

# The emergence of monkey V4 topology in a retinotopically constrained self-organizing map

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# Reviews

## Primate V4

- Mid-level ventral visual stream to extract color, shape, and surface information (2-3).
- Proto-organization of visual space in primate visual system at birth (4-5).
- Inborn retinotopy can be observed at matured primate V4 (6).

## Organizational Principles

- IT-like motif emerges in spatially regularized topological deep convolutional neural network (7).
- Self-organizing map give rise to IT-like spatial orders of animacy and object size, along with a face preferring domain (8).

# V4 Dataset

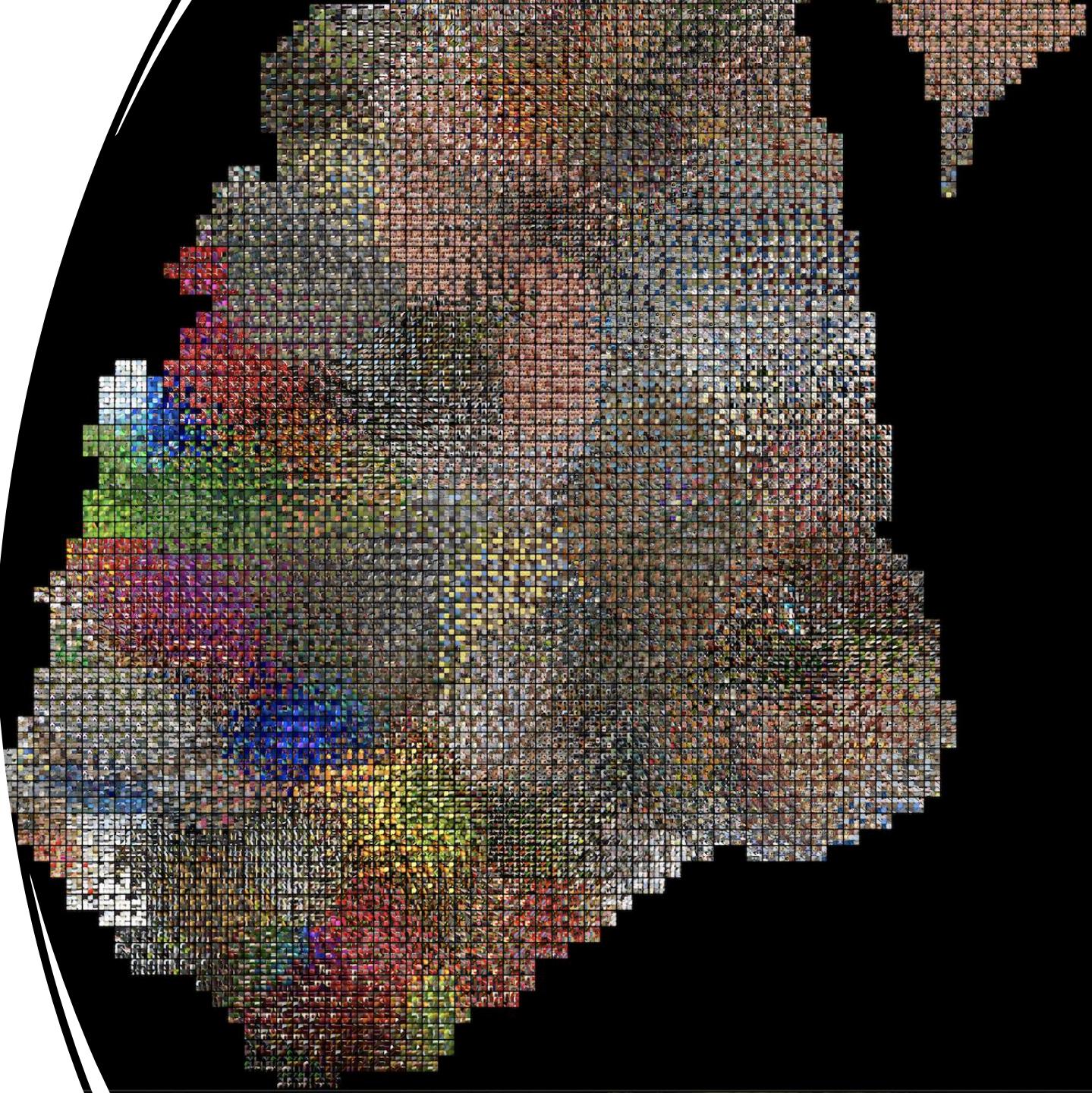
Widefield calcium imaging records macaque monkey V4 responses (3048 voxels) to 17,000 color natural images at 100- $\mu\text{m}$  scale.



An V4 digital twin (1) that accurately predict voxel response to a given image.



An enriched yet accurate tuning curve: each voxel responses to 50,000 color natural images

