Place-field and spatial memory formation in the rodent hippocampus

Attractors and memory?

We have a growing knowledge about how hippocampal networks store and represent information and also a strong development in formal theories describing behaviour of neural network models was seen, but there have been few studies trying to bridge the two areas, that is, putting the theory at test whether are networks within the brain really guided by attractor dynamics and pattern completion predicted by theoretical studies. Two recent experiments, Wills et al (2005) and Leutgeb et al (2005) have attempted to find an answer to this question by teaching rats two testing boxes, a square and a circle, differing only in their shape but similar in any other respects, and testing the animals in a series of intermediate morph shapes ranging from square to circle. If natural neural networks would be driven by attractor dynamics, one would expect representation in the morphs would align with either that of the square or that of the circle. The two studies, however, contradicted in their outcomes. Wills et al (2005) found, as expected from theory, neural representation of square-like morphs to be similar to that of the square, whereas representation of circle-like morphs were found to align with that of the circle. Leutgeb et al (2005), however, observed a gradual transformation between neural code of the square and circle as rats visited testing chambers from square through the morphs to the circle.

To harmonize these contradicting findings, two main hypothesis emerged. The one suggested that a difference in the sequence animals visited morph shapes may have caused different outcomes in the two experiments (Blumenfeld et al, 2006). Another view supposed a difference in teaching square and morph could have been an important factor, as a trick used by Wills et al. ensured a higher degree of decorrelation between representation of square and morphs, than in the case by Leutgeb et al. Indeed, later analysis of Leutgeb et al's data revealed firing rate maps for square and circle remapped only partially, there was thus a higher correlation between representation of the square and circle than that found in Wills et al's experiment.

I explored both hypothesis by means of computer simulations. I set up, using threshold-linear units, a network storing multiple maps and tested representation of morph maps. Neural code of morphs with zero correlation between square and circle showed strong pattern completion, thus representation for square-like morphs was similar to that found in the square. Place-fields of most cells was found to switch abruptly near the middle morph, similar to findings of Wills et al (2005). Introducing, however, correlation, linearized transition between neural code found in the extremes (Papp et al, 2007b). Place-fields were found to switch independently from each other, similar to that found in Leutgeb et al (2005) experiment.

Simulating learning the morphs, if learning was superficial (small saliency for morphs), left attractors for square and morphs intact, and representation of morphs aligned with either the one or the other attractor. Extensive learning (large saliency for morphs), however, abolished memories for square and morph and only representation for the middle morph could have been recalled, independent of which map was presented. Simulations near the turning point showed, as saliency for morphs was increasing, memory states wandering from end-position towards the middle point. Still, morphs aligned with one or the other attractor, however near they were to each other, thus learning the morphs, according to our
simulations, is not likely to have reversed strong pattern completion into a gradual transition. We thus concluded that initial correlation between representation of square and circle caused gradual transition between the two neural codes, and sequence how morphs were visited (and possibly learnt) did not have a major effect on recall.

**Place-fields and memory**

The hippocampus receives its afferents mainly through the entorhinal cortex. Hafting et al (2005) described firing rate maps of neurons in the dorsocaudal region of medial entorhinal cortex. Neurons were found to fire in multiple peaks arranged on vertices of a triangular lattice, hence termed grid cells. These cells were found to carry similar amount of information about physical space as did hippocampal CA1/CA3 neurons (Quirk et al, 1992), it was thus believed that grid cells may be the source of spatial firing correlates of CA1/CA3 cells. It is however not clear, how a highly regular and repetitive firing pattern, that is the grids, can be mapped through one or two synaptic connections on place-fields found generally in hippocampal CA3 cells. Most studies have shown that simply combining grid patterns would usually lead to formation of multiple peaks in CA3. Also, previous works concetrated on explaining place-cell formation via the perforant path only, disregarding dentate gyrus, nor did they estimate stability of resulting memory.

In our simulations we tried to give a model of both place-field and memory formation using activation resulting only from the region containing grid cells of medial entorhinal cortex (mEC), and by comparing performance of two networks of threshold-linear units, one comprising only of mEC and CA3, the other one incorporating also the DG. DG, for the sake of simplicity, was assumed to have single fields and connected through one-to-one connections to CA3, modeling sparse and strong connections found between DG and CA3 in hippocampus. Dentate region, in addition, was set to be active only during training, modeling a possibly crucial role of DG played during the encoding but not retrieval processes. According to the study by Rolls et al (2006), associative learning was able to decrease number of resulting fields in CA3 region in both networks, but a network using DG showed a much stronger memory. Analysis revealed strength of dentate connections influence strongly the amount of spatial information that can be retrieved. In further developing our model we also tried to take into account multiple firing fields found recently in DG (Leutgeb et al, 2007) and a sparsely branching connectivity from DG to CA3. Our results showed CA3 may possibly form large fields extending over multiple peaks received from DG during training, using a simplified model of grid cells.

**CA1 and “purifying” associative recall**

Several lesion and some fMRI experiments, single unit recordings as well as considerations based on anatomical data have lead researchers to make strong predictions on the role hippocampal subfields DG and CA3 would play in hippocampal function. Former is thought to take part in efficient pattern separation and encoding of new patterns, whereas latter is believed to be the core autoassociator of hippocampus. Experimental techniques, however, since CA1 is the only output towards regions outside of hippocampus, have left us without a clear role of CA1 played in hippocampal function. A large number of theories have suggested different roles, like in comparing memories with current
sensory representation, in associating patterns over a longer period of time than CA3, in prediction or in further increasing information content of inputs received from CA3. Latter ideas were developed by Treves (1995) and Rolls (1995). Storing multiple memories in CA3 would impose noise on memory states, that could be possibly further “polished” through an additional synaptic, feed-forward step in CA1. Simulations with point-like attractors as well as calculations have shown that a further synaptic step, feed-forward in its nature increased the precision memories were recalled. Treves (2004), reformulating his model storing now spatial memories, that is continuous attractors, showed a similar behaviour when CA3 was near to storage capacity, that is, CA1 increased spatial information in respect to CA3. Preliminary results from monkey spatial view cells suggested CA1 would indeed carry larger amount of metric content (remainder of spatial information after subtracting percent correct) about space as would CA3 cells (Treves et al, 1997).

The model of Treves (2004) was near storage capacity, storing one spatial representation. We thus aimed to analyse whether would the prediction hold with a larger storage capacity using multiple maps. Interestingly, CA1 showed similar amount of spatial information as did CA3, or, in some cases did slightly better, depending on parameters, the difference however remained little. In order to test results, we analyzed data from neurons of CA3 and CA1 regions from rats (data courtesy of Stefan Leutgeb) and found CA1 carried more spatial information as did CA3. Results, however, were best explained by a difference in sparsity (Papp et al, 2007a). CA1 cells were found to fire more abundantly than CA3 cells, and information was found to covary with sparsity. It seems thus that CA1 may play a role in further purifying information recalled from CA3, this benefit in spatial domains seems however to be little, compared to non-spatial domains.

Cited literature


