Neurophysiological correlates of spatial navigation optimization in the rodent

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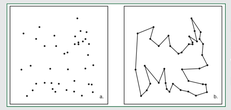
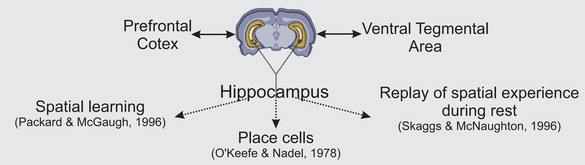
Introduction

The Traveling Salesperson Problem (TSP) involves the search for an optimal solution among a discrete set of possible solutions. TSP extends beyond physical distances: imaging celestial objects, airport traffic control, manufacture of microchips, DNA sequencing...



Humans and animals are able to find good solutions (Macgregor & Ormerod, 1996; Menzel 1973, Watkins et al. 2011). The neural substrate of spatial navigation optimization is largely unknown.

The Brain Mechanisms of Spatial Navigation Optimization



This multi-goal task makes it possible to relate the activity of place cells from trial to trial as to the rat's convergence on a specific trajectory.

Main General Questions

- Is the dorsal hippocampus (DH) necessary for the TSP?
- What are the behavioral strategies used in the TSP?
- Are the rate and spatial distributions of Sharp Wave Ripple complexes (SPWs) and replay events within and between trials correlated with the convergence onto a path?

Methods

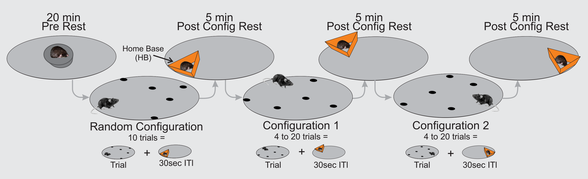
- Rats were exposed to both, random configurations (different cup locations every trial, 10 trials) and standard configurations (same cup locations, until convergence or up to 20 trials) of the TSP task with 5 cups per configuration.

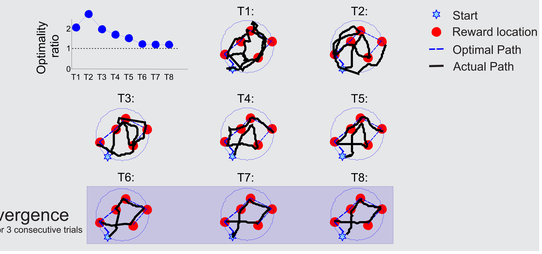
- Bilateral inactivation of the DH (bupivacaine (2.5%) or ropivacaine (10mg/ml)) before TSP task (standard configurations only).

- Multi-tetrode recordings from the DH CA1. SPWs extracted by filtering (100-300 Hz). Spike cutting using Spike2.

- Computational models of the hippocampus-BG system (decision making) and PFC (efficient path formation) to model the experimental data.

Experimental Protocol

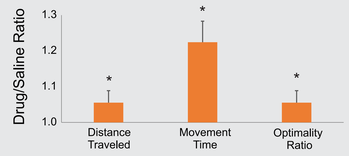




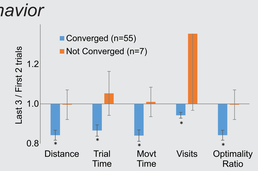
Results: *Inactivation*

Inactivation (bupivacaine/ropivacaine) of the dorsal hippocampus significantly increases:

- distance traveled
- movement time
- optimality ratio



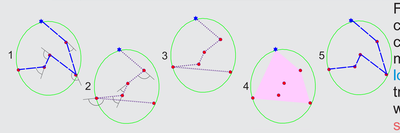
Behavior



Rats mostly converged to a near-optimal path in less then 10 trials.
When rats converged, optimization was reflected in the decrease in distance traveled, trial completion time, movement time, number of visited reward locations and optimality ratio.

Behavioral Performance

Configurations / Features	First 2 trials: Distance Traveled	First 2 trials: Trial Time	First 2 trials: Visits	First 2 trials: N of Opt Segments on the Path	First 2 trials: Optimality Ratio	Last 3 trials: Distance Traveled	Last 3 trials: Trial Time	Last 3 trials: Visits	Last 3 trials: N of Opt Segments on the Path	Last 3 trials: Optimality Ratio
1. Optimal Path Turning Angle		−	−	−	−				−	
2. Greedy Path Turning Angle		−			−					
3. Greedy Path Length	+					+	−	+		+
4. Cvxhull Area					−	+	−			
5. Optimal Path Length						+	−			

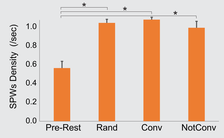


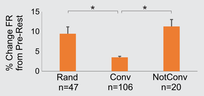
First trials of the converged configurations were mostly associated with local strategies, last trials were associated with local and global strategies.