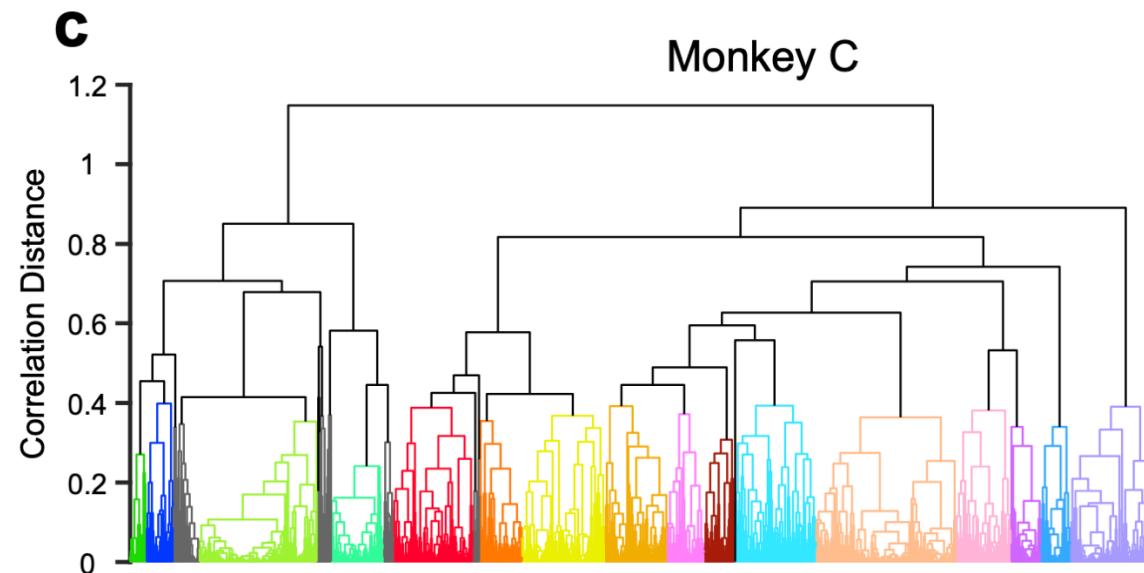


# V4 Dataset: Rich functional domains (1)

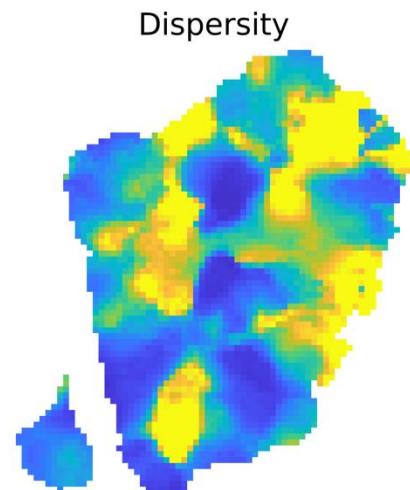
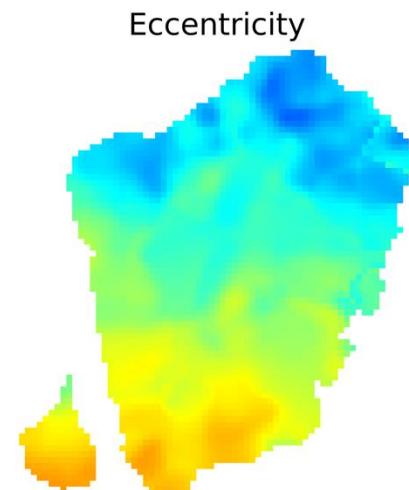
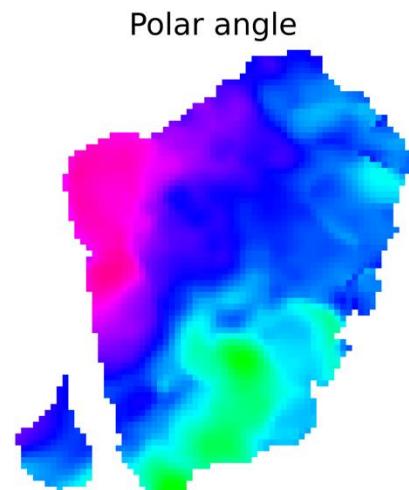
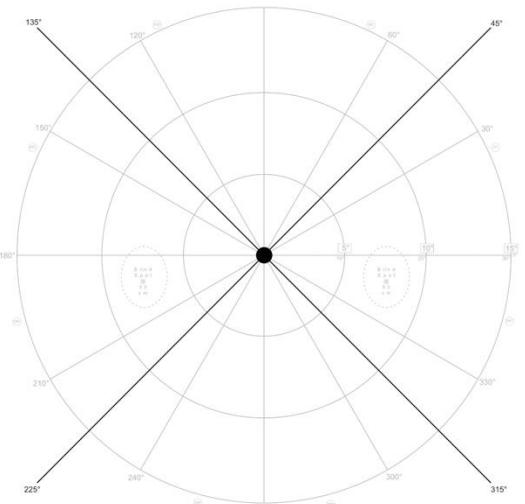
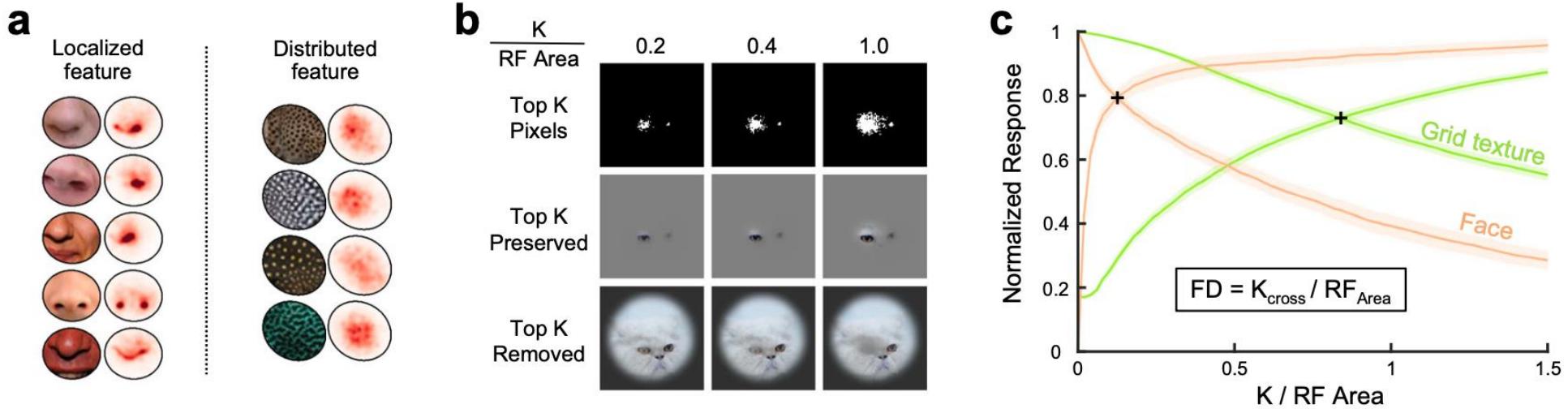
Hierarchically cluster all 3048 voxels into 16 domains base on each voxel's responses to all other voxels top 9 preferred images.



connected V4 domains



# V4 Dataset: Receptive field & dispersity of V4 voxel: Saliency measure (1)



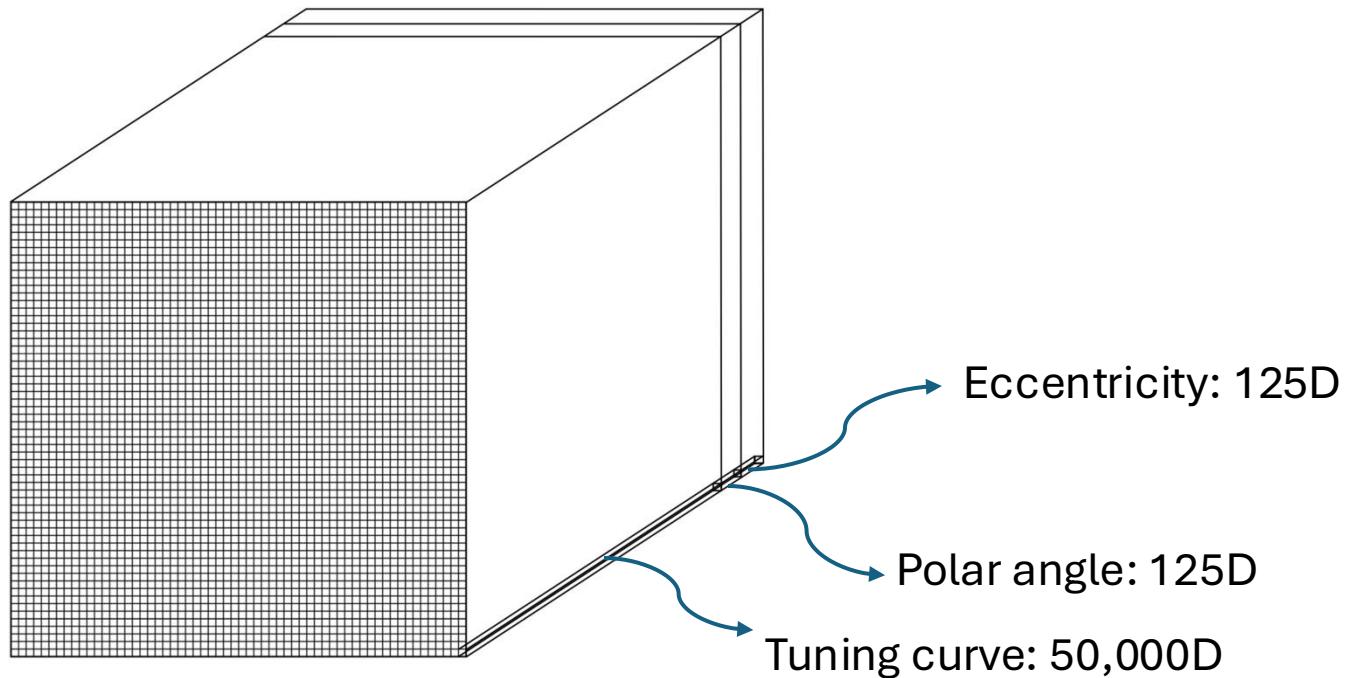
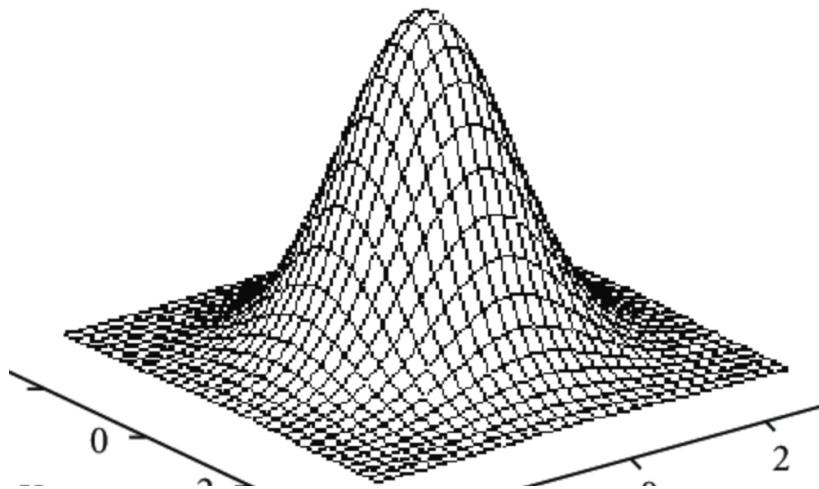
# Results: Self Organizing Map (SOM) (9)

