Topological organization

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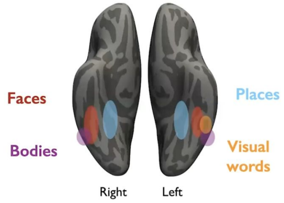
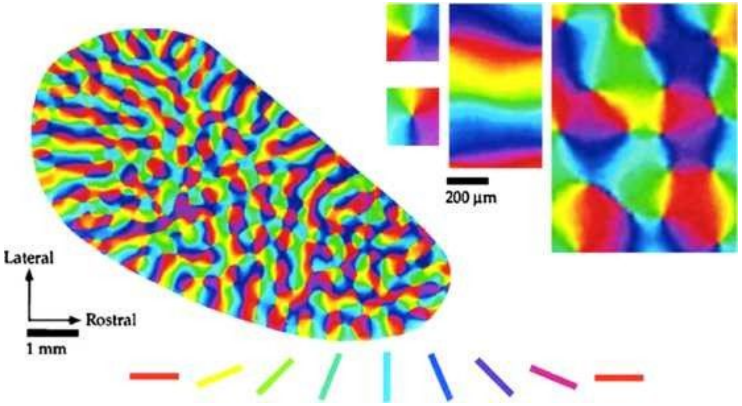
Functional organization



Functional organization is among the most ubiquitous of neuroscience findings, appearing in the topographic maps of the visual system, and in auditory, parietal, sensorimotor, and entorhinal areas

What processes govern their emergence?

What computational function they serve?



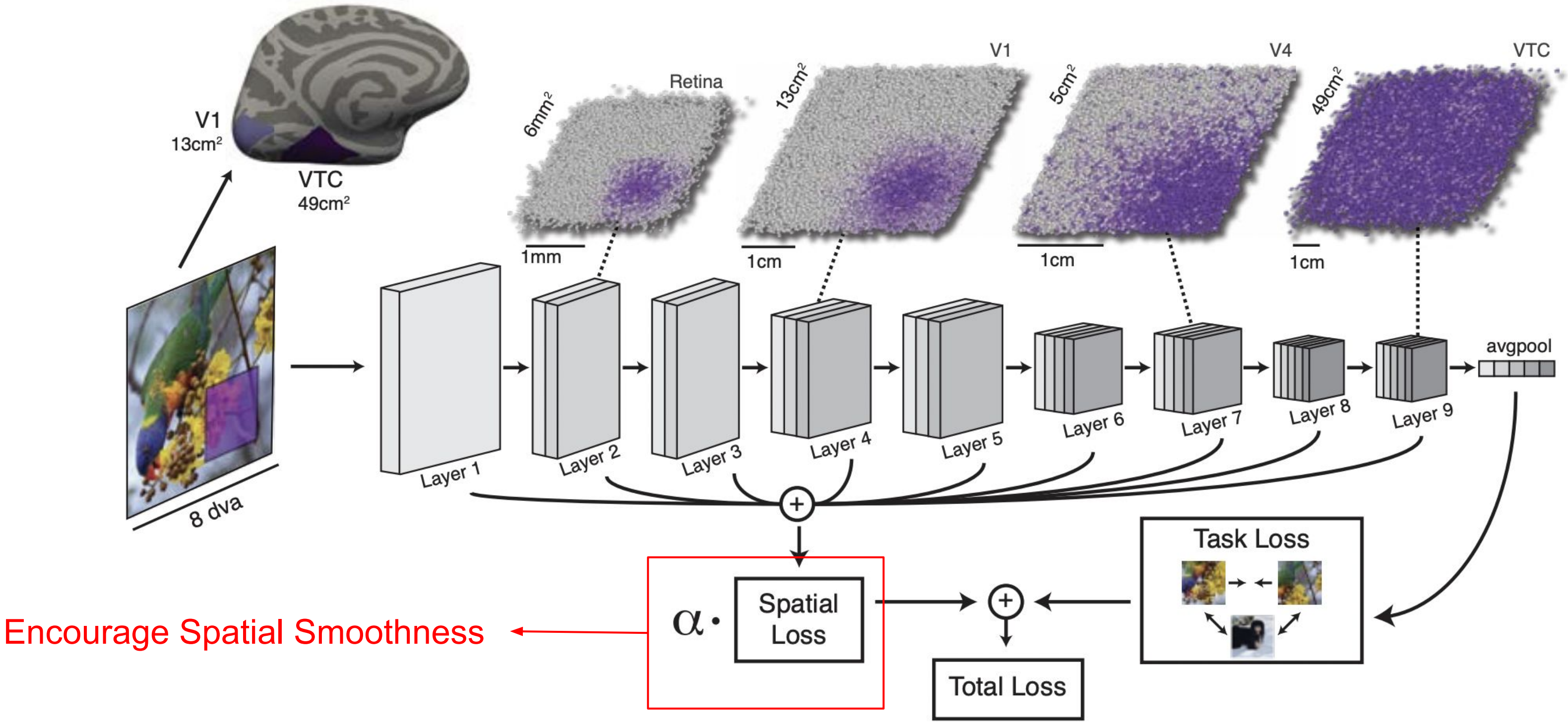
Orientation tuning in V1

Hypothesis

- Wiring Cost Hypothesis:
    - Neuron fire together wire together.
    - To minimize total wiring cost

