Experience-dependent Dynamics of Spatio-temporal Precision and Synchrony in Place Cells

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The hippocampus is crucial for the formation of episodic memories, the What, When and Where of events. The fine time scale temporal precision of hippocampal neural activity is thought to be essential for binding these memories together across time. Hippocampal activity occurs during two main states, an active state where the 8 Hz theta rhythm strongly modulates hippocampal firing and a quiescent state where short (~100 ms) high frequency (100-200 Hz) bursts of activity known as ripples are prominent. In the active state, place cells show phase precession where the phase of theta at which spikes occur becomes progressively earlier as the animal moves through the place field. As a consequence, cells with overlapping place fields fire together within short windows (< 60 ms). Similar patterns are seen during ripples, where neurons that were active together during active exploration fire together within each ripple. The presence of these forms of temporal organization is well established, but little is known about whether and how this organization changes to reflect the encoding of new memories.

We developed a new adaptive algorithm that makes it possible to accurately describe the dynamics of phase precession during learning, and applied this to recordings of CA1 neurons from rats performing a spatial alternation task in both an entirely familiar environment and in an environment which contained one novel arm. The new model fits the data well: for approximately 70% of the neurons, the model prediction was statistically indistinguishable from the actual spike train at a 99% confidence level, as compared to less than 50% for previous adaptive models. These models can therefore be used both to analyze spatio-temporal dynamics in place cells and to simulate highly realistic place cell spike trains.

When we examined the dynamics of phase precession, we found clear dynamics as a function of experience in the novel arm. Some cells showed clear phase precession on the first exposure to the novel arm, but on average the precision of phase precession was significantly lower than in the familiar environment. Phase precession in the novel arm evolved with experience, becoming more precise over 2–3 days until it was indistinguishable from that in familiar environment. The difference in theta phase precession seen on day 1 was not a result of differences in the theta rhythm or the modulation of spiking activity by theta, but rather reflected disorganization of the spatio-temporal structure of the spike train. The dynamics of phase precession were accompanied by an evolution in the synchrony of activity during ripples. On day 1, cell pairs with overlapping place fields on the novel arm fired more synchronous spikes during ripple events than did pairs with overlapping place fields in the familiar arm or pairs with *non*-overlapping place fields on the novel arm. Furthermore, synchronous firing diminished within 2–3 days, similar to the dynamics of phase precession. These results provide the first direct link between the dynamics of place cell activity during exploration and the dynamics of activity during the quiescent state, and suggest that synchronous activity during ripples may be important for establishing spatio-temporal organization during active exploration.

Acknowledgments
This work was supported by the Swartz and Sloan Foundations, the John Merck Scholars Program, the McKnight Foundation for Neuroscience and NIH RO1 MH59733.