A Cortical Circuit For Sensorimotor Learning And Recognition

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Overview

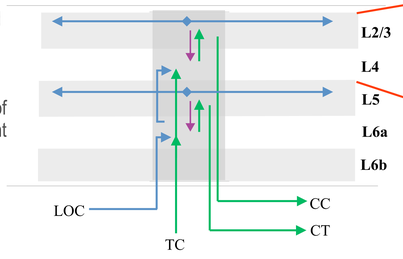
Prevailing models of recognition are purely sensory and bottom-up, but:

1) Active movement is key to all inference

2) Existing models cannot account for anatomy:

Cortex is organized into columns and layers

Canonical pattern of lateral and recurrent connections



We propose that:

1) Cortical columns combine sensory and location information to form predictive models of objects.

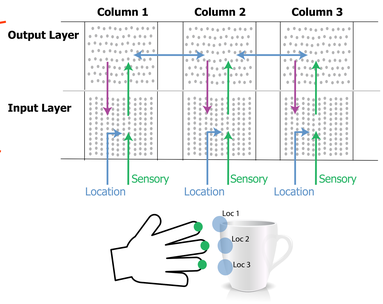
2) Cortical columns use lateral connections to integrate sensorimotor information over time and space to quickly and robustly recognize objects.

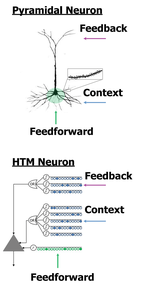
3) Cortical regions are much more powerful than suggested by naive feedforward models.

Network model

Network Structure

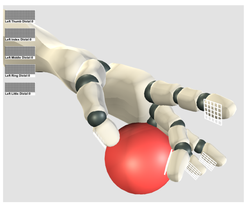
- The network models a two-layer motif that repeats twice in each cortical column.
- Input layer integrates features and location signals to form allocentric representations.
- Output layer learns stable representations of objects.
- Lateral connections across cortical columns integrate information across sensors.
- Feedback biases input layer towards representations that are consistent with recent inputs.
- Neurons incorporate active dendrites and multiple integration zones.





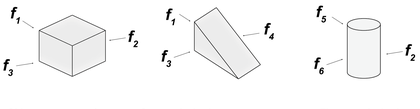
(Hawkins & Ahmad 2016)

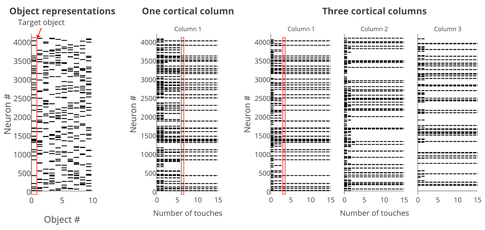
Simulated robot hand can grasp any object and recognize it.
Sensors on each fingertip sends touch information to corresponding column.



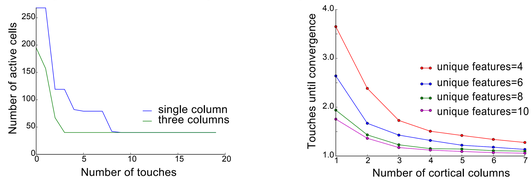
Dataset: Yale YCB Object Benchmark
Contains 77 objects

Simulation results

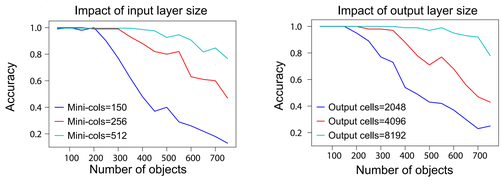




Convergence: Faster recognition using multiple columns



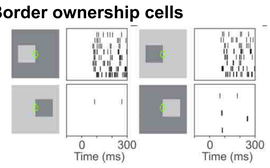
Capacity: A small network can store hundreds of complex objects.



Experiment setup: Input layer: 256 mini-columns, 16 cells/mini-column. Output layer: 4096 cells

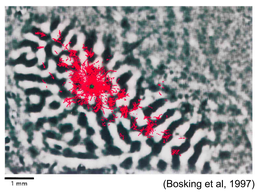
Supporting experimental evidence

Border ownership cells



(von der Heydt, 2015):
- Some cells in V1 and V2 respond to location of specific features within an object's reference frame.
- Cells do not respond to same feature in different location.

Long range connections in layer 2

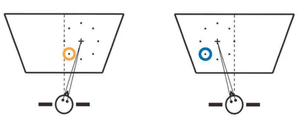


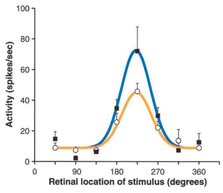
(Bosking et al, 1997)

(Bosking et al, 1997):
- Layer 2/3 cells have very long range lateral connections
- Connections are more dense locally

(Gur and Snodderly, 2008):
- Layer 2 activity is more stable
- Layer 2 cells have wider RF's

Gain fields





(Salinas & Sejnowski, 2001)

(Brotchie et al, 1995):
- Sensory responses modulated by body position
- Thought to be basis for reference frame transformations and allocentric location computations
- Widespread in primary and higher order cortical regions

Predictions of the theory

- Each region contains cells stable over movement of the sensor. The range of movements over which a cell is stable will be related to the extent of the long-range lateral connections in that region.
- The activity of these stable cells are specific to object identity.
- The output layers (those with long-range lateral connections) form these stable representations. Their activity will be more stable than input layers.
- Object representations within each column will converge on stable representation faster with lateral connections.
- Object representations within each column will quickly become sparser as more evidence is accumulated for an object. Cell activity in output layer is denser for ambiguous objects.
- Each region contains cells tuned to location of features in object's reference frame (invariant to ego-position, e.g. border ownership).

Additional details

Activation rules

Input Layer:
- If any cell in an active mini-column has lateral inputs, only those cells fire.
- If no cell in an active mini-column has lateral inputs, all cells in the mini-column fire.

Output Layer:
- Output cells with strong feedforward inputs and lateral inputs fire first.
- If no cell has lateral inputs, output cells with only feedforward inputs fire.
- Output cell activity persists if no feedforward inputs is provided.

Hebbian learning rules

- Whenever a cell is active, reinforce synaptic connections (LTP).
- The reinforcement for distal and apical segments is branch specific.

References

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