- Multiple Behavior Demand Hypothesis:
    - Function specialization emerges evolutionary to parallel process distinct tasks

Topographic Deep Artificial Neural Network (TDANN)



Method

Spatial loss The spatial loss function encourages nearby model units on the simulated cortical sheet to be correlated in their responses to the training stimuli. Specifically, SL_l is the spatial correlation loss computed for the l-th layer and SL_l is computed on a given batch by randomly sampling a local cortical zone and calculating for pairs of units, (1) correlation (Pearson's r) between the response profiles, ($\overrightarrow{R}$), and (2) the the stabilized reciprocal Euclidean distances ($\overrightarrow{D}$):

$$\overrightarrow{D} = \frac{1}{(1 + \overrightarrow{d})} \tag{S1}$$

where $\overrightarrow{d}$ is the vector of pairwise cortical distances. These two terms are then related as follows:

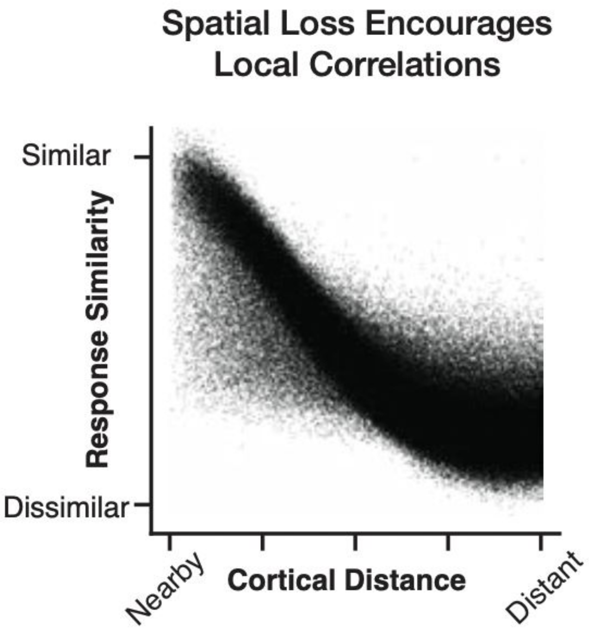
$$\mathrm{SL}_l = 1 - \mathrm{Corr}\left(\overrightarrow{R}, \overrightarrow{D}\right) \tag{S2}$$

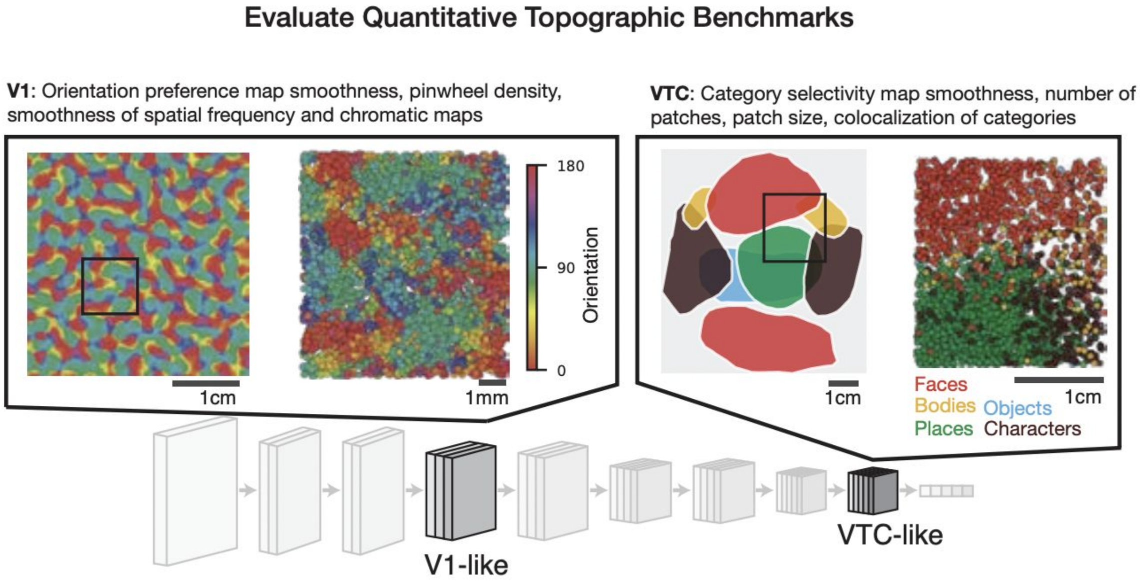
such that SL_l is minimized when nearby units have correlated responses to the training stimuli.

