A mechanism for sensorimotor object recognition using cortical grid cells

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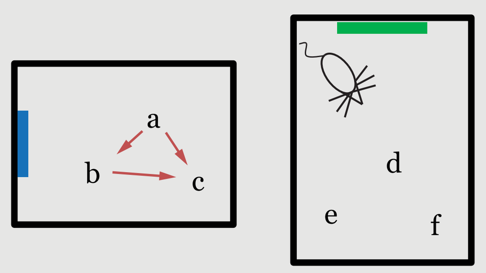
Summary

Question

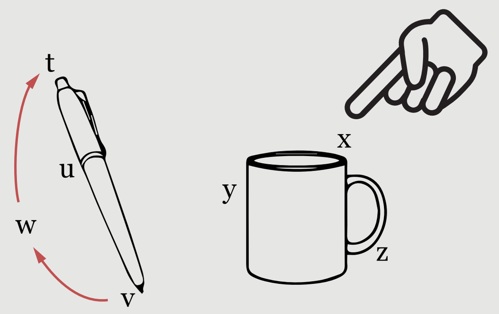
How does sensory cortex incorporate self-motion?

This model's answer

- Sensory cortex uses movement and sensation to build maps of objects.
- The neocortex uses analogs of grid cells to represent locations in the reference frame of objects.
- The neocortex and hippocampal formation use similar mechanisms to model objects and environments.



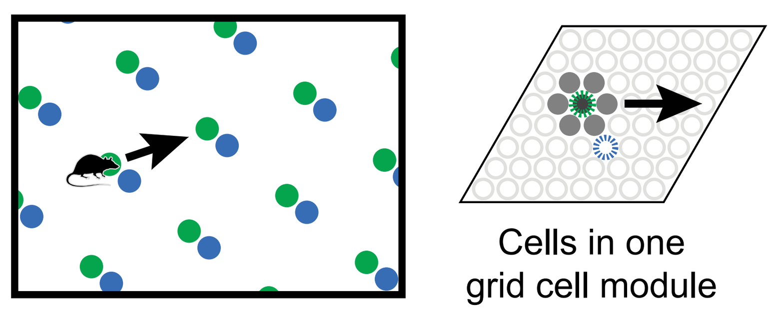
Locations in the hippocampus: Body relative to environment



Locations in the neocortex: Sensor patch relative to object

How grid cells represent locations

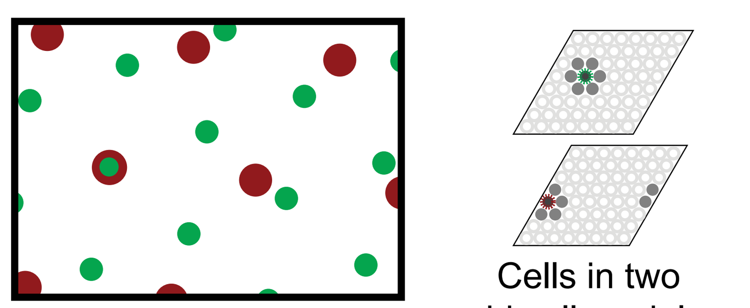
Grid cells are arranged into modules. A single grid cell module represents locations ambiguously.



Environment

Cells in one grid cell module (sorted)

Multiple grid cell modules can represent locations uniquely.



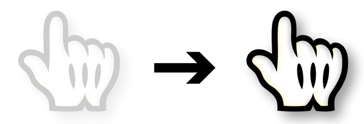
Environment

Cells in two grid cell modules (sorted)

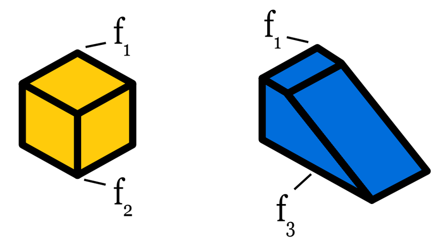
Animals could learn a novel environment by activating a random bump in each module then relying on path integration.

Task

Learn and recognize objects using a moving sensor.
Each object is a different arrangement of common features.



