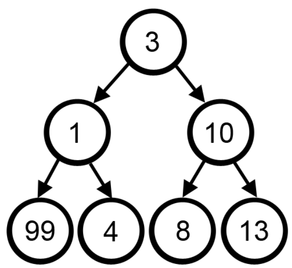
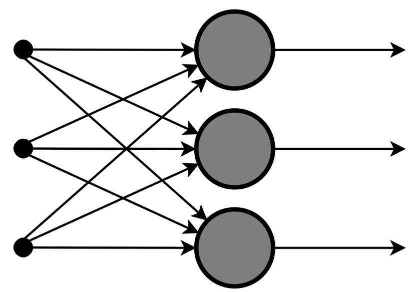
CSE 40171: Artificial Intelligence





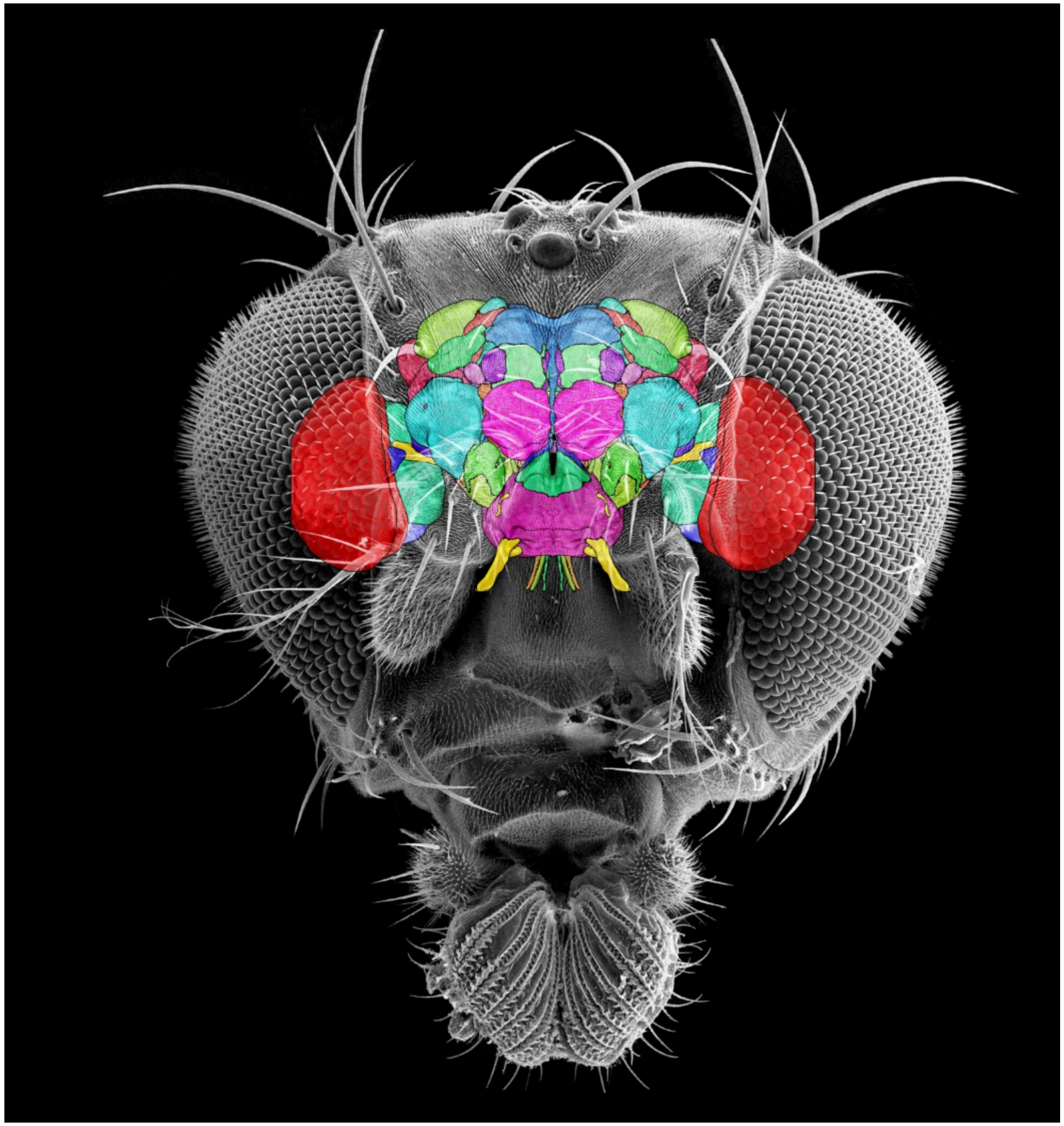
Artificial Neural Networks with Anatomical Fidelity:
Connectome-Based Artificial Neural Networks

Homework #6 has been released
It is due at 11:59PM on 11/22

Project Updates are Due on 11/25 at 11:59PM

(See Course Website for Instructions)

How can a connectome be used to inform an artificial neural network architecture?



Ito et al. Neuron 2014

Progress in Fly Connectomics

Zheng et al. Cell 2018

- A **complete** adult *Drosophila* brain was imaged with EM and has been made publicly available
- The imaged volume enables brain-spanning mapping of circuits at synaptic resolution
- All mushroom body (MB) calyx inputs were mapped, revealing a new cell type, MB-CP2
- Previously unidentified synaptic partners form recurrent microcircuits in MB calyx