TDANN hurts classification performance

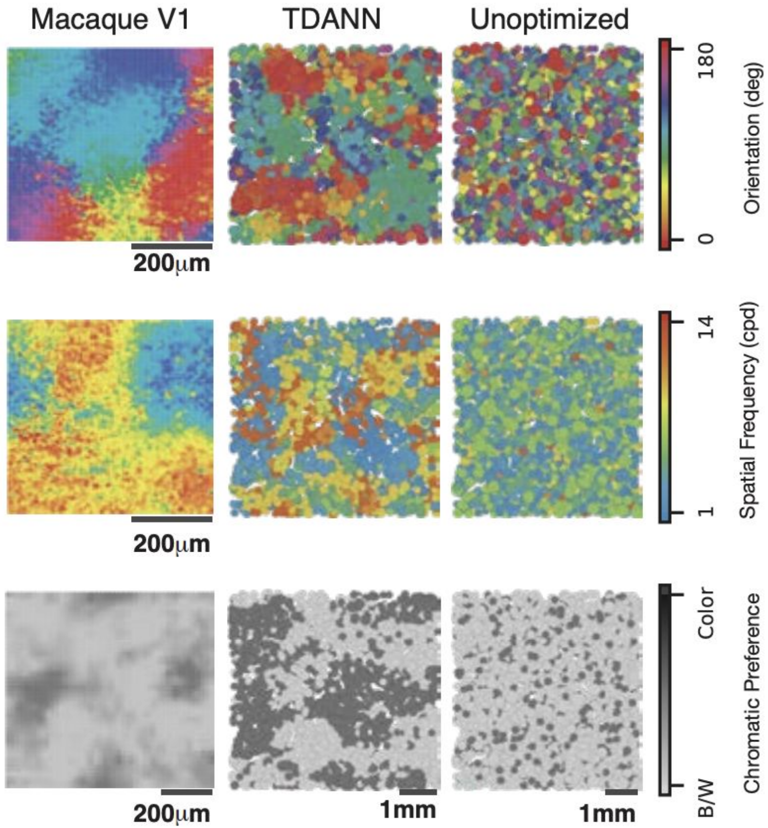
Method	ImageNet classification accuracy
Baseline (ResNet-18)	48.5%
TDANN (ResNet-18 + spatial loss)	43.9%

