Computational model of spatio-temporal coding in CA3 with speed-dependent theta oscillation

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Abstract

Hippocampal sequences associated with theta oscillation have been shown to carry spatio-temporal information. In particular, cells in CA1 become active sequentially in a stable unidirectional order during spontaneous run periods and under minimal external cues (Villette 2015). These recurring cell sequences seem to integrate either the distance that the animal has run or the time that has elapsed, two related coding states that can be separated through the change in cellular dynamics with speed. Other studies indicate that these cell sequences depend on theta oscillation from the medial septum and may reflect input from CA3 (Wang 2014, Salz 2016, Guzman 2016). Running speed of the animal has been shown to influence theta oscillation frequency and amplitude. This oscillation could thereby carry the spatio-temporal information input required to determine distance/time coding.

Inspired by Wang 2014, we modelled a circular recurrent network of excitatory cells with short-term synaptic plasticity (Mongillo 2008) and global inhibition. By applying speed-dependent theta oscillation, we reproduced the dynamics of spatio-temporal coding observed in experimental data and propose a mechanism of switching between the two coding states through a change in integration of theta input. In particular, our firing rate model reproduces the sequence properties (recurrence, unidirectionality, sparse activity, memory) based on the network characteristics of CA3 and allows exploring the dynamics of the sequential activity. Simulations with this model show a non-trivial relationship between sequence slope and the frequency/amplitude of the oscillatory input: depending on the amplitude range of the theta oscillation, sequence dynamics can either be independent of speed (time coding) or linearly dependent on speed (distance coding). Therefore, the model proposes a network structure that could give rise to two basic and possibly default, self-referenced coding states observed in the hippocampus.

This model provides insight into how a recurrent network operates in the absence of spatially specific input, but still allows for such input to modulate sequential activity towards place field representation (Wang 2014). We will next explore further the mechanisms of sequence generation and coding correlates in both theoretical and experimental work.

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