Fly Visual System

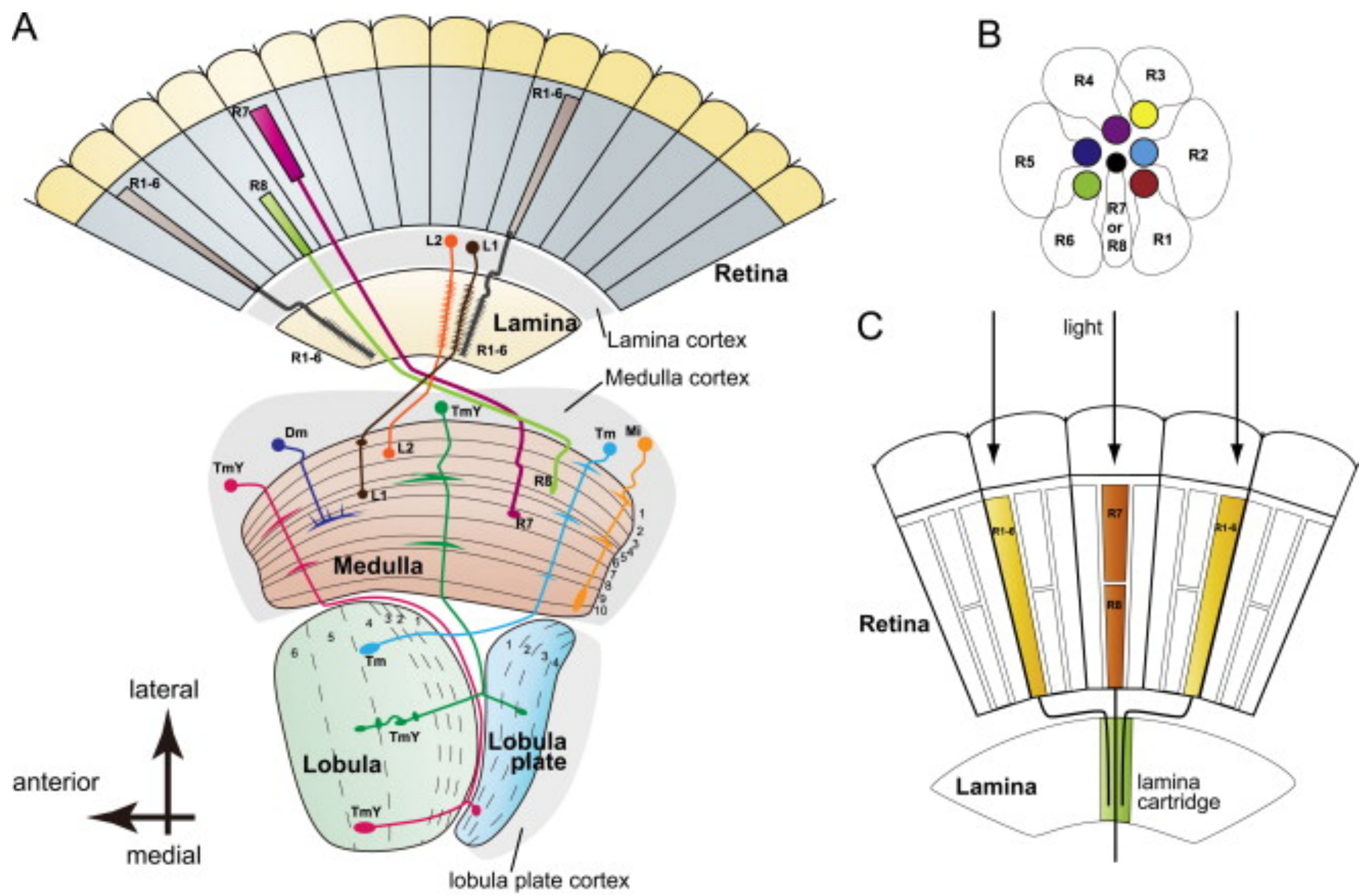


Image Credit: Sato et al. 2013

A Connectome Based Hexagonal Lattice Convolutional Network Model of the Drosophila Visual System

Tschopp et al. arXiv 2018

A network with anatomical fidelity to the brain

- Simplified model of the first two stages of the fly visual system
  - Lamina and Medulla
- Hexagonal lattice convolutional network trained with backprop
- Networks initialized with weights from connectome reconstructions automatically discovered well-known orientation and direction selectivity properties
  - Random networks do not

Lamina

Responsible for contrast enhancement through lateral inhibition

- Five distinct classes lamina monopolar cells: **L1-L5**
- L1-L3, receive direct synaptic input from the photoreceptors in the lamina, and send axons into the medulla
- Two GABAergic feedback neurons **C2** and **C3**
- Two wide-field feedback neurons (Lawf1 and **Lawf2**)
- Basket cell **T1**
- Lamina amacrine cell **Am**

Medulla

Processes movement and shows movement direction sensitivity.

Possesses local motion detectors.

Many cell types:

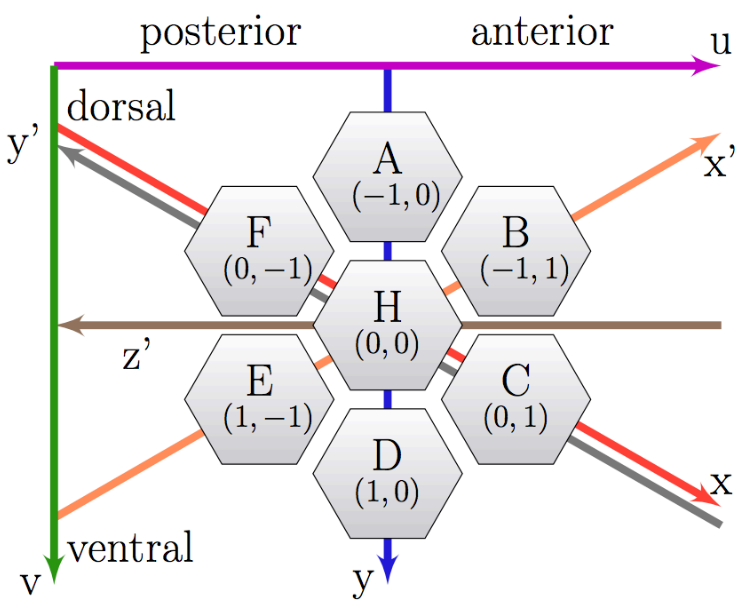
Mi1, Mi4, Mi9, T2, T2a, T3, Tm20, Tm1, Tm2, Tm4, Tm9, TmY5a, Dm8, Dm2

T4a-T4d and T5a-T5d

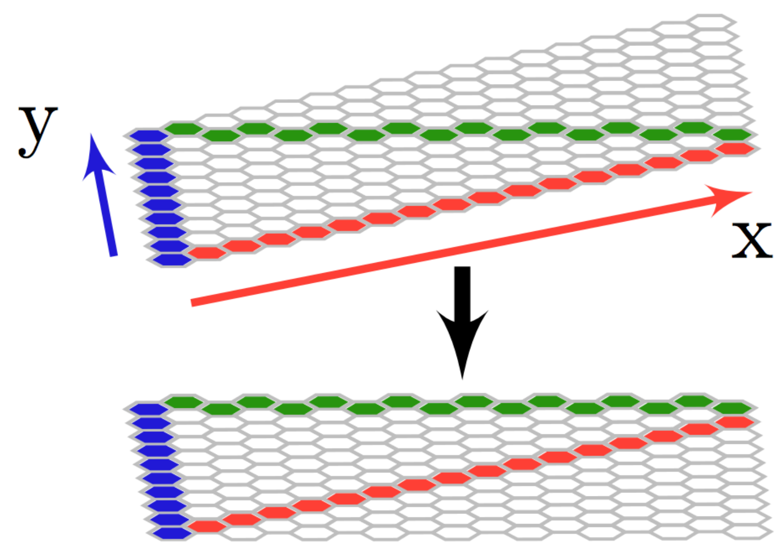
Hexagonal lattice convolutional network model

- Based on published connectomics studies of the lamina and medulla, model connectome of 43 cell types
- These neurons have a repeating columnar architecture, each spanning 5 degrees of visual angle
  - Forms a hexagonal lattice
- Repeat the locally described connectome in a spatially invariant manner, leading to a hexagonal lattice convolutional network

Hexagonal lattice convolutional network model



7 column structure with 6-neighborhood offsets along the principal y and x axis.