TDANN successfully encourage spatial arrangement

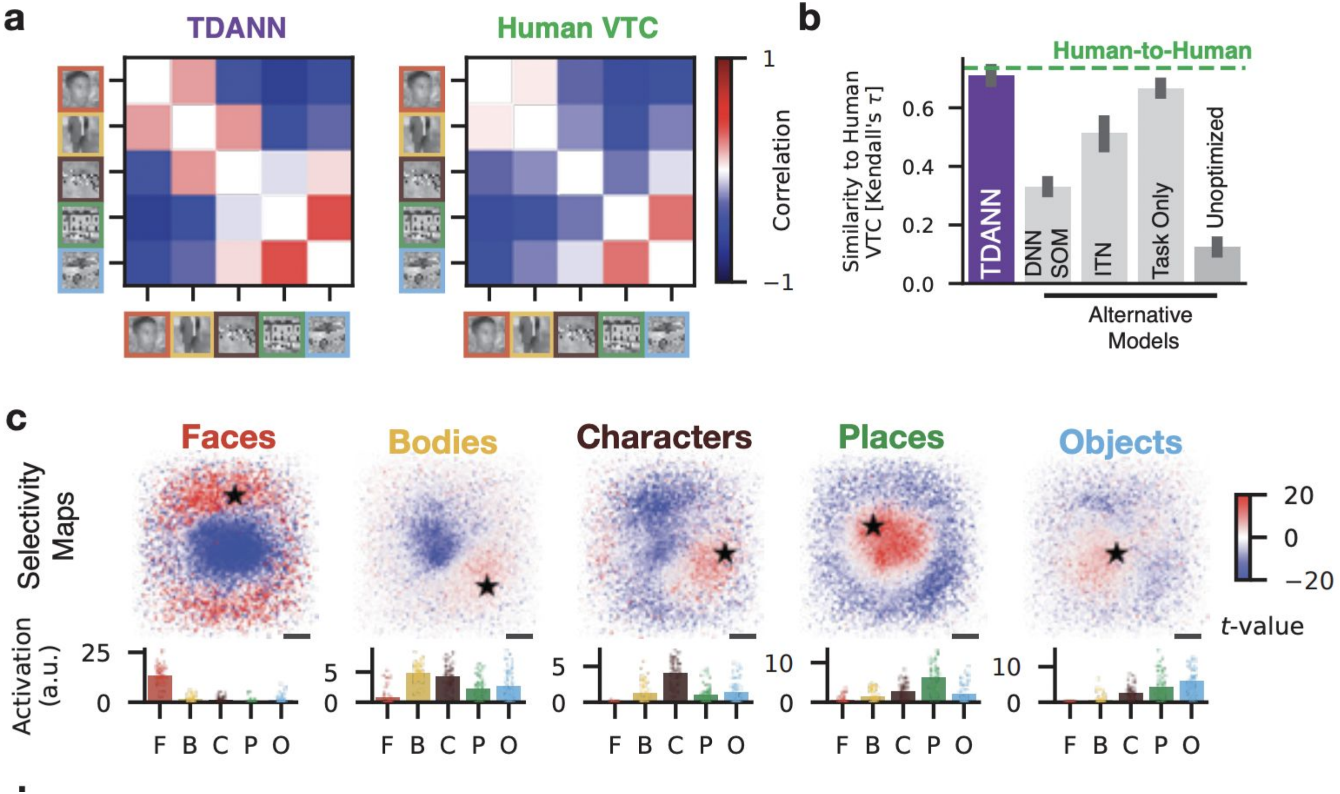




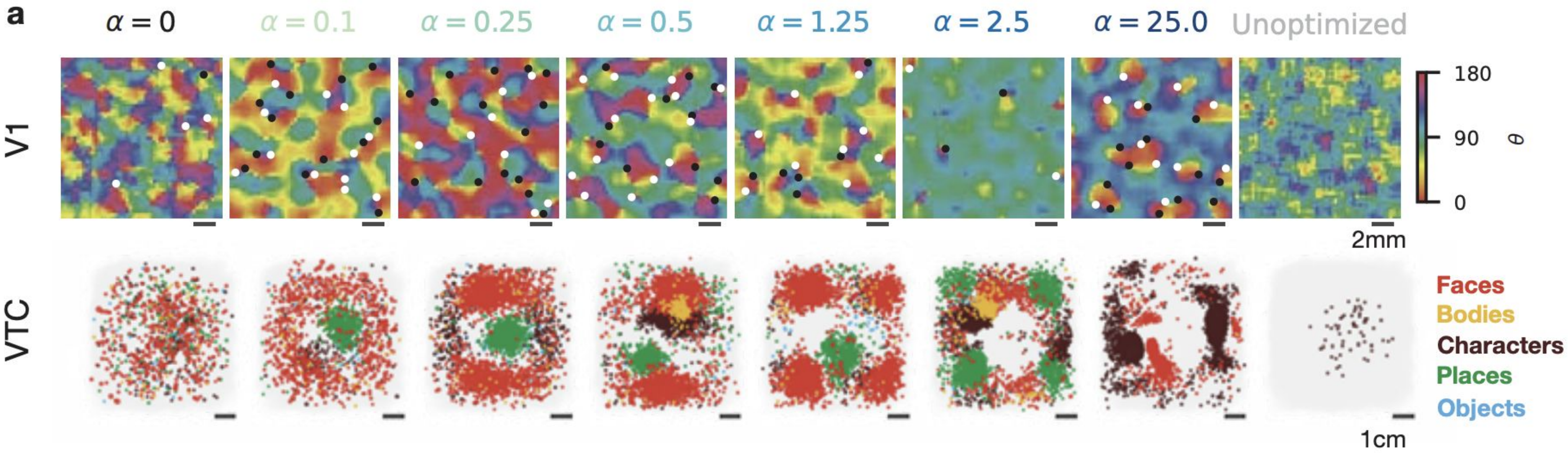
TDANN successfully encourage spatial organization in V1