Question: what is the organization principle leading to the monkey V4 we observed?

Purposes: mapping high-dimensional data onto a lower-dimensional grid while preserving topological relationships.

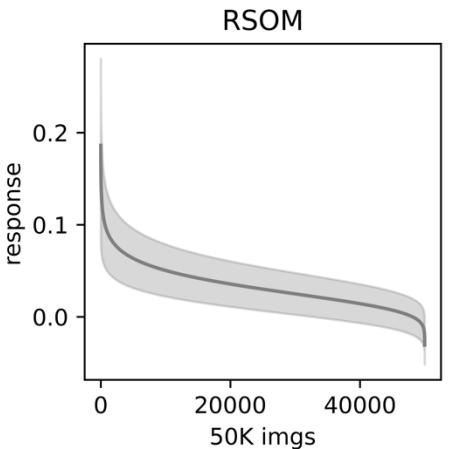
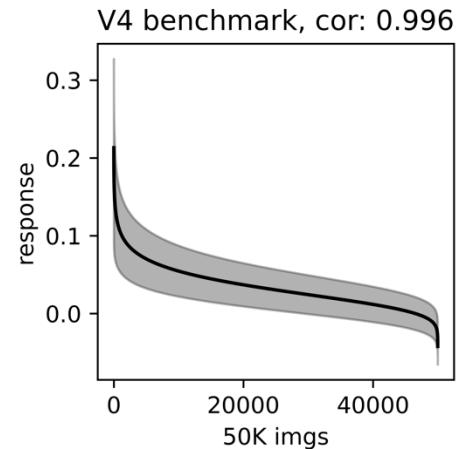
Structure: for each input, find the most similar grid among all as the center of a gaussian neighborhood filter to change all grid weights to be similar to the input instance(s).

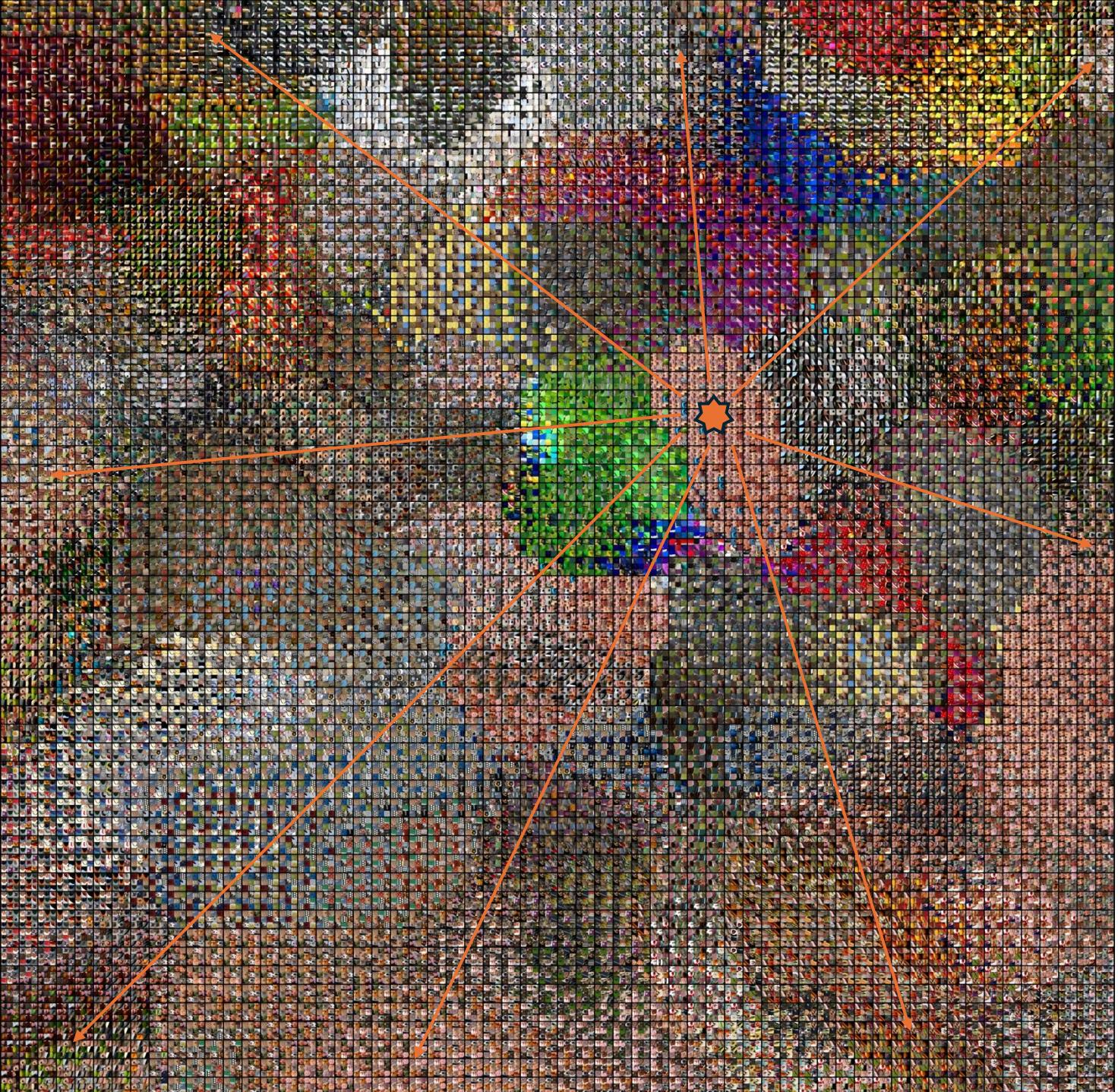
**RSOM:** Iteratively training 120 epochs, Shrinking neighborhood size (large to medium), Tuning + retinotopy.