Semantic arrangement of the hexagonal lattice as a 2D tensor

Image Credit: Tschopp et al. 2018

Implementation details

- A hexagonal lattice of y = 20, x = 35 point neurons with continuous activations
  - ~700 ommatidia and retinotopic columns
- Every neuron is defined as node with intrinsic properties
  - Sparsity along the y and x-axis
  - ReLU
  - Bias value and operator (addition)

Cell morphology is ignored. Is that a problem?

Connectome-based Network Weights

- Connections between neurons are defined as edge between source and target neuron
- All weights are replicated spatially for all neurons of the same type (like in regular convolution filters)
- Replaces all synapses counted between two connected distinct neurons in the connectome by a single synapse
  - Resulting synapse initialized with a weight equal to the number of counted synapses divided by an arbitrary normalization factor
  - Factor was chosen to be as small as possible, but large enough so that gradient-based optimization was stable
- No info from connectome for bias; initialized to constant

Physiology-based synaptic delays

- The model is an RNN
  - Activity of every downstream neuron can only be computed when all inputs to a neuron are determined for step t
  - Linearize the connections so that the network graph becomes a directed acyclic graph through time
- Synaptic delay added for symmetric connections between neurons
- Neurons read their input from state $t - 1$
- Additional synaptic delays were introduced where physiological data suggested necessary delays

Objective: Track Objects in Videos of Natural Scenes

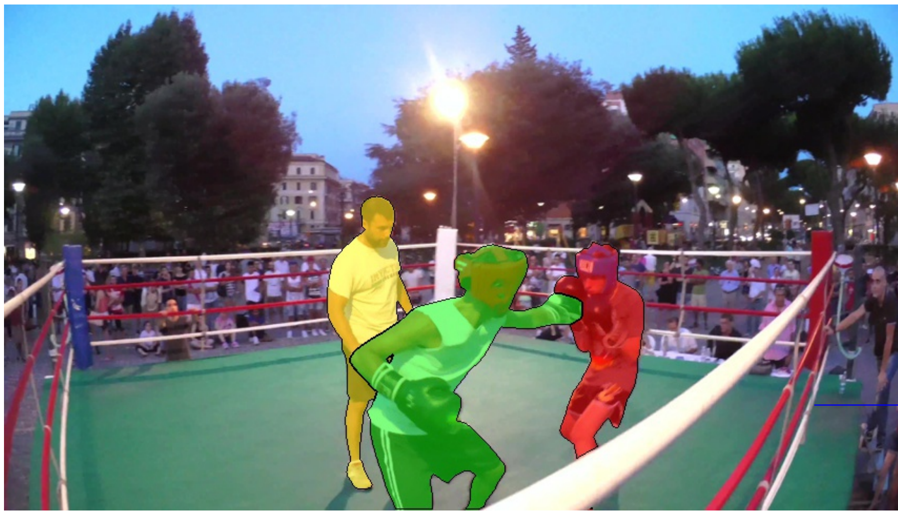
Proxy-task that depends on the circuit's ability to compute a moving object's position and velocity

In contrast to explicitly training the network to learn an encoding model based on physiologically measured neural responses