TDANN reproduce spatial organization in ventral temporal cortex



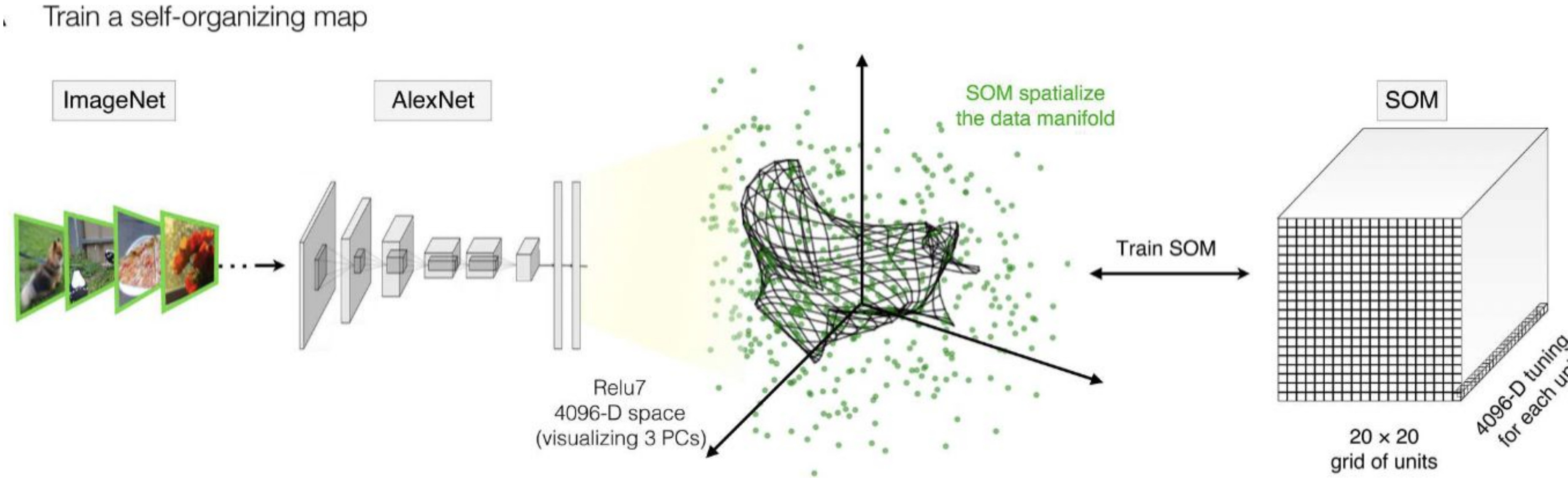
Topological map in TDANN



Other Topological Organization Generation

DNN-SOM

Doshi, Fenil R., and Talia Konkle. "Cortical topographic motifs emerge in a self-organized map of object space." *Science Advances* 9.25 (2023): eade8187.



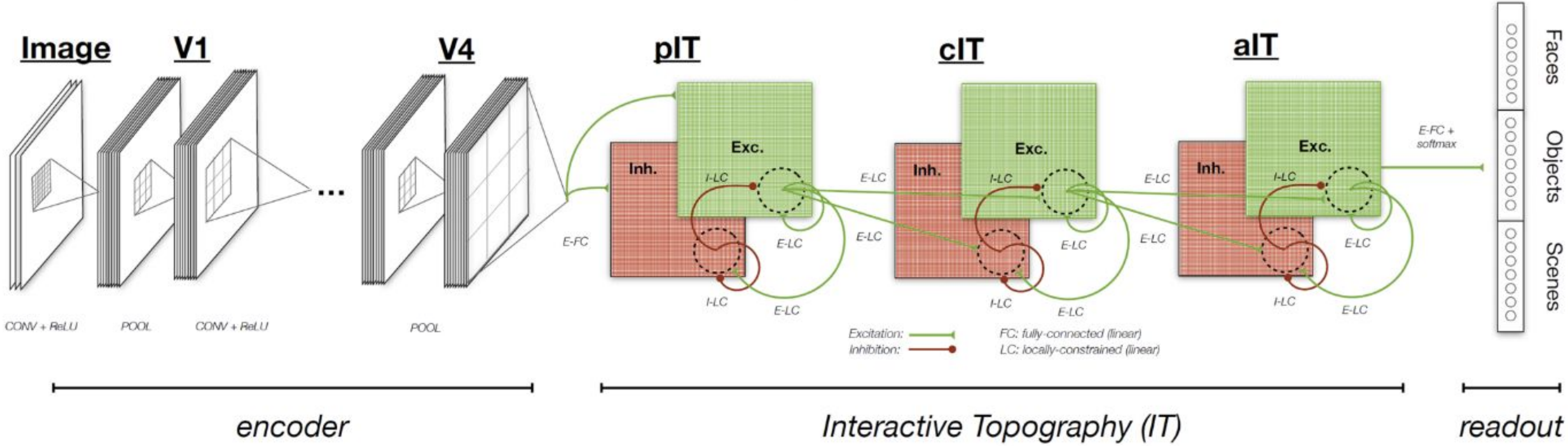
Other Topological Organization Generation

$$L_w^{(a,b)} = \sum_{i,j} \frac{\left(D_{ij}^{(a,b)}\right)^2 \left(W_{ij}^{(a,b)}\right)^2}{1 + \left(W_{ij}^{(a,b)}\right)^2}.$$