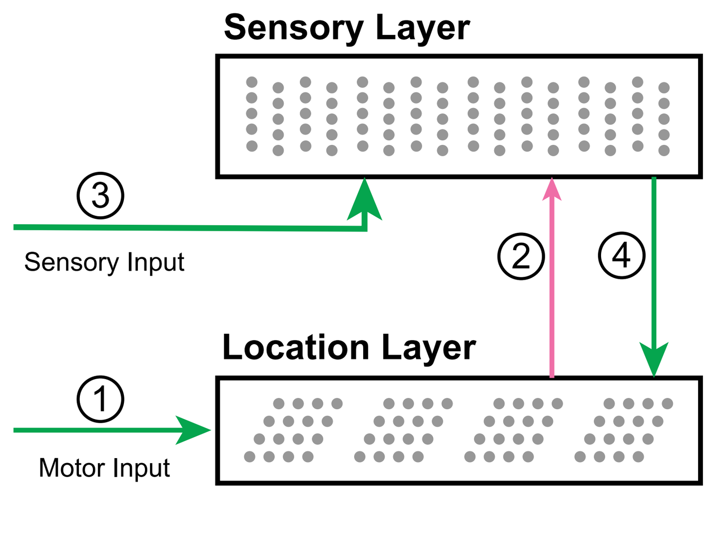
Moving sensor



Two example objects with common features

A network receives sensory and motor input as the sensor moves.

Model



Conjunctive feature at location

Location in external reference frame

Each timestep of the network consists of 4 stages.

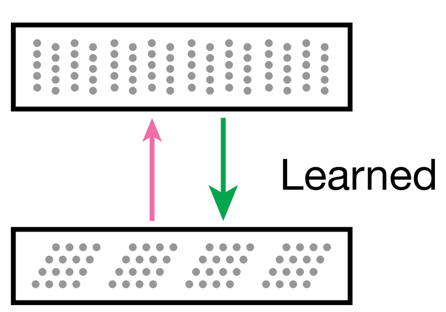
1. Use motor input to update the location.
The location layer consists of independent grid cell modules. Each uses the motor input to update.

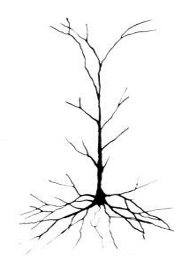
2. Use updated location to predict sensory input.
Cells in the sensory layer receive location input on their distal dendrites. This input primes certain cells, preparing them to spike.

3. Use sensory input to confirm predictions.
Many cells receive driving sensory input. Cells that were predicted quickly fire and inhibit the others. *(Hawkins and Ahmad, 2016)*

4. Use confirmed predictions to update the location.
If there were no predictions, multiple locations become active.
If there were multiple predictions, only the locations that caused correct predictions remain active.

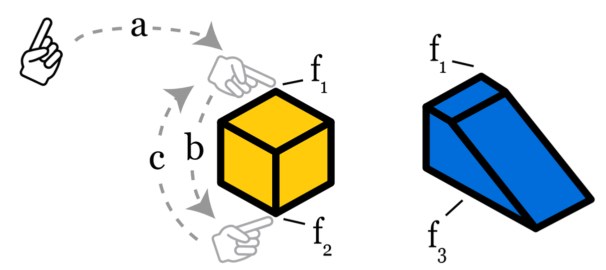
Each object is learned as a set of reciprocal connections between the two layers.



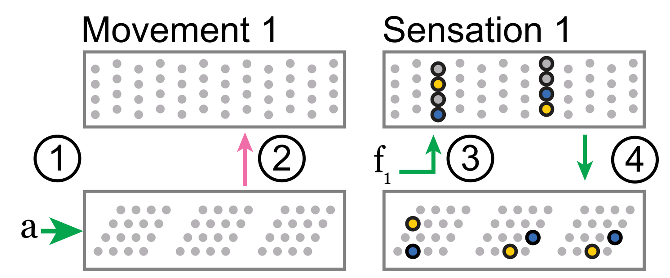


Compartmentalized dendritic segments

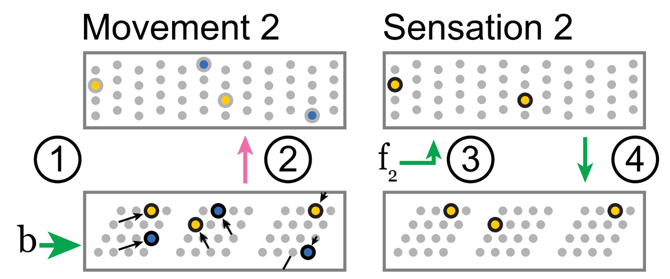
Object recognition example



Over time, the network receives three motor and three sensory inputs.