Requires only anatomical information, and no recordings of neural activity

Davis Dataset

https://davischallenge.org/




Neural Fidelity of Hexagonal Lattice CNN

Drosophila visual system connectome-based model with 3-layer decoder

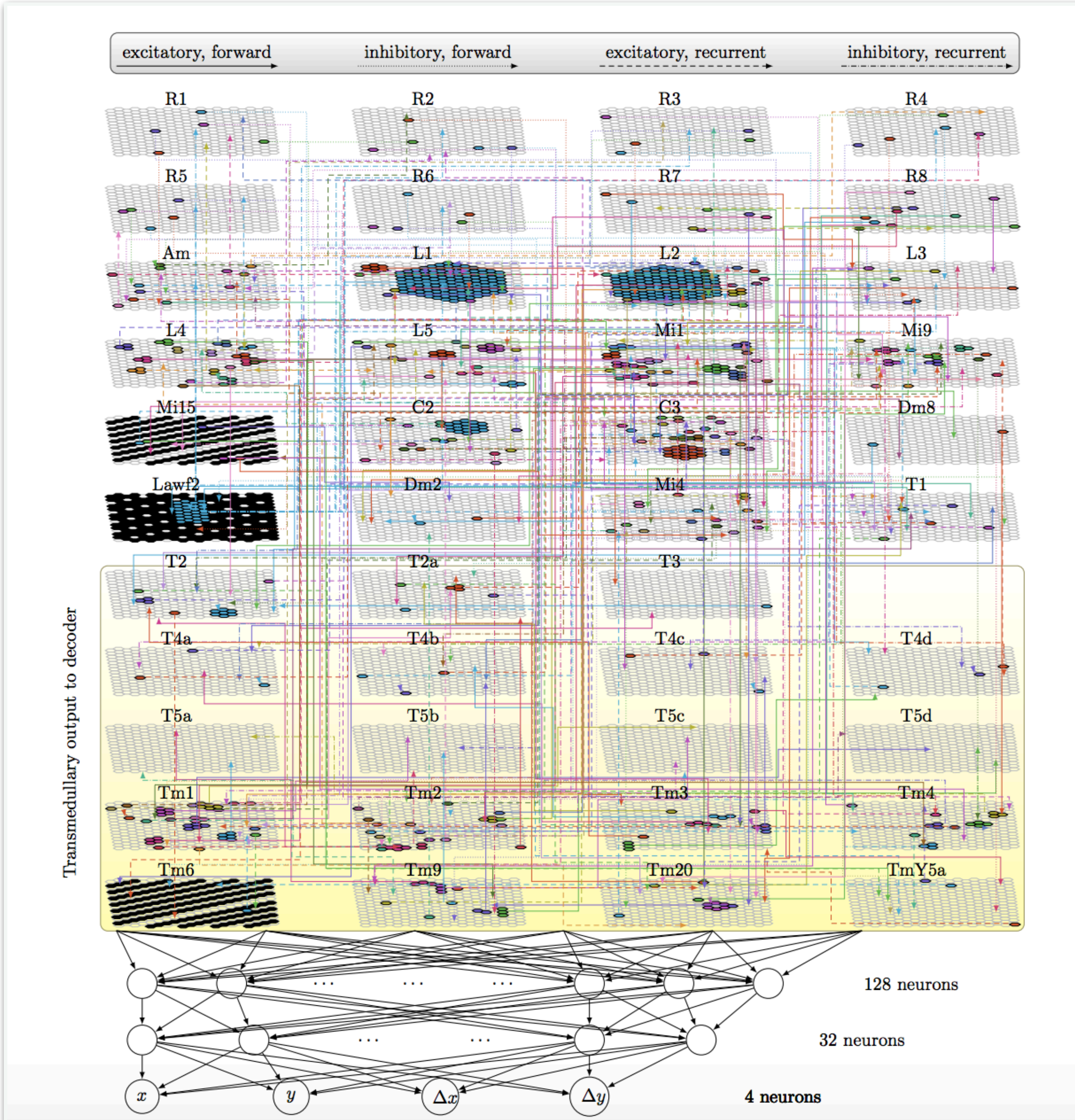


Image Credit: Tschopp et al. 2018