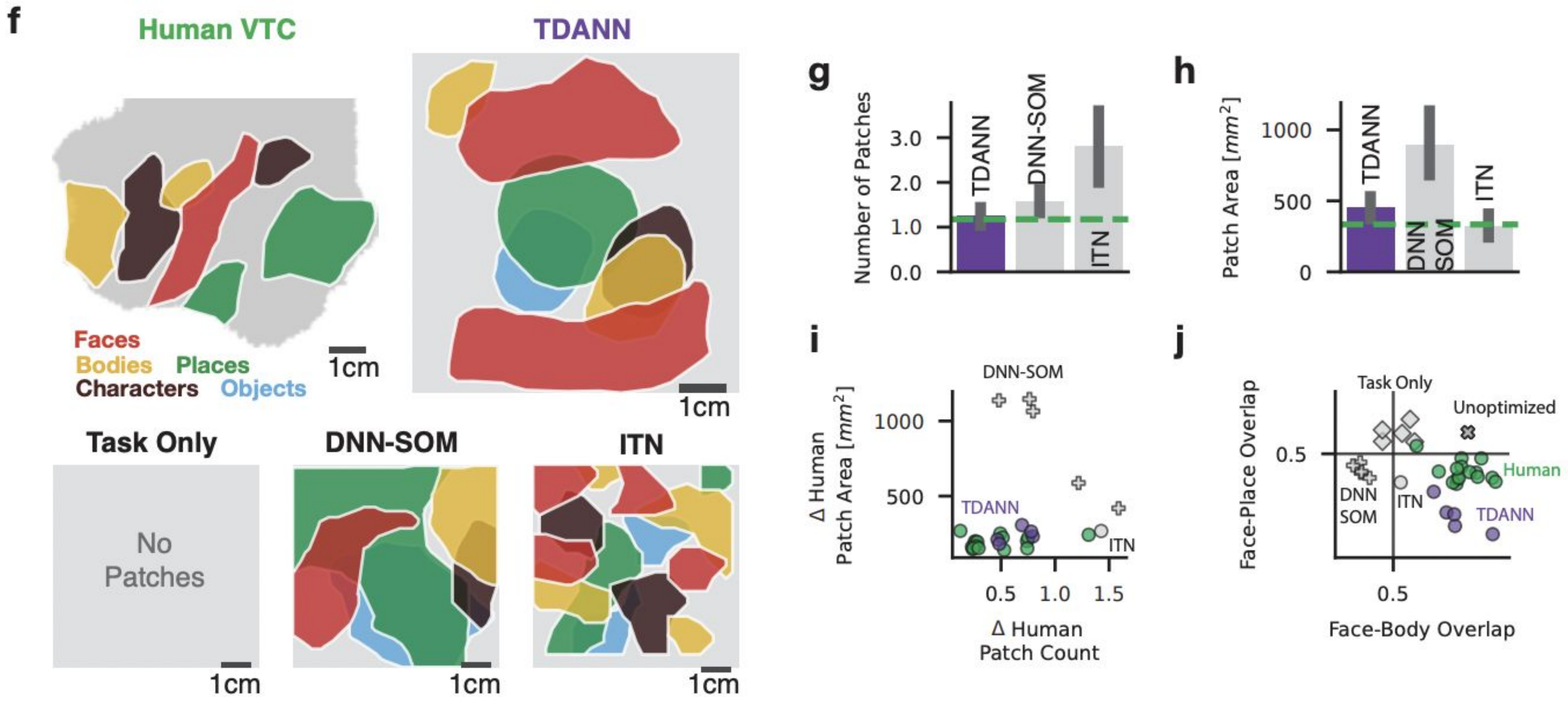
ITN

$$\tau \frac{dx_t^{(a)}}{dt} = -x_t^{(a)} + W^{(a,a)} r_t^{(a)} + W^{(a-1,a)} r_t^{(a-1)} + b^{(a)}$$

Blauch, Nicholas M., Marlene Behrmann, and David C. Plaut. "A connectivity-constrained computational account of topographic organization in primate high-level visual cortex." *Proceedings of the National Academy of Sciences* 119.3 (2022): e2112566119.

