation

LSTM was trained to output the next coordinate from the direction of movement, offset by panoramic image of the surrounding poles if this image was available on the current location. Ratio of image availability among all locations was determined by the "visual offset frequency" parameter.



Results



LSTM error (blue, red): classification error, test error (red): mean±sem (n=20)

Citation

[1] O'Keefe, J., & Dostrovsky, J. (1971). The hippocampus as a spatial map. Preliminary evidence from unit activity in the freely-moving rat. *Brain research*, 34(1), 171-175.

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[3] Wills, T. J., Cacucci, F., Burgess, N., & O'Keefe, J. (2010). Development of the hippocampal cognitive map in preweanling rats. *Science*, 328(5985), 1573-1576.

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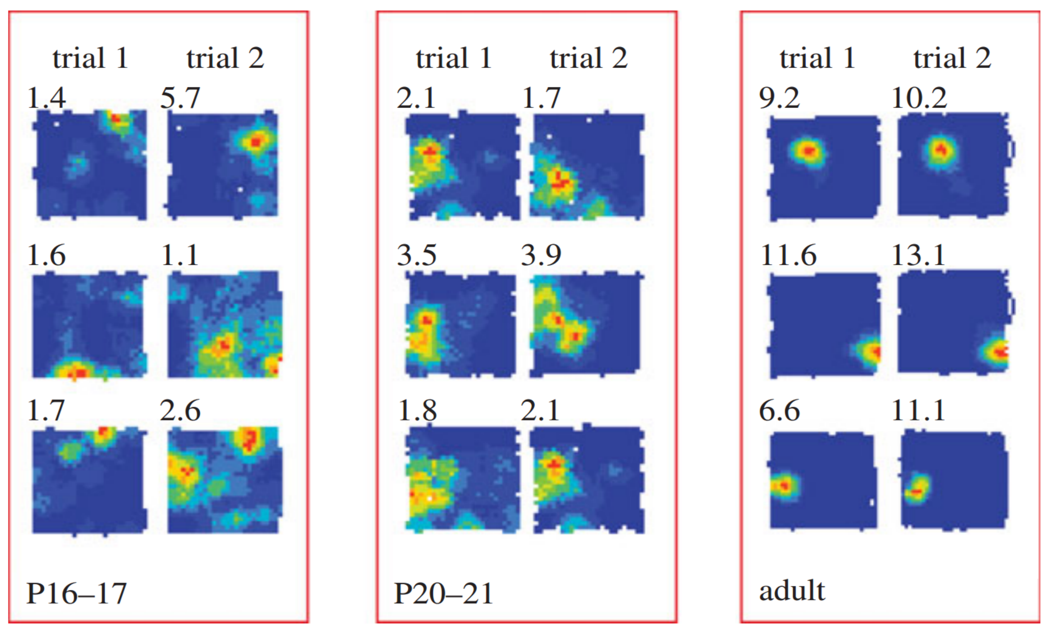
[6] Kropff, E., Carmichael, J. E., Moser, M. B., & Moser, E. I. (2015). Speed cells in the medial entorhinal cortex. *Nature*. 523(7561), 419-424.