Total num. input synapses to a neuron & synapses per neuron type-to-type edge

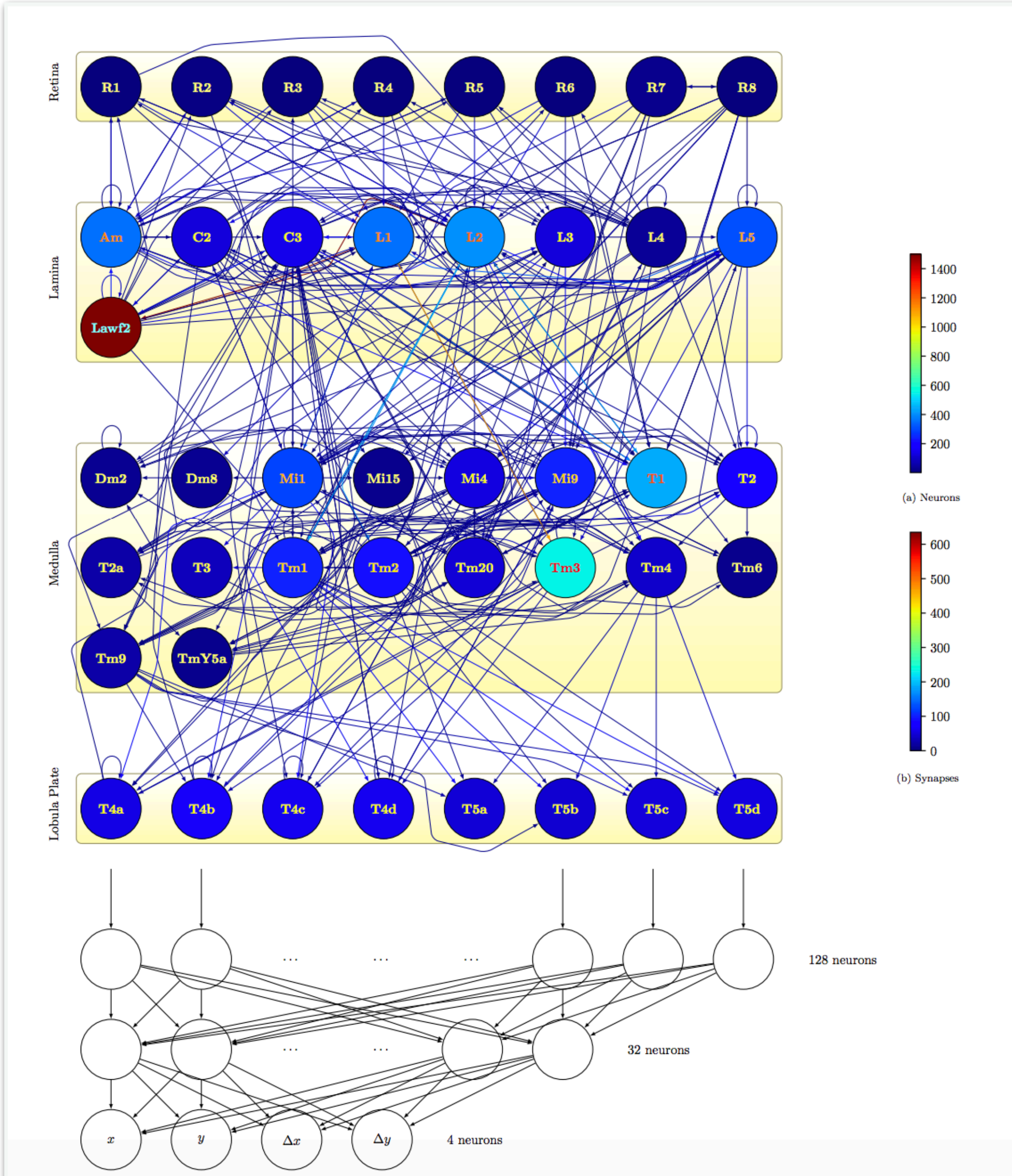


Image Credit: Tschopp et al. 2018

Correlation coef. computed between trained and connectome initialized weights

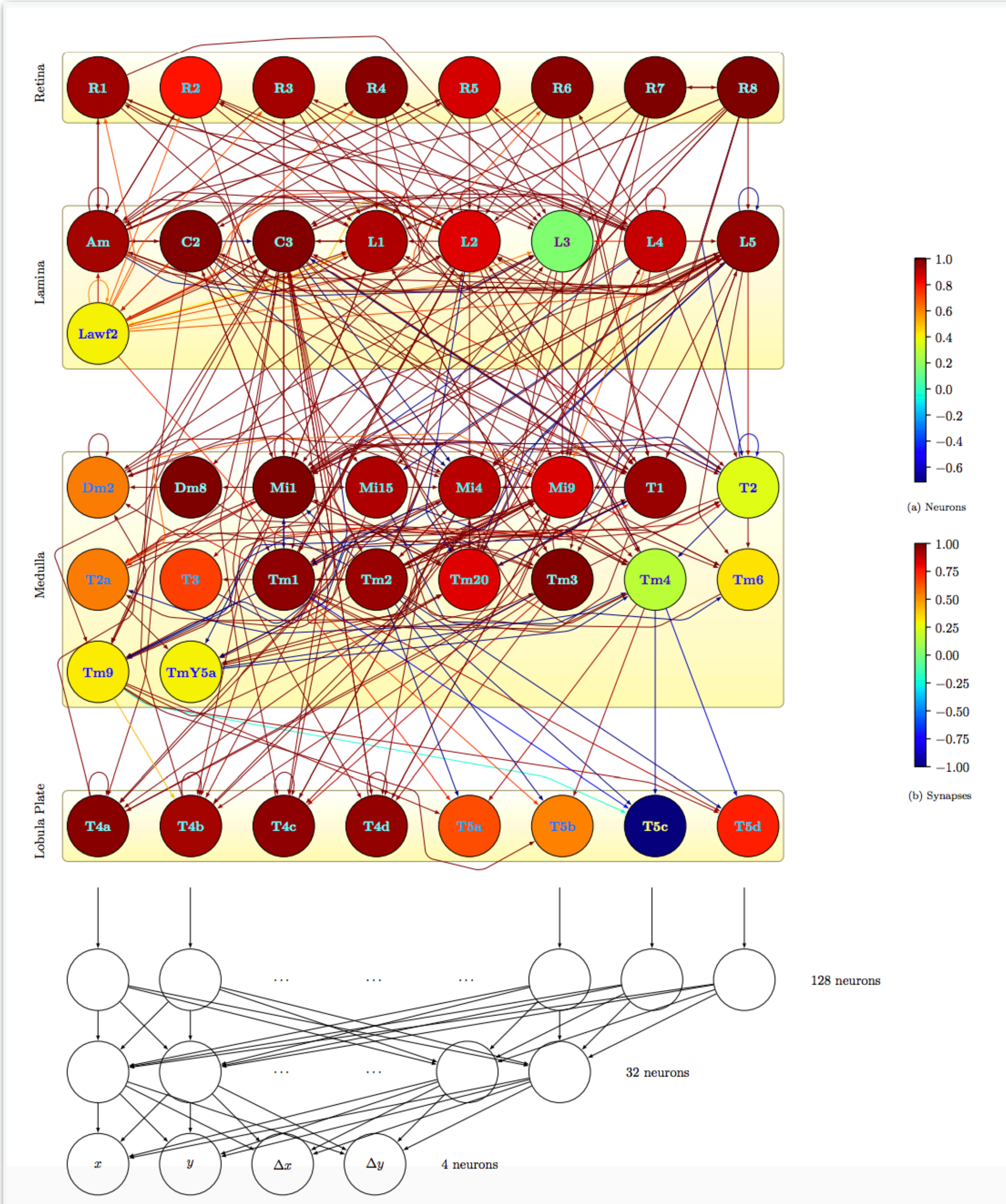


Image Credit: Tschopp et al. 2018

Takemura 2017 initialized and trained network