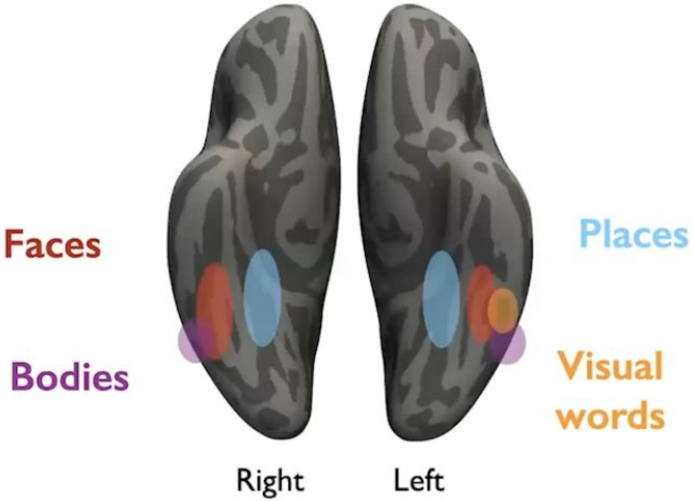


TDANN is doing better than previous topological networks



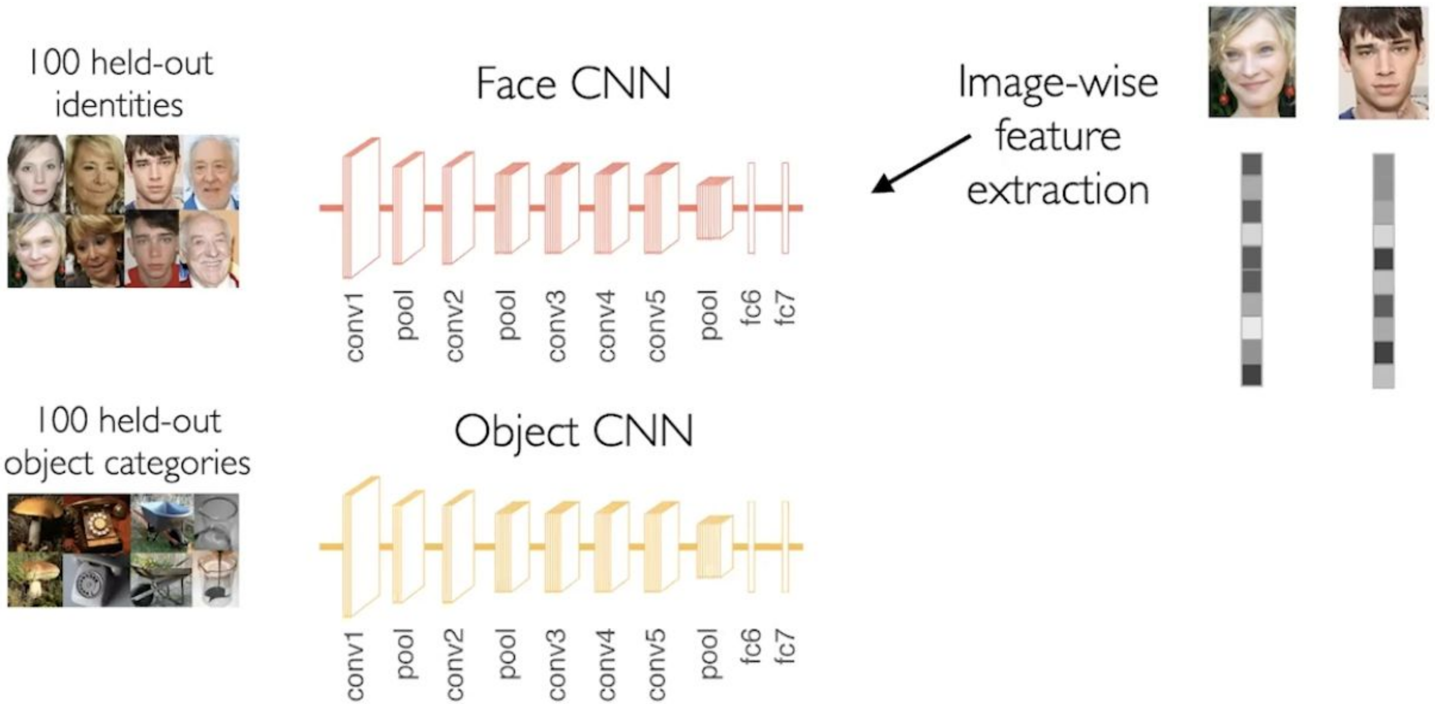
Another perspective of functional specialization