SPWs and Firing Rate within SPWs

Sharp wave–ripple complexes occur:
1. In HB, between configurations (5 min rest)
2. In HB, between trials (30 sec rest)
3. At the reward locations

1. SPWs Post Configurations

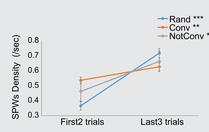


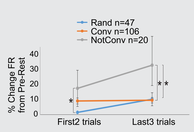


SPWs density was significantly higher after the task in all conditions.

However, place cells fired more in SPWs after the Random and Not Converged sessions than after the Converged condition.

2. SPWs Between Trials

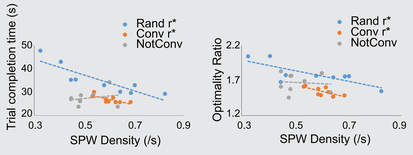




SPWs density increased significantly across trials in all conditions.

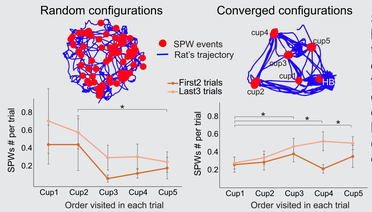
Place cells did not significantly fire more in SPWs across trials in any condition. Their contributions to SPWs were however greater if the rat did not converge.

3. SPWs Between Trials vs Performance



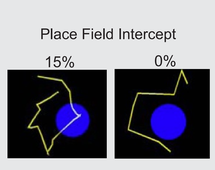
Post-Trial SPWs density was correlated with trial completion time and optimality ratio in the random and converged conditions.

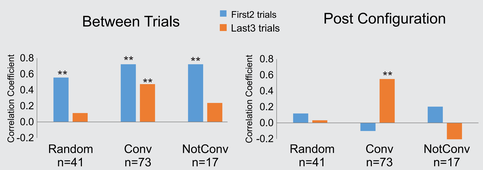
4. SPWs at Reward Locations



The number of SPWs at reward locations during the last 3 trials decreased from first cups to last cups in random configurations but increased in converged condition.

5. Place Field Intercept Correlations with FR within SPWs



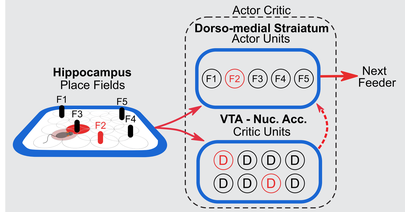


The firing of place cells during SPWs was correlated with the intersection of the path with their place field after the first 2 trials in all conditions, but remained significant only if the rat converged.

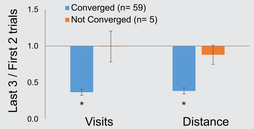
The correlation after convergence remained significant in the 5 min post configuration periods.

Computational modeling results

Computational model of the Hippocampus



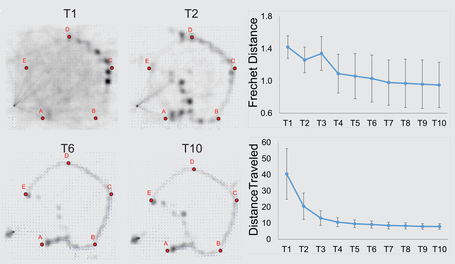
The model learns which feeder to go to next. The decision is solely based on the current location, but the model can perform global optimization using reinforcement learning strategies, implemented through the HPC-BG interactions.

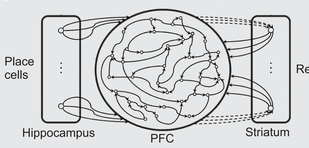


The model results agree with experimental results showing a decrease in distance traveled and in the number of visited reward locations across trials only in converged condition.

Role of the prefrontal cortex and 'Reservoir Computing'

PFC is modeled as an instantiation of the reservoir computing paradigm called the Temporal Recurrent Network. Reservoir input is the replay of place cell subsequences (snippets) during SPW events, as the animal generates increasingly efficient trajectories in the TSP task across trials. Recurrent dynamics consolidate snippet representations and create efficient sequences by rejecting sequences that are less robustly coded.





The model results agree with experimental results showing convergence to a near-optimal path in about 10 trials.

Summary

1. The dorsal hippocampus is important for spatial optimization.

2. Optimization in the TSP task may be the result of a transition from local to global strategies, as a subject becomes more familiar with the reward locations.

3. SPWs density increased from trial to trial and stays high several minutes after the TSP task, whether the task involves optimization or not.

4. SPWs density between trials was positively correlated with performance irrespective of convergence. However, the number of SPWs at target locations increased from cup to cup if the task involved optimization, but decreased if optimization was not possible.

5. After convergence, while there was a general decrease in place cells firing within SPWs, there was a high correlation between their firing and the extent to which the place fields intercepted the trajectory. The correlation remained high in the last trials and a few minutes after the task only in converged conditions. This suggests that post-task replay preferentially involves cells whose fields are on the converged path.

6. Modeling studies suggest that the hippocampus-BG system could implement path optimization during **active** spatial navigation using reinforcement learning, and that the PFC could further optimize the trajectories during **post-task rest** using reservoir-like computation aimed at producing short elementary paths (snippets).

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