# Results: RSOM weight 50,000D top 9 images

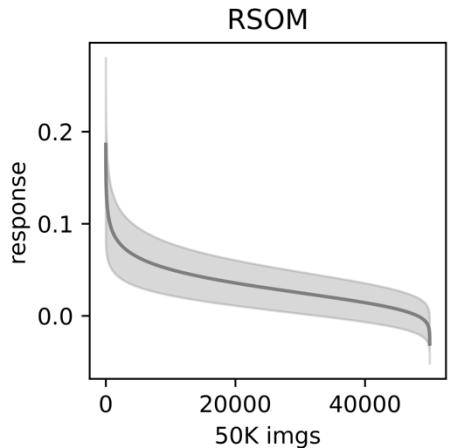
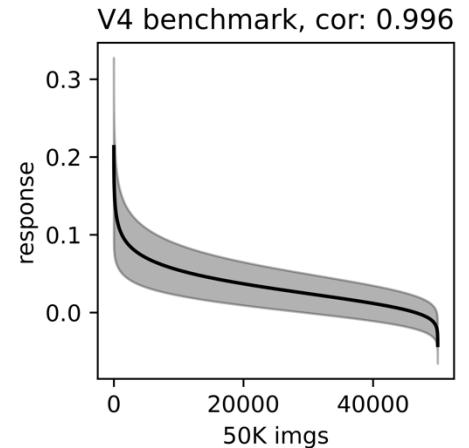
Tuning curve:



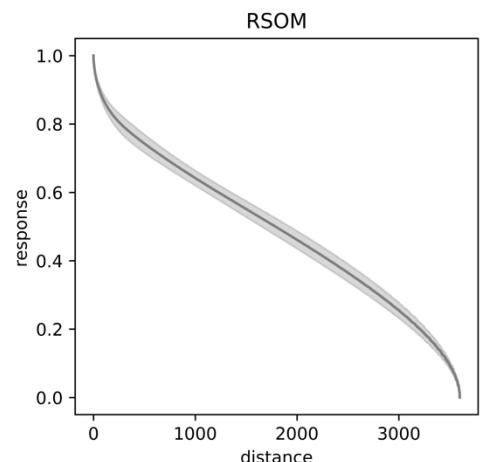
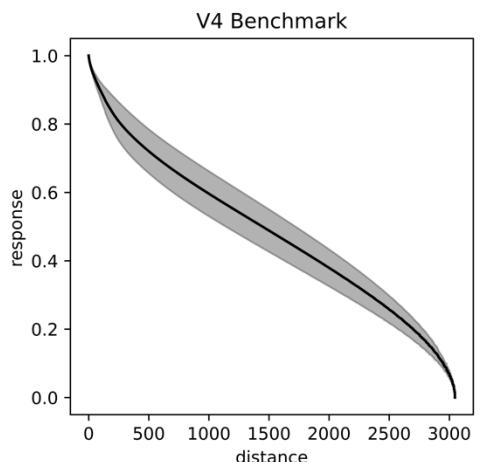


# Results: RSOM weight 50,000D top 9 images

Tuning curve:



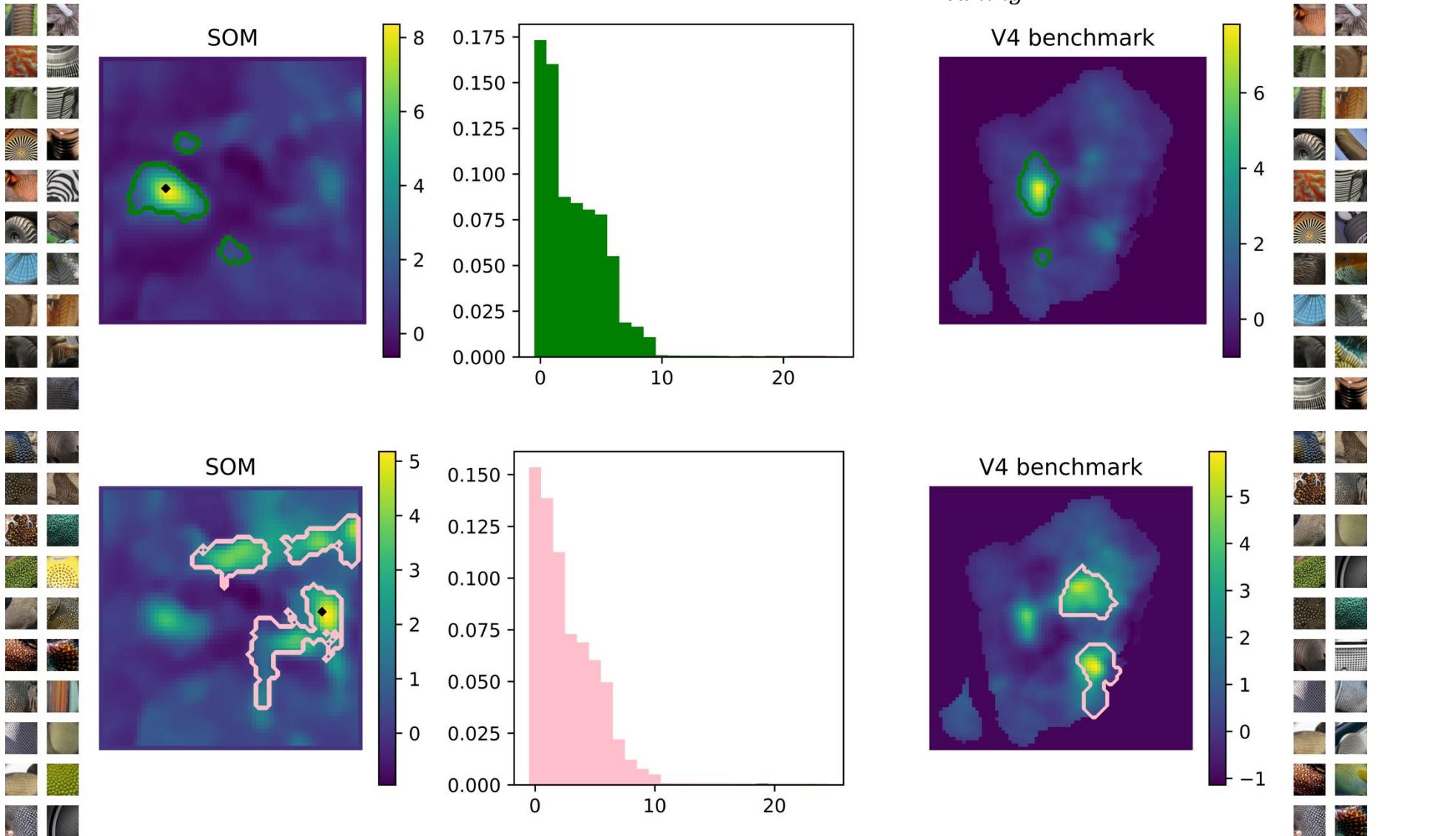
Responses to other grid preferred top 9 images as a function of physical distance:

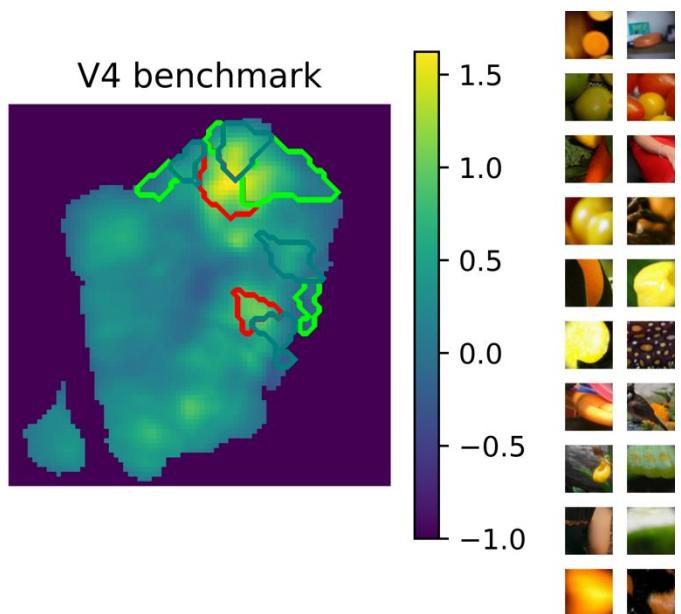
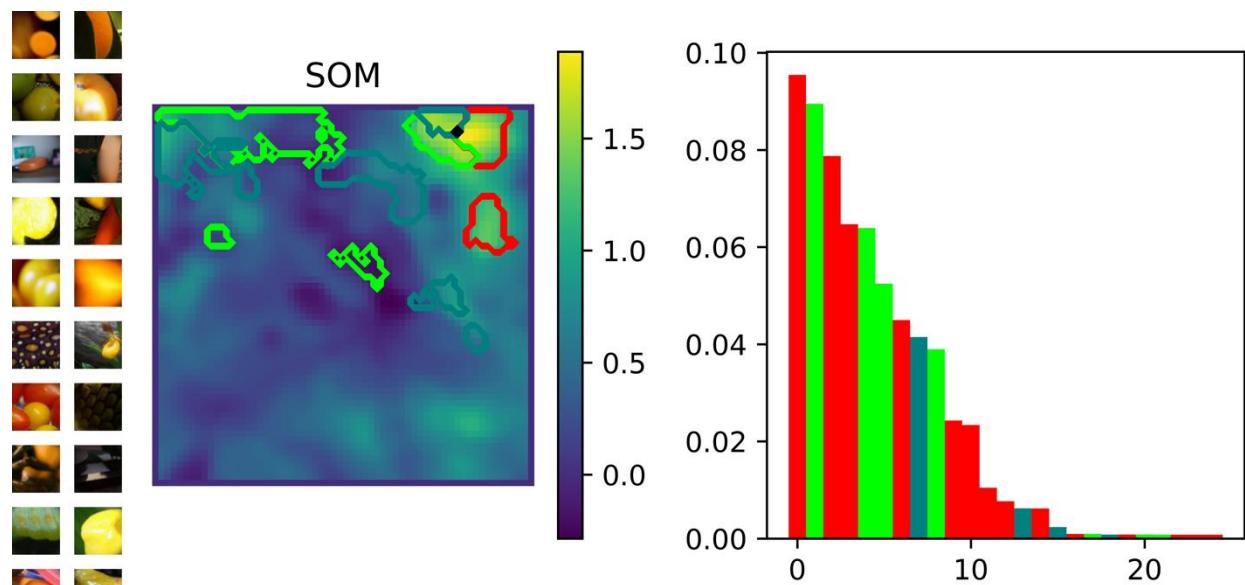
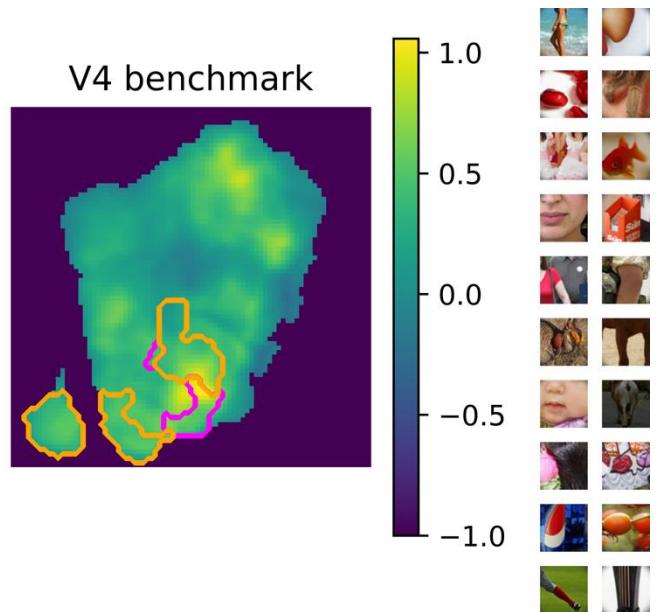
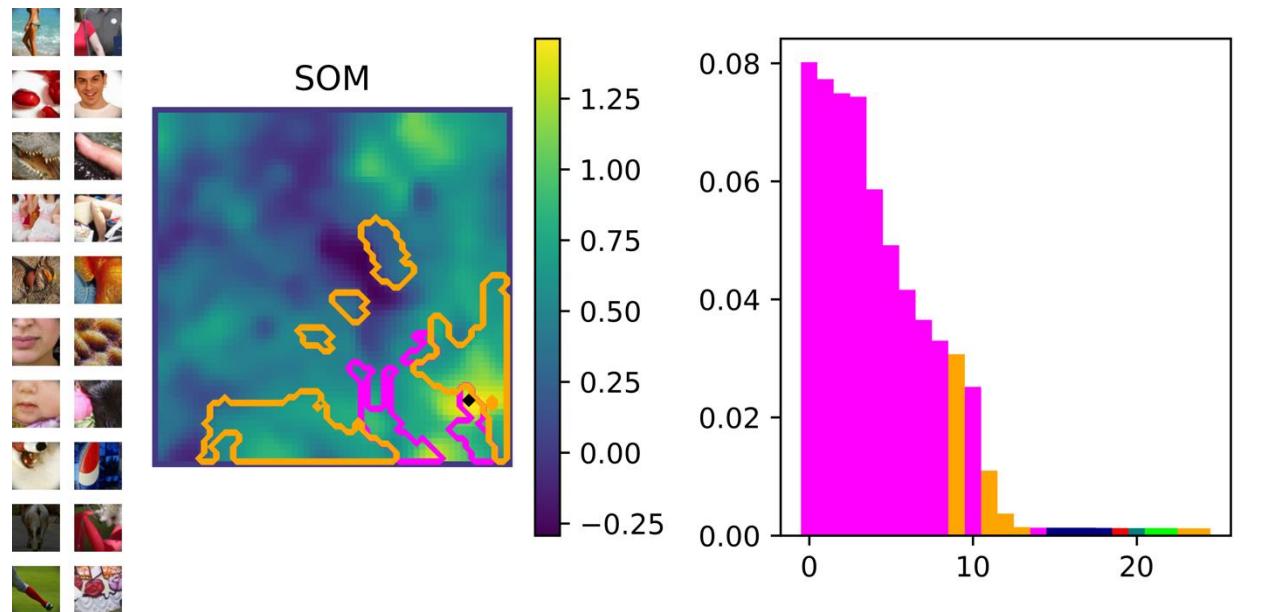


# Results: What are RSOM grid learning?

For an example gird, survey its top 1k tuning curve and fit a L1-regularized linear regression model as a linear combination of all 3048 V4 voxel tunings:

$$Example_{1k_{tuning}} = w_{3048} * 3048V4\_voxels_{1k_{tuning}}$$





# Results: Domain adjacency

raw SOM domains



connected SOM domains



connected V4 domains



Domain adjacency completion rate:

“0.832” for 50,250D RSOM

“0.627” for 50,000D SOM

For each SOM domain, survey all of its adjacent domains. For the corresponding V4 domain, survey all of its adjacent domains. Calculate an overlap ratio and a falsely adjacent ratio. If the latter exceeds a threshold, a penalty is given.