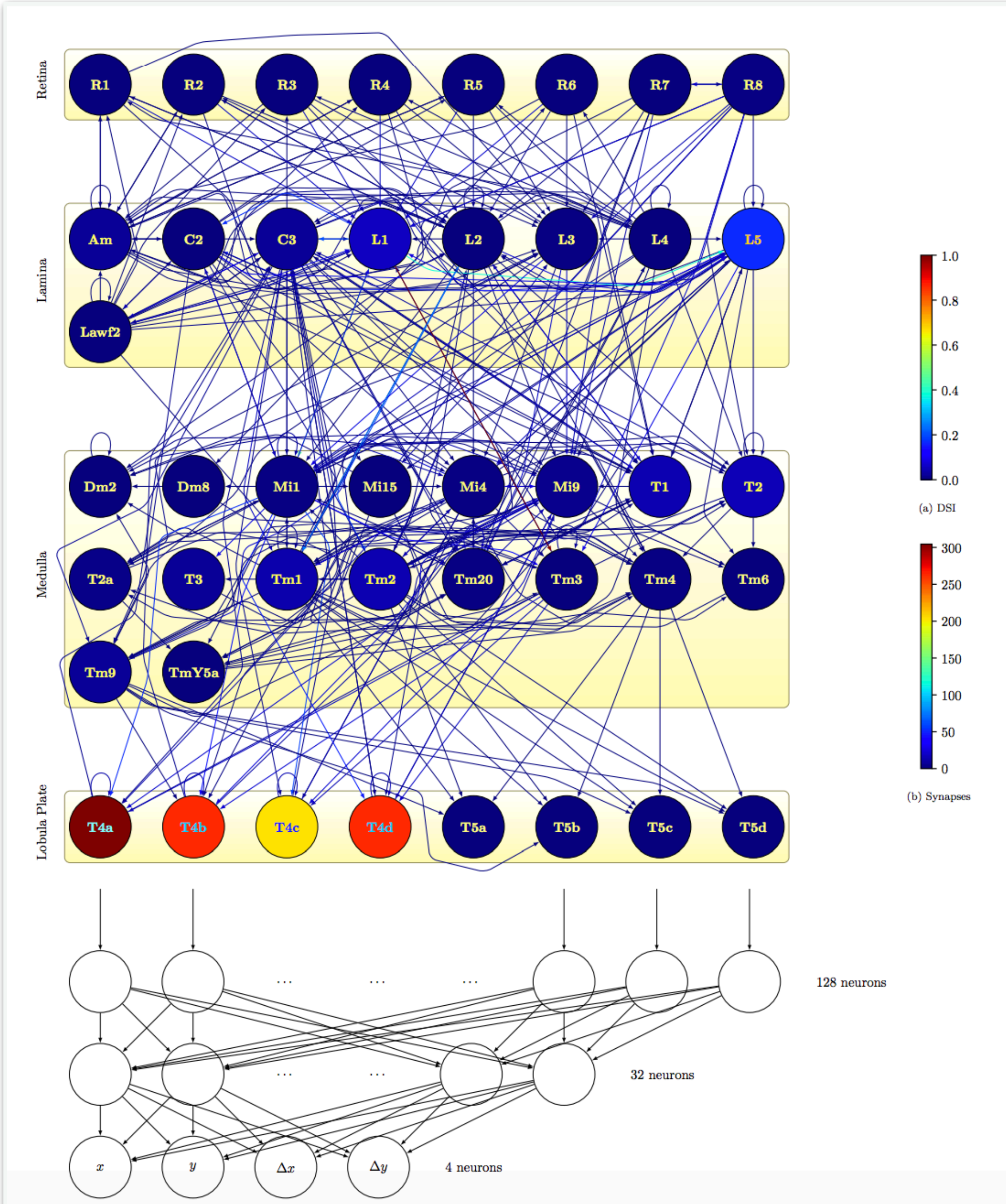


Image Credit: Tschopp et al. 2018

T4a input filters according to the Takemura 2017 model

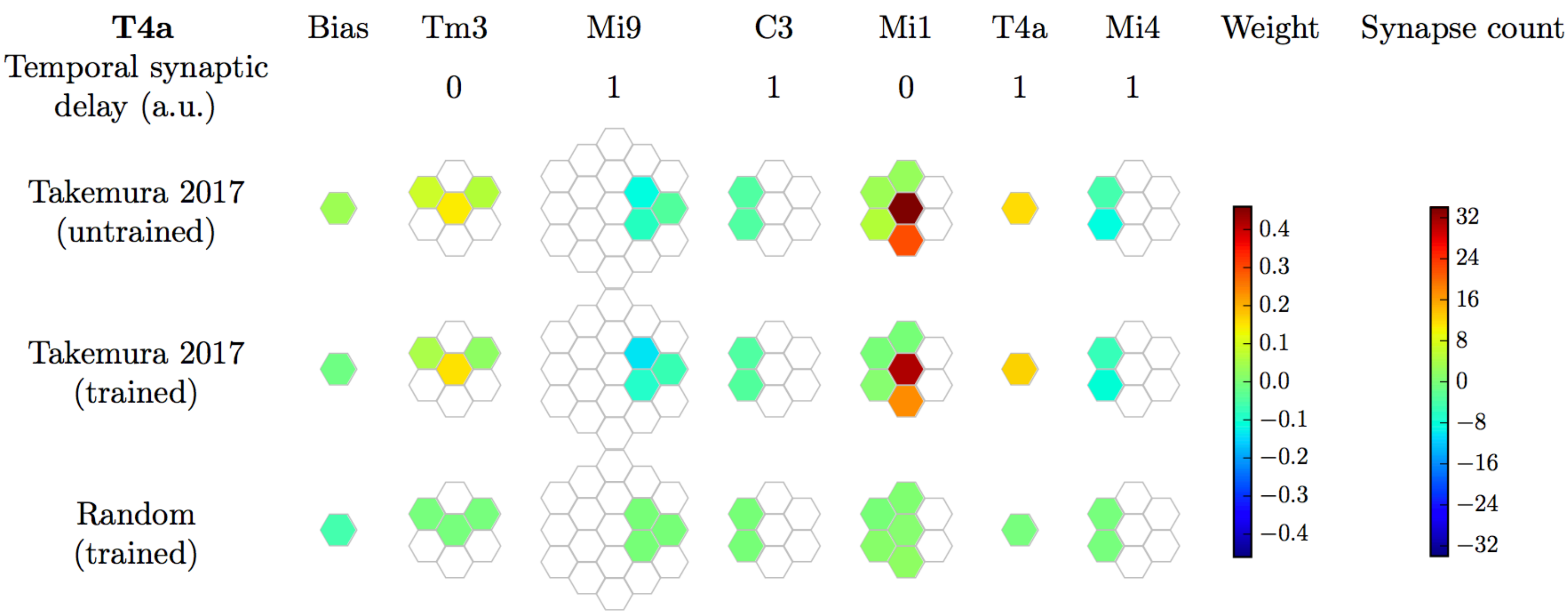


Image Credit: Tschopp et al. 2018

T4a input filters according to the Takemura 2013 model

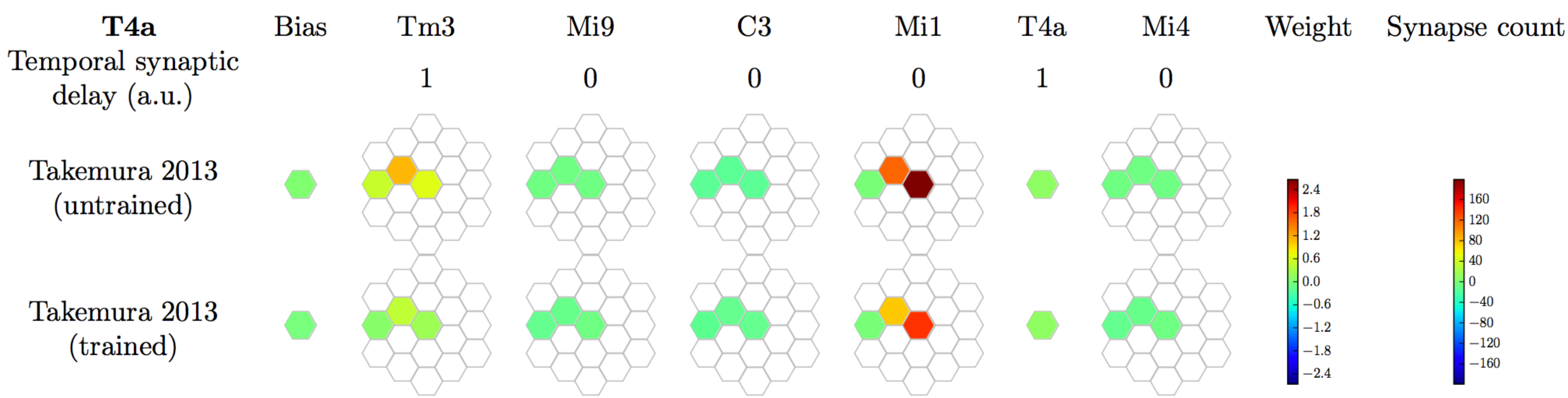
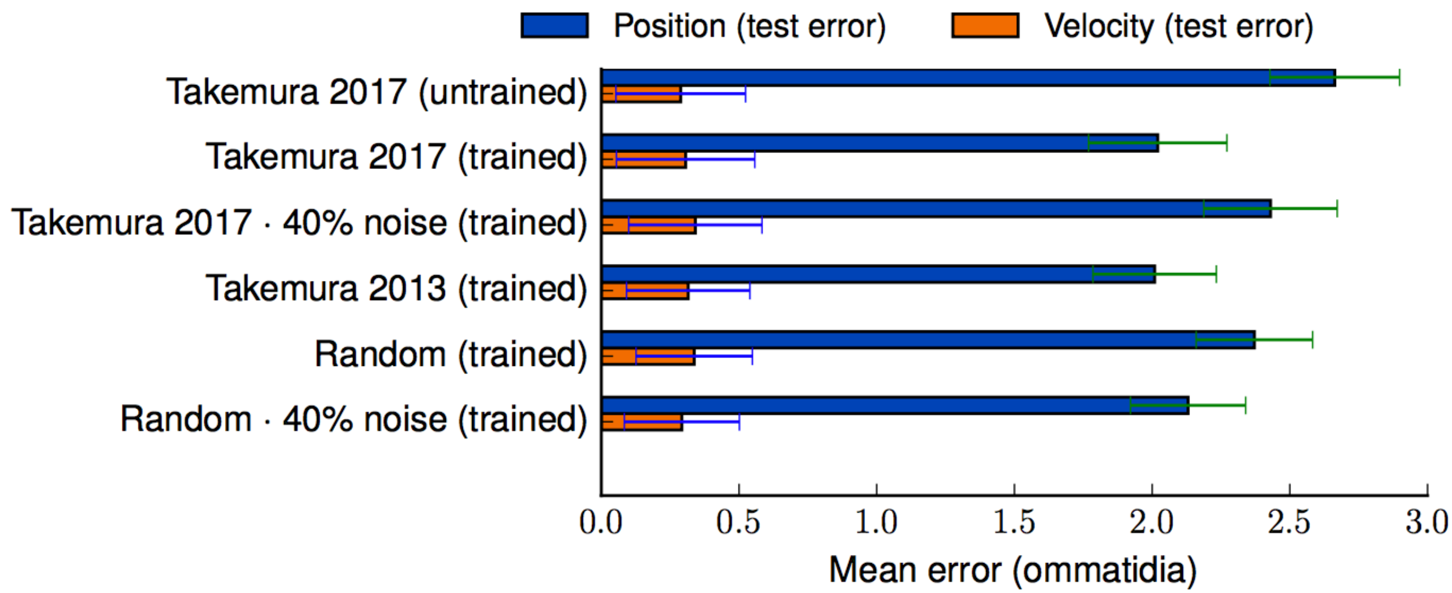