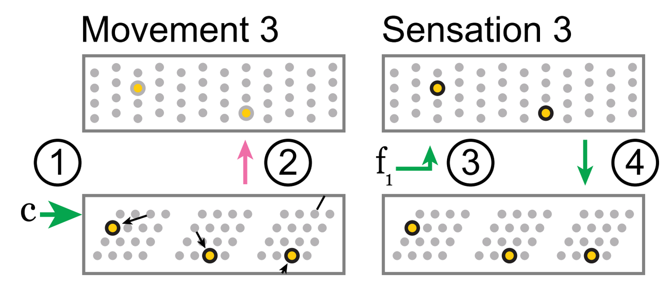


The first sensation causes the network to recall two locations.



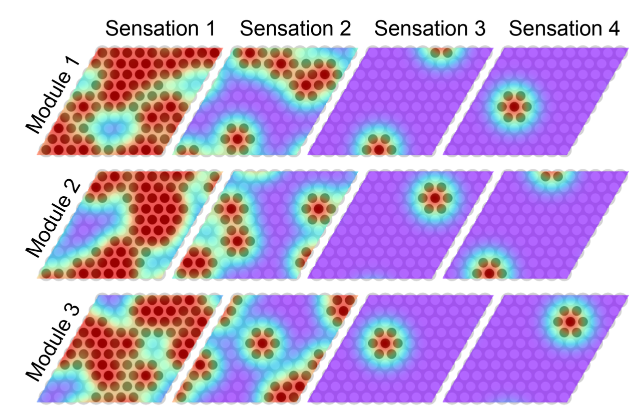
Motor input causes each module to update. This new location predicts two possible inputs.

One of those inputs arrives, disambiguating the location.

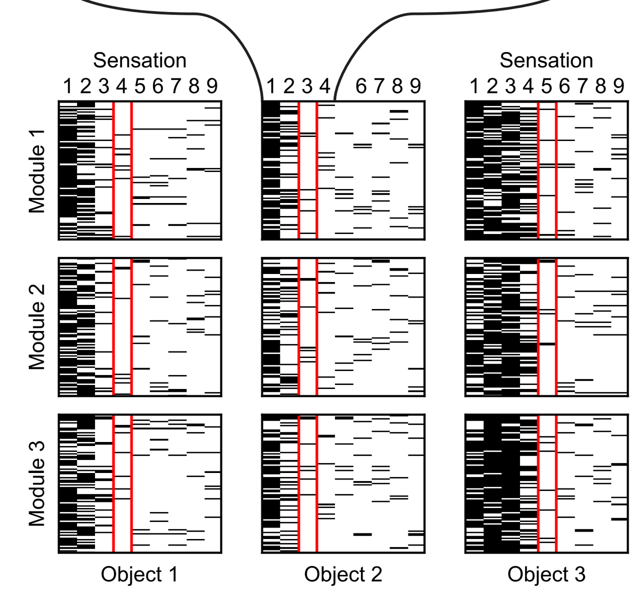


For each subsequent movement, the input is correctly predicted.

Results

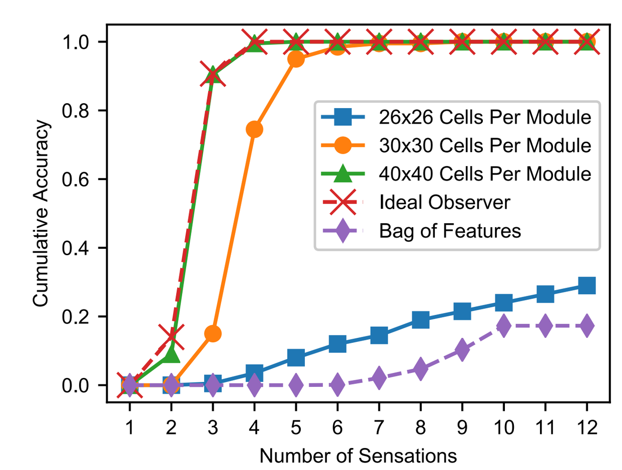


During recognition, activity converges from dense to sparse.



The circuit performs localization relative to objects.

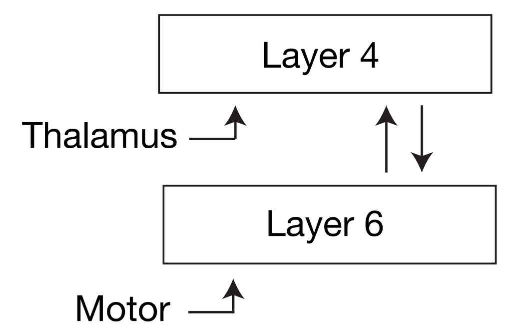
The sparse activity uniquely represents a specific location on a specific object.



This neural circuit approximates the ideal computational algorithm for identifying arrangements of shared features.