$$\text{Completion}_{\text{rate}} = \sum \text{overlap} * \text{domain}_{\text{size}} * \text{penalty}$$

raw SOM domains



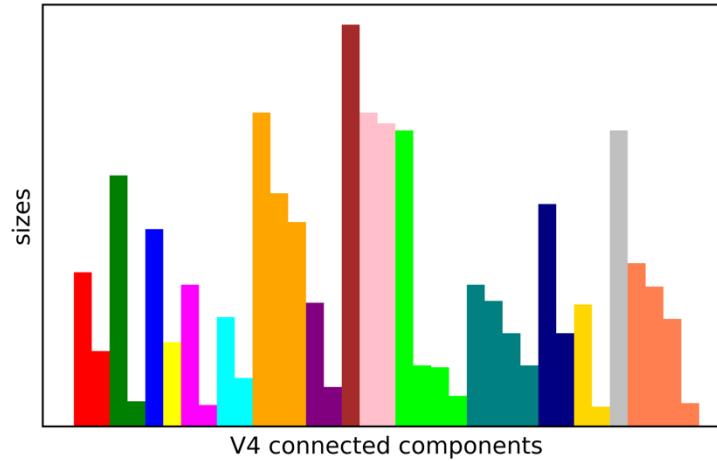
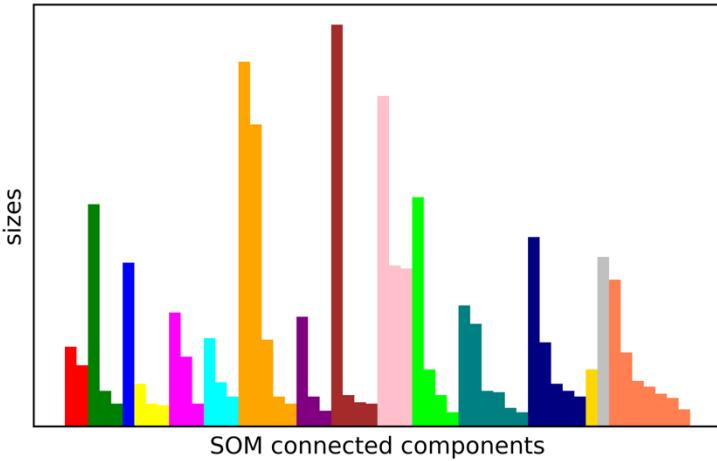
connected SOM domains



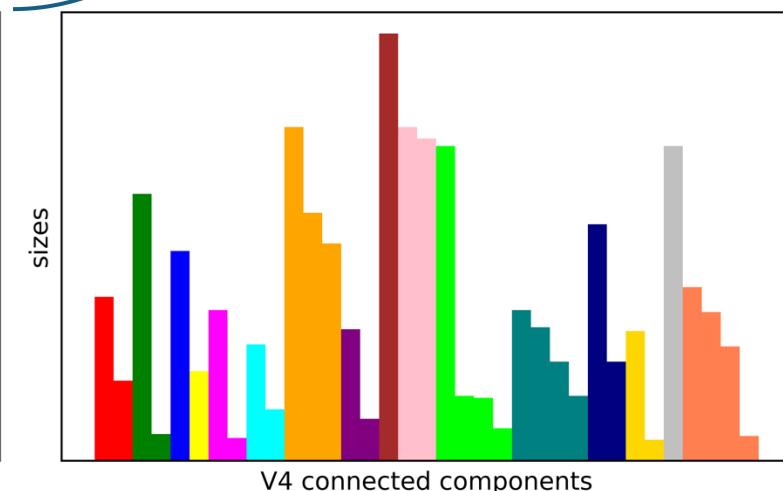
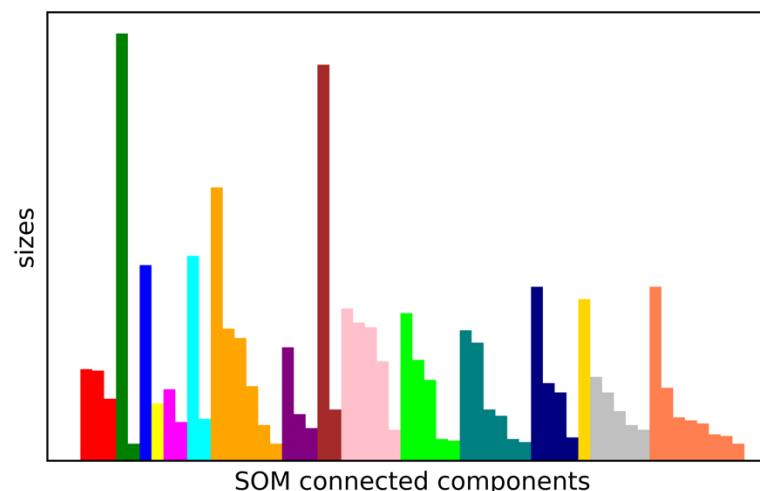
connected V4 domains



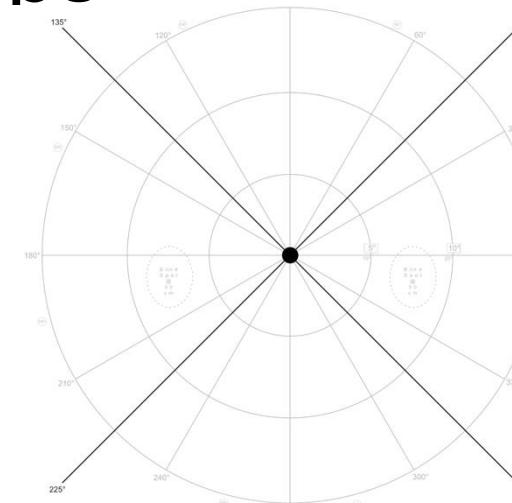
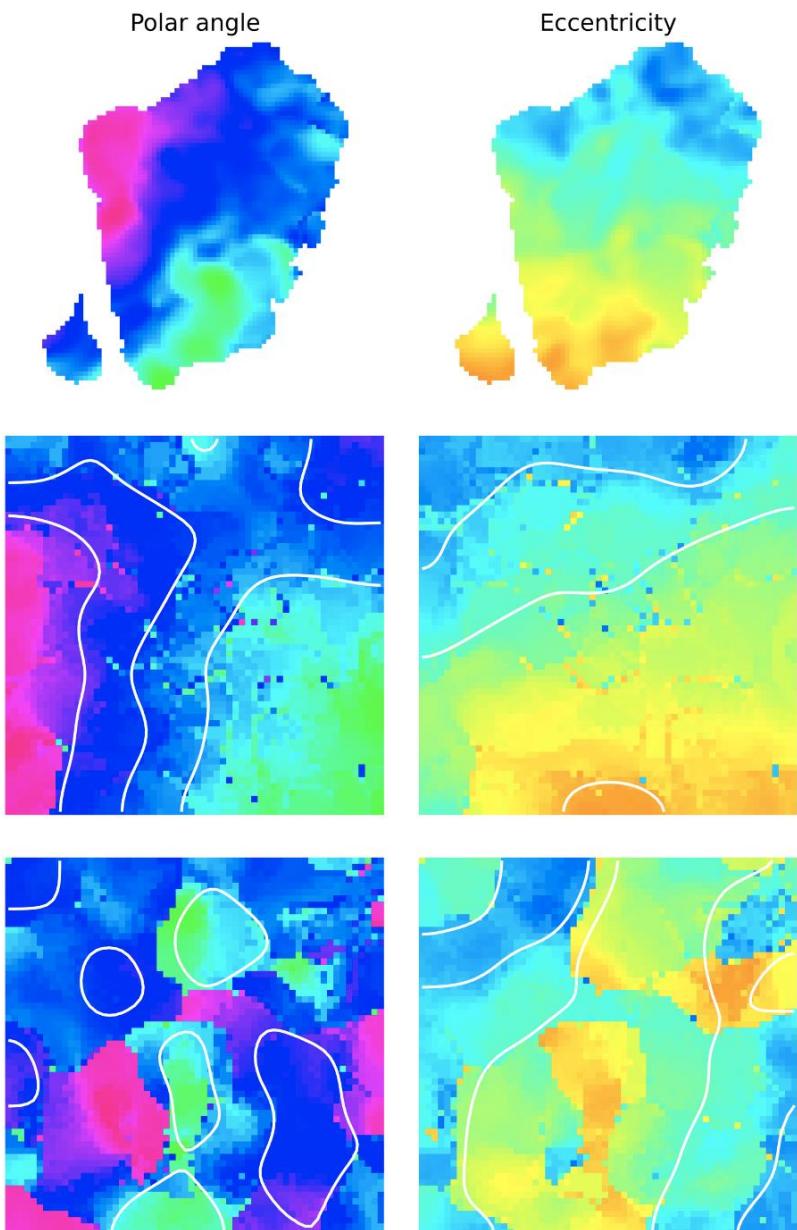
# Results: Domain sizes