Visual predictive place cell

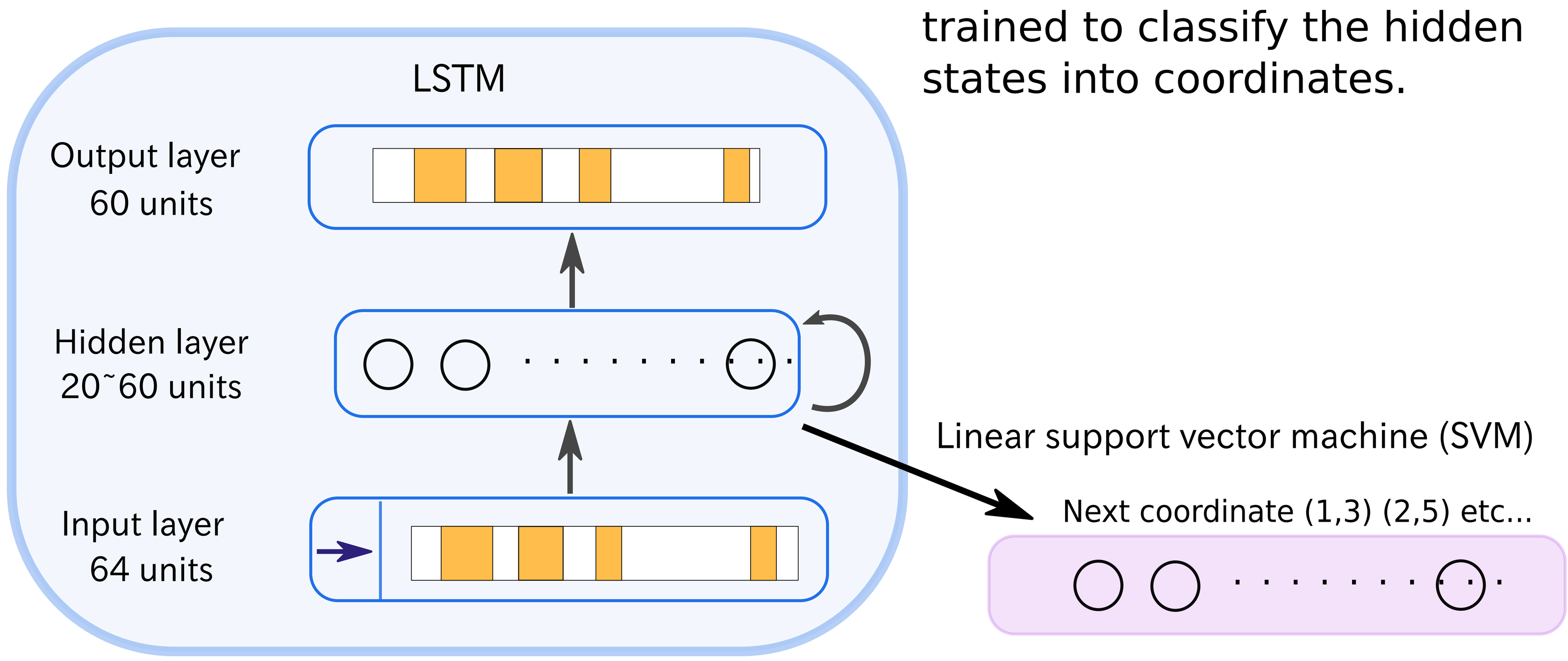
Visually guided development of place cell