Image Credit: Tschopp et al. 2018

Gradient-based circuit optimization for object tracking

Performance on the DAVIS dataset



L_2 error on 20 frames for each of the 8 selected sequences in the DAVIS dataset

Image Credit: Tschopp et al. 2018

Training from connectome vs random initialization

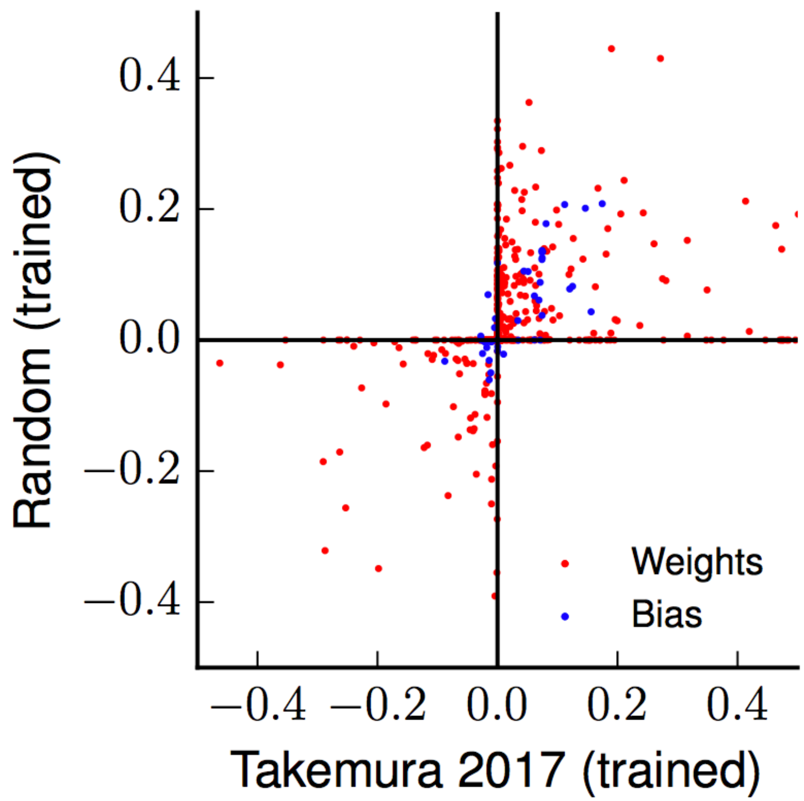
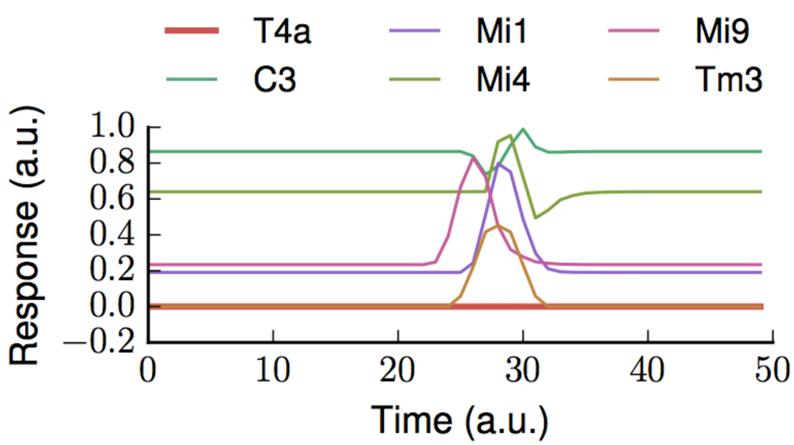
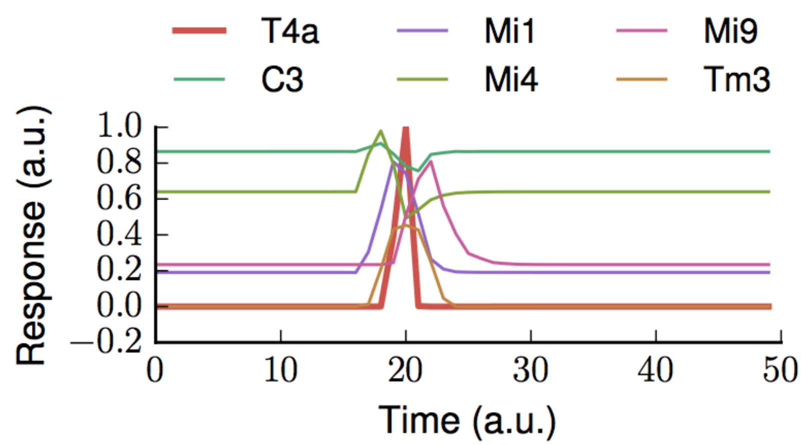


Image Credit: Tschopp et al. 2018

Orientation (OS) and direction (DS) selectivity of T4 cells



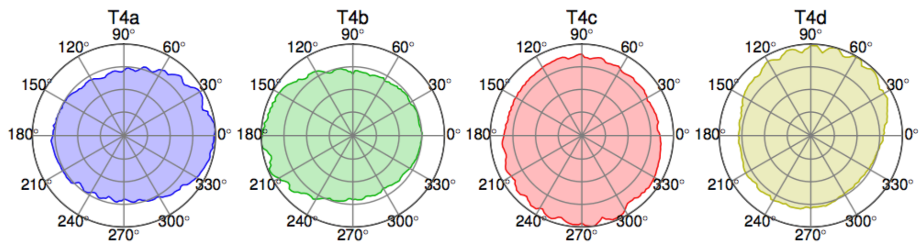
(a) T4a NULL response (0°).



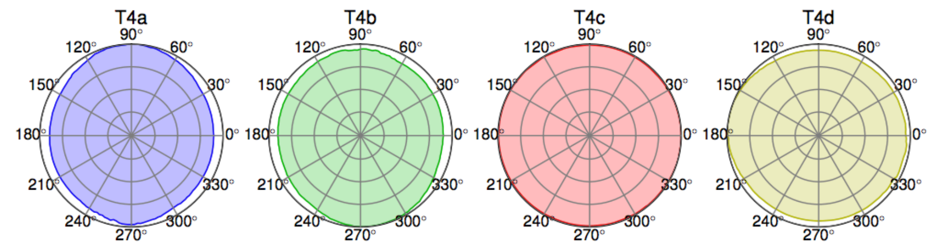
(b) T4a preferred direction (192°) response.

Image Credit: Tschopp et al. 2018

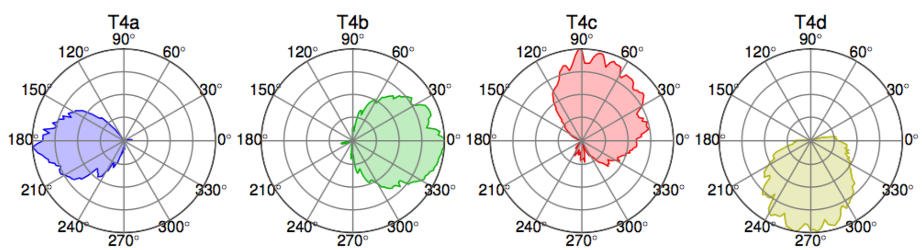
Orientation (OS) and direction (DS) selectivity of T4 cells



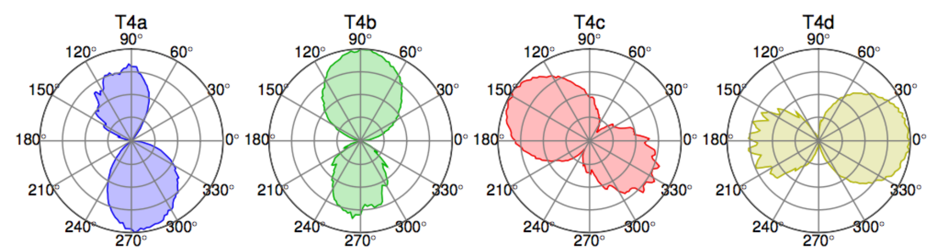
(c) DS, Takemura 2017 (untrained).