Mapping to biology

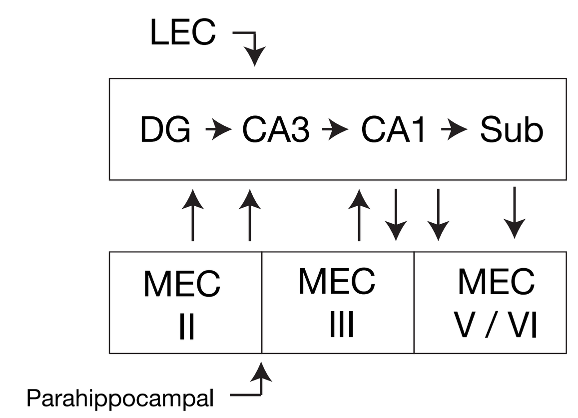
Cortical anatomy



Layer 4:
- Receives driving sensory input from thalamus
- Receives modulatory input from Layer 6
- More sensory-driven activity

Layer 6:
- Receives input from Layer 4
- Receives input from motor areas (e.g. M2 -> V1)
- More “spontaneous” activity

Analogous to hippocampal formation



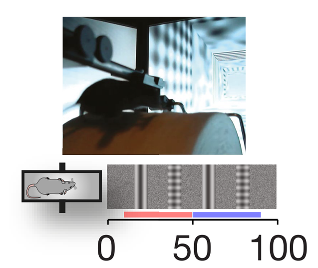
Hippocampus:
- A mix of pure locations and conjunctive “item-place” cells

Medial Entorhinal Cortex:
- Pure locations
- Updated by movement
- Anchored by sensation

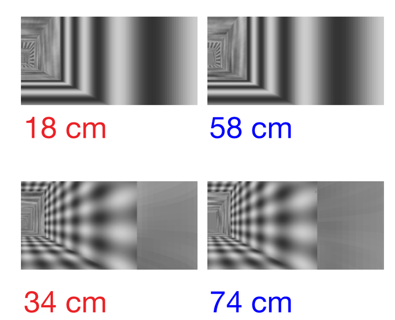
Empirical support

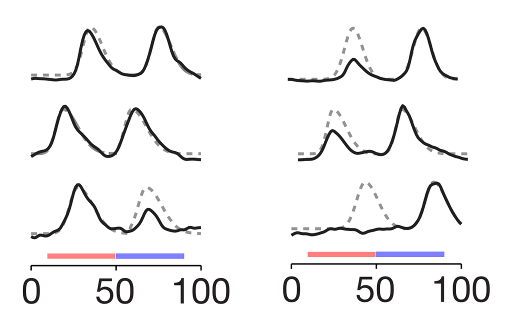
Evidence of grid cells in multiple areas of neocortex
(Doeller et al., 2010) *(Jacobs et al., 2013)*

Evidence of locations in V1 *(Saleem et al., 2018)*



Position (cm)





Example cell responses

Predictions

- The neocortex uses analogs of grid cell modules to represent locations of sensor patches relative to objects. Within a module, pairs of cells fire at consistent relative locations.
- Cortical grid cell modules are in Layer 6 of the neocortex.
- The projection from Layer 6 to Layer 4 modulates which cells in Layer 4 become active. If Layer 6 input is experimentally inhibited, activity in Layer 4 will become more dense.
- Conversely, the connection from Layer 4 to Layer 6 can drive the Layer 6 cells to become active.

References

Lewis, M., Purdy, S., Ahmad, S., & Hawkins, J. (2018) Locations in the Neocortex: A Theory of Sensorimotor Object Recognition Using Cortical Grid Cells. bioRxiv, 436352.

Hawkins, J. & Ahmad, S. (2016) Why Neurons Have Thousands of Synapses, a Theory of Sequence Memory in Neocortex. Front. Neural Circuits, 10, 1–13.

Doeller, C.F., Barry, C., & Burgess, N. (2010) Evidence for grid cells in a human memory network. Nature, 463, 657–661.

Jacobs, J., Weidemann, C.T., Miller, J.F., Solway, A., Burke, J.F., Wei, X.X., Suthana, N., Sperling, M.R., Sharan, A.D., Fried, I., & Kahana, M.J. (2013) Direct recordings of grid-like neuronal activity in human spatial navigation. Nat. Neurosci., 16, 1188–1190.

Saleem, A.B., Diamanti, E.M., Fournier, J., Harris, K.D., & Carandini, M. (2018) Coherent encoding of subjective spatial position in visual cortex and hippocampus. Nature.