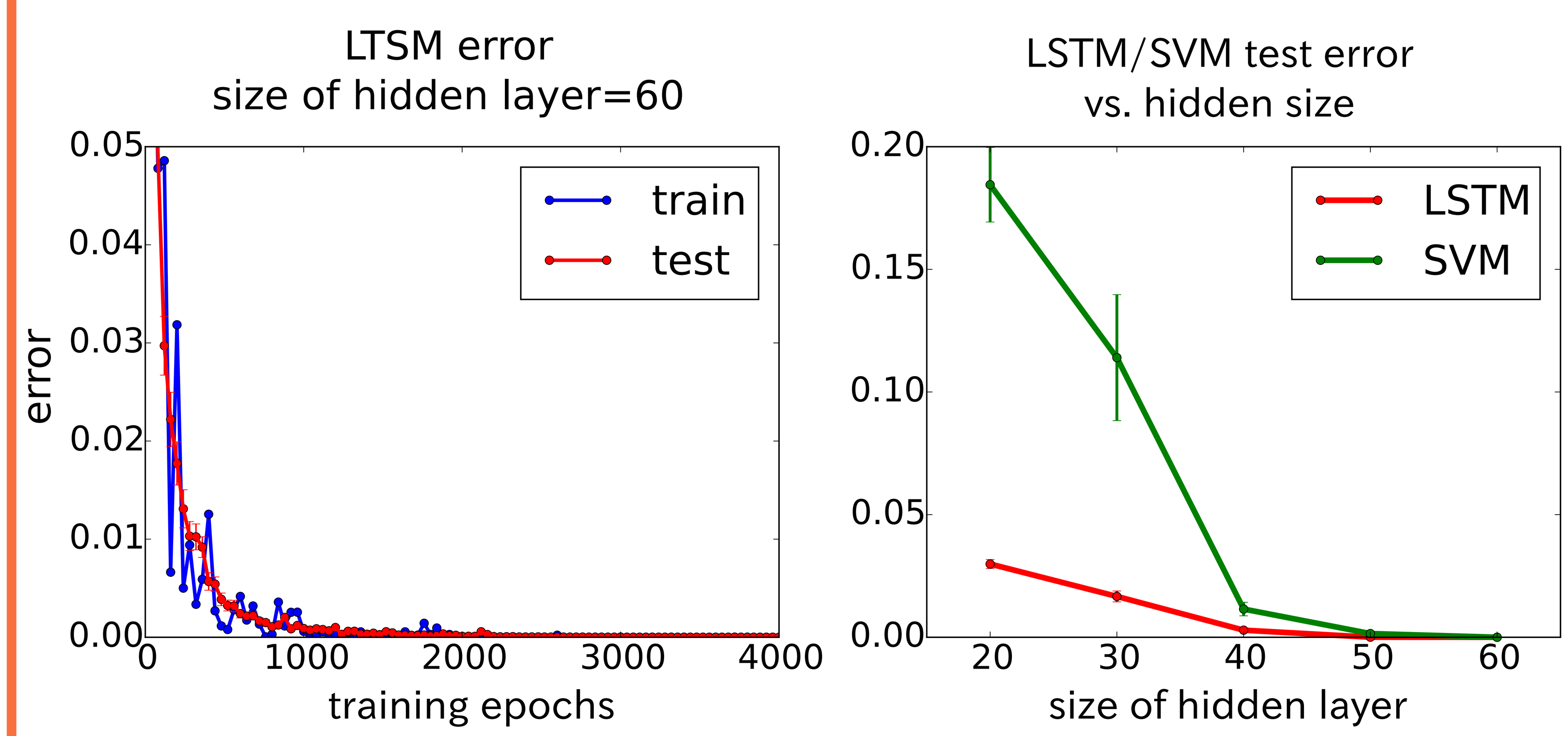
The stability of the place field gradually improve after eye opening (Postnatal 13~15 days) [3].

Implementation

LSTM received both the direction of movement and visual image as its input and was trained to predict the image following the movement. We hypothesized that the features of hidden states corresponded to the next coordinate, so a linear support vector machine (SVM) was subsequently trained to classify the hidden states into coordinates.



Results



LSTM error (blue, red): mean squared error, SVM error (green): classification error
test error (red, green): mean±sem (n=20)

Both LSTM and SVM achieved 100% accuracy in test data when the hidden size was 60. We were thus able to mimic the developmental process of acquiring the representation of space.

Future prospects

Preprocessing of visual images

In this model, place cells used visual stimulus itself as their input. In real brain, however, visual information is preprocessed in visual cortex before entering hippocampus. This preprocessing can be simulated when our model is combined with a dimensionality reducer like stacked autoencoder.

Plasticity of place fields

Previous biological experiments showed that place fields accumulated on specific locations (e.g. maze goal [4], food location [5]). These phenomena might be simulated by extending our model.

Relationship with head-direction cells and speed cells

In this model, the agent was kept to move to the vertically or horizontally adjacent locations. To extend to more realistic situations, an increased choice of directions and speeds for the agent is a good alternative. This simulation may contribute to understanding how place cells interact with head-direction cells and recently-discovered speed cells [6].

Ackowledgements

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