(d) OS, Takemura 2017 (untrained).



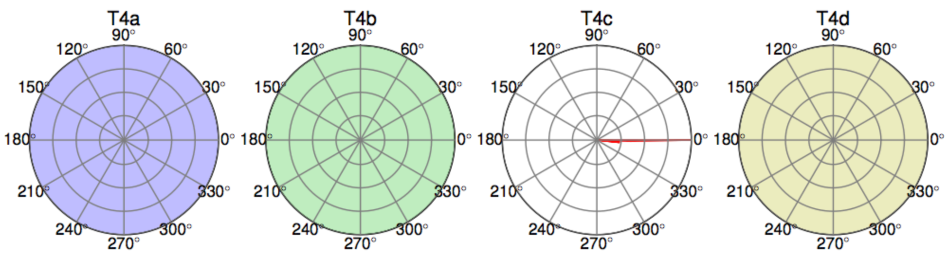
(e) DS, Takemura 2017 (trained). Each T4 cell is direction selective in one of four principal directions (T4a: 192°, T4b: 359°, T4c: 51° and T4d: 275°).



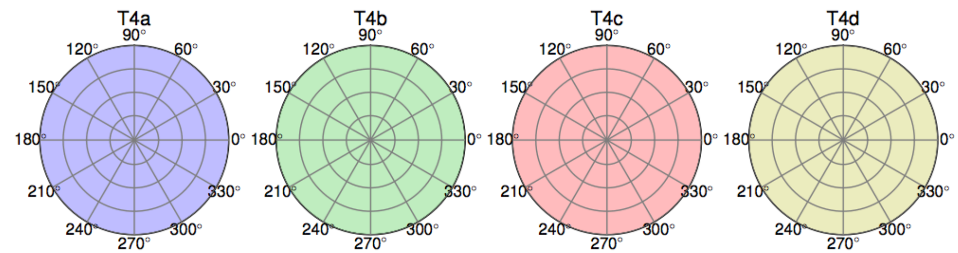
(f) OS, Takemura 2017 (trained). Two-lobed orientation selectivity with strong center-surround inhibition for bars orthogonal to the preferred direction as shown by [38].

Image Credit: Tschopp et al. 2018

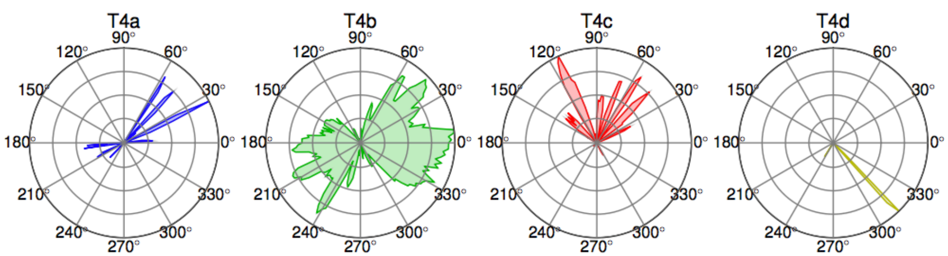
Orientation (OS) and direction (DS) selectivity of T4 cells



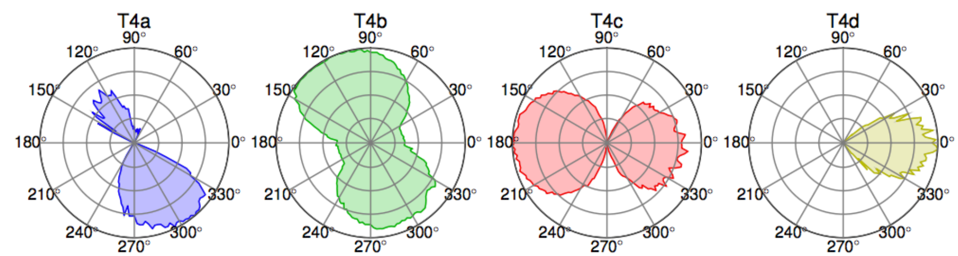
(g) DS, Random (trained).



(h) OS, Random (trained).



(i) DS, Takemura 2013 (trained).



(j) OS, Takemura 2013 (trained).

Image Credit: Tschopp et al. 2018

Direction selectivity index (DSI) scores

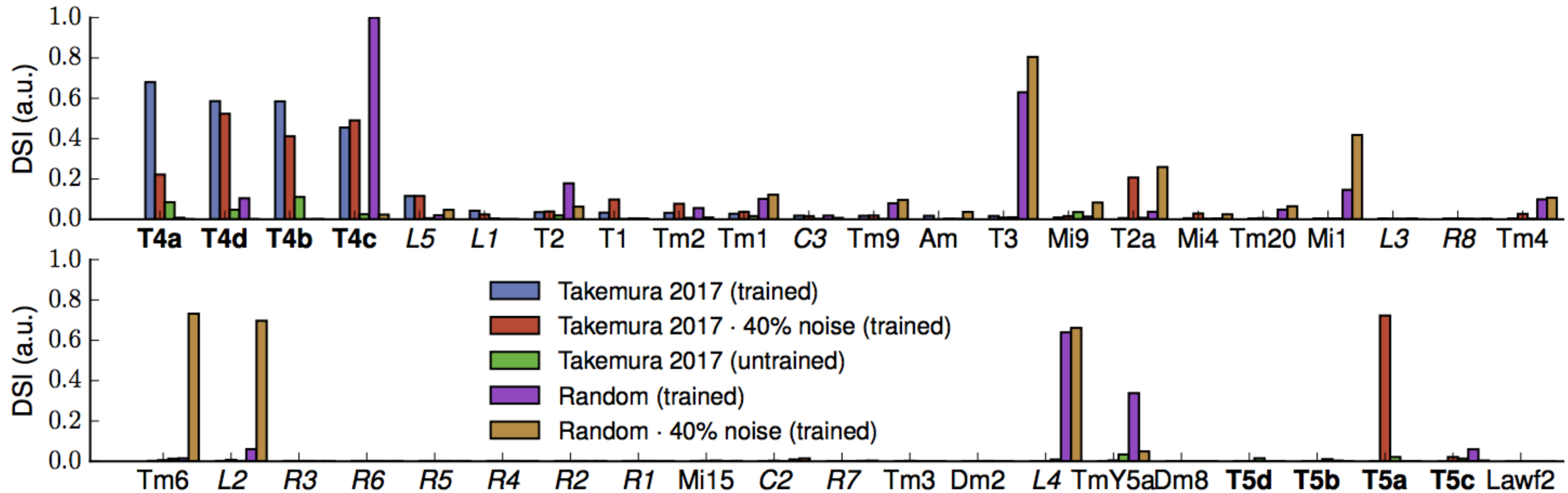


Image Credit: Tschopp et al. 2018