Pearson correlation between averaged  
SOM domain sizes and that of V4:  
0.804 for 50,250D RSOM  
0.388 for 50,000D SOM



# Results: Polar angle, eccentricity maps



Polar angle contour lines tends to intersect vertically with eccentricity contour lines.

Local patches lack a global contour shape, thus no proper vertical intersection.

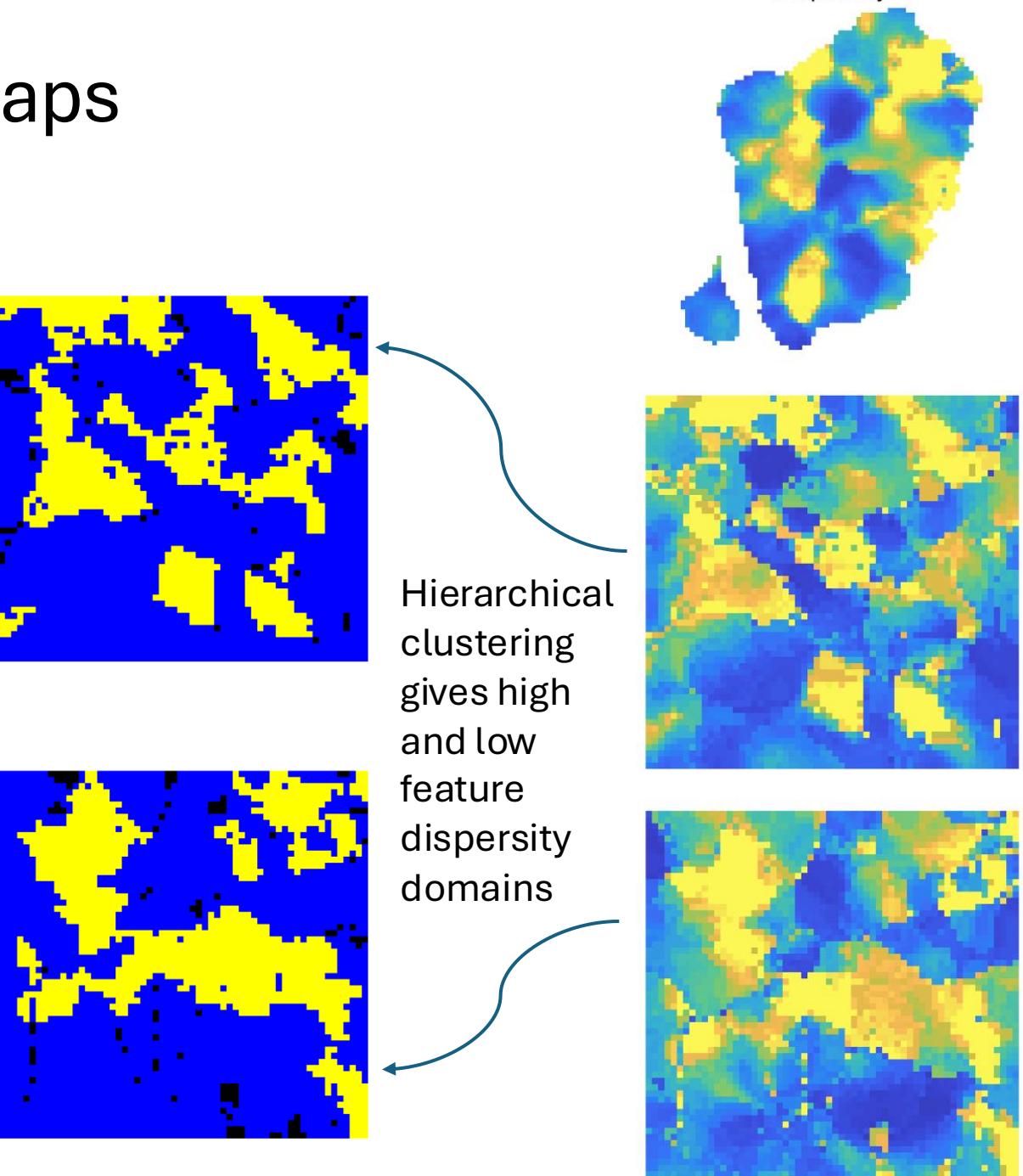
# Results: Feature dispersity maps

Cortical Sheets	num	sum	mean	std	min	max
1. V4	7	0.31	0.04	0.04	0.01	0.09
2. SOM	6	0.31	0.05	0.08	0.01	0.23
3. RSOM	8	0.29	0.04	0.03	0.01	0.08

**Table 1. Relative high dispersity component sizes**

Tuning alone drives high feature dispersity components to be physically closer together, forming gigantic high dispersity continent.

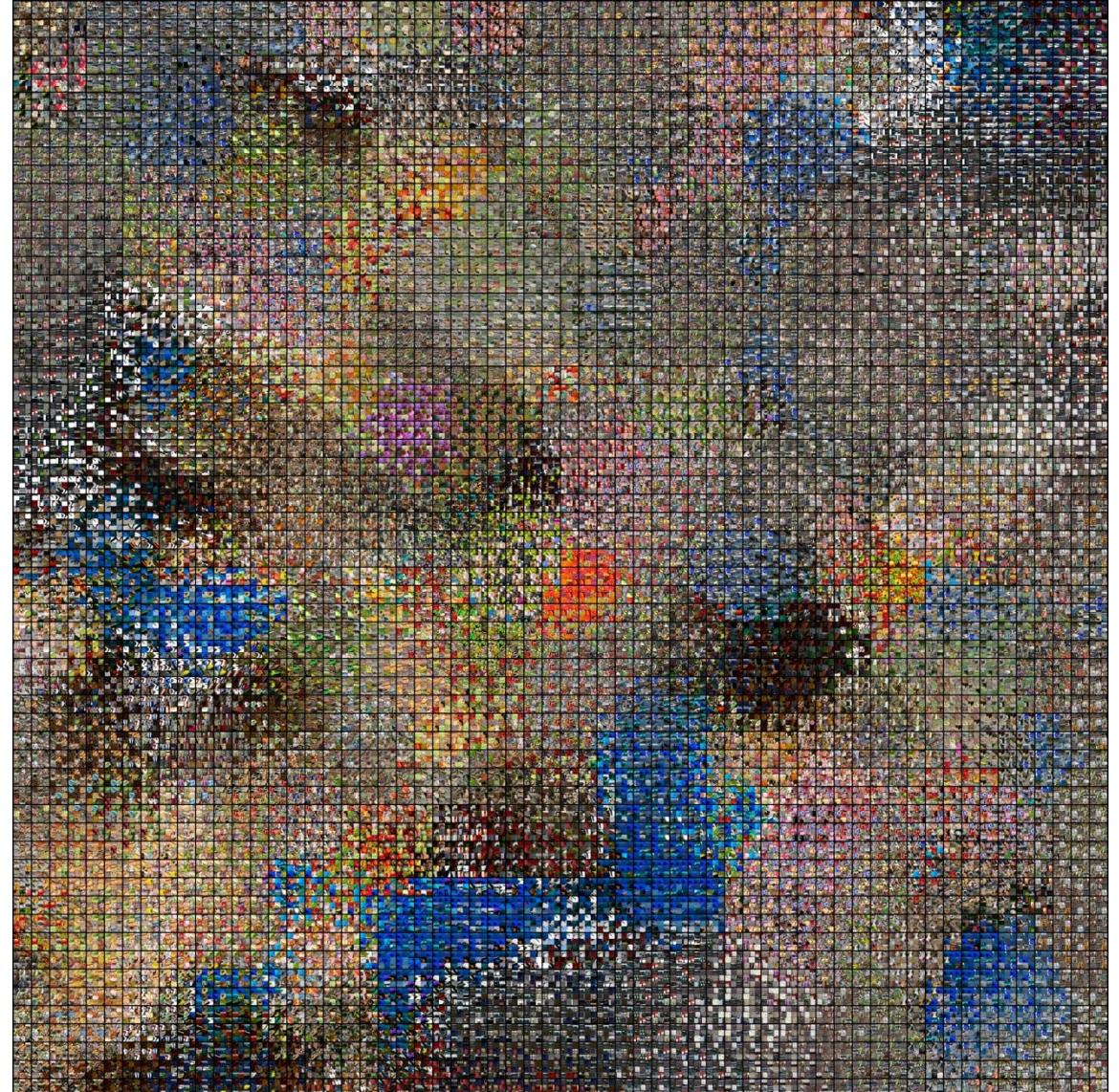
Whereas V4 forms smaller high dispersity islands that are captured by RSOM.



# Results: Generalizing SOM strategy to organize ResNet18 Units

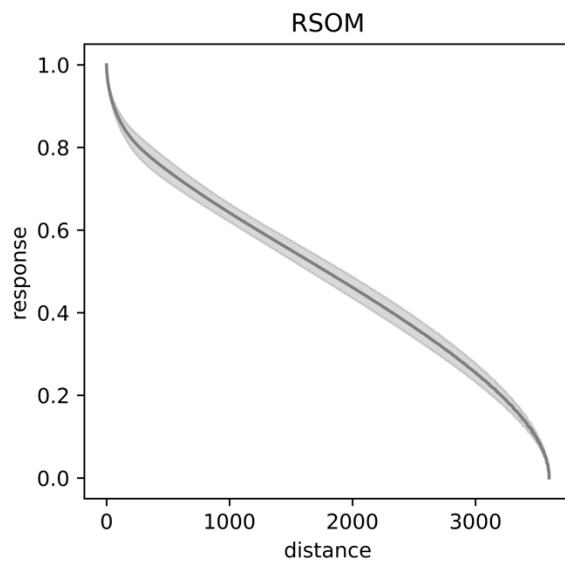
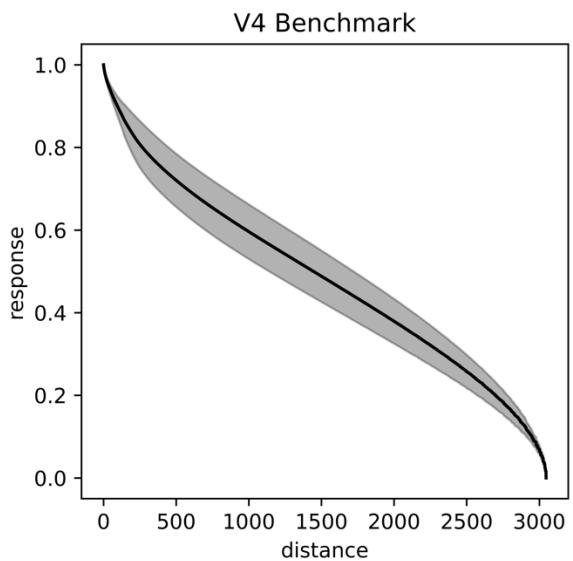
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- Trunk 4 second convolution layer: 7-by-7-by-512 units.
- The same 50,000 natural image data set gives 50,000D tuning curve.
- Hypothesized to have a visual field between [0, 60] degrees polar angle and [2, 3] degrees eccentricity.



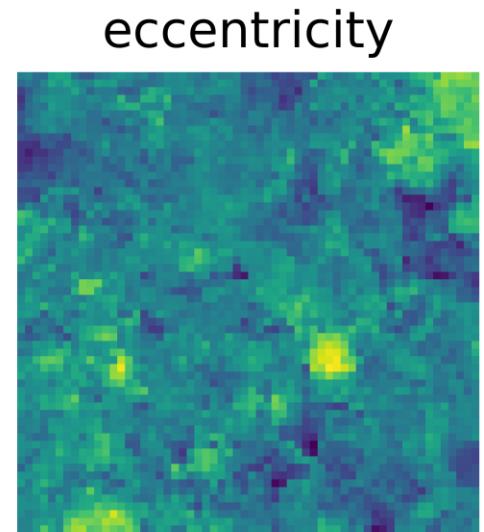
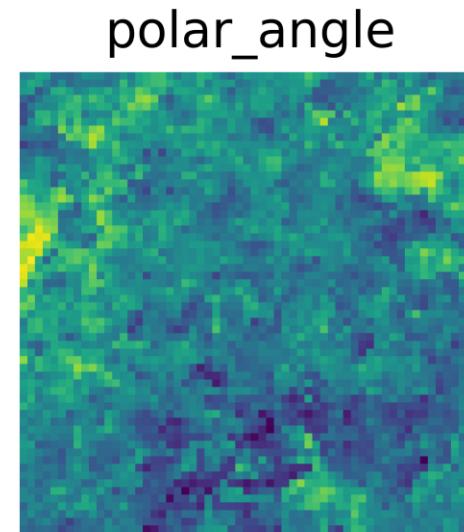
## Similarity with V4

- Smooth tuning continuum with domains of distinct image preferences.



## Divergence

- Noisy retinotopy map.



# Discussions

SOM with large starting neighborhood size that gradually shrinks contribute to a smoothly mapped tuning continuum.

Retinotopically constrained SOM reproduces monkey V4 domain-domain relative positioning on a 2D simulated cortical sheet.

Feature dispersity organization is mutually guided by tuning and retinotopy and can naturally emerge.

The symbiotic relationship between retinotopy and tuning

# References

- Large-scale calcium imaging reveals a systematic V4 map for encoding natural scenes
- Functional organization for color and orientation in macaque V4
- Shape Representation in Area V4: Position-Specific Tuning for Boundary Conformation
- A hierarchical, retinotopic proto-organization of the primate visual system at birth
- Mechanisms Underlying Development of Visual Maps and Receptive Fields
- The Retinotopic Organization of Primate Dorsal V4 and Surrounding Areas: A Functional Magnetic Resonance Imaging Study in Awake Monkeys
- A Unifying Principle for the Functional Organization of Visual Cortex
- Cortical topographic motifs emerge in a self-organized map of object space
- The Self-Organizing Map

Q & A