Topological organization is due to functional specialization of modules

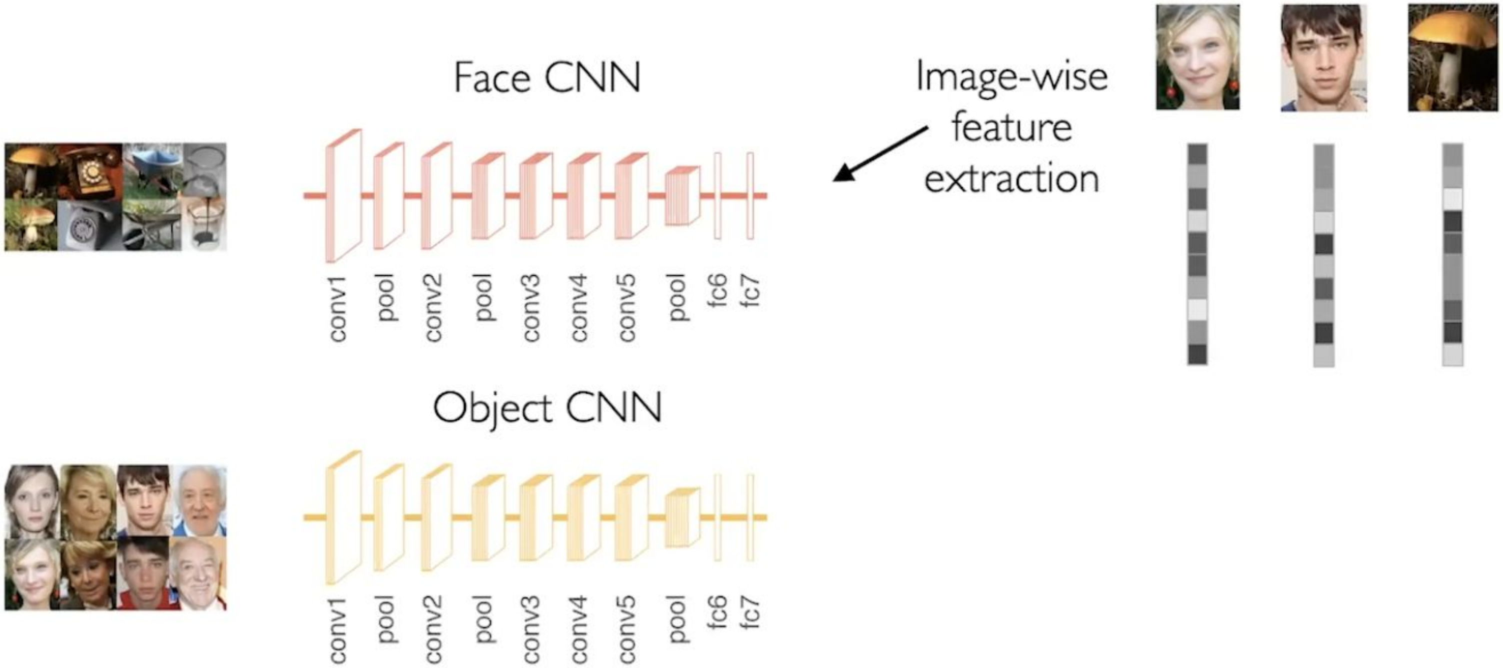


Dobs, Katharina, et al. "Brain-like functional specialization emerges spontaneously in deep neural networks." *Science advances* 8.11 (2022): eabl8913.

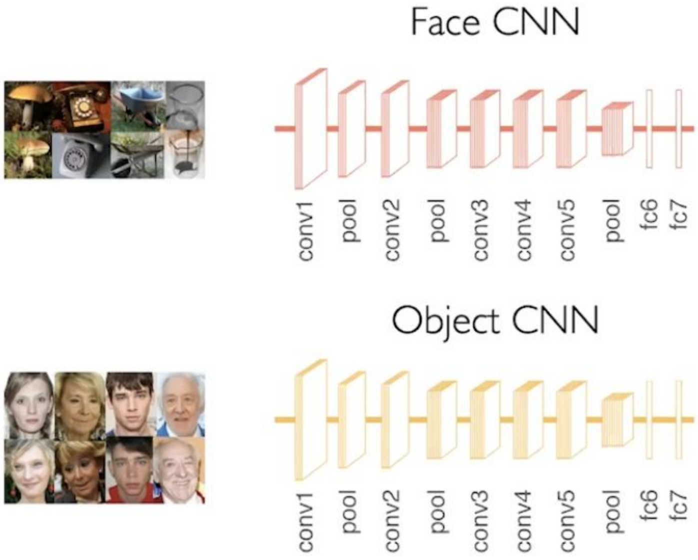
Simulate different region by separately trained CNNs

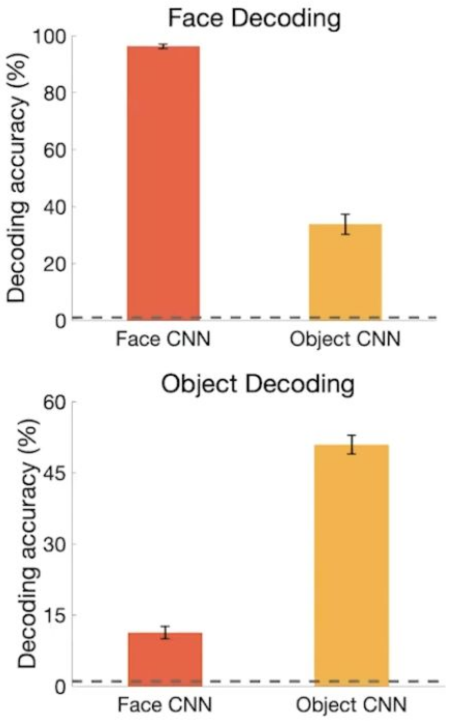


Swap the input domain and use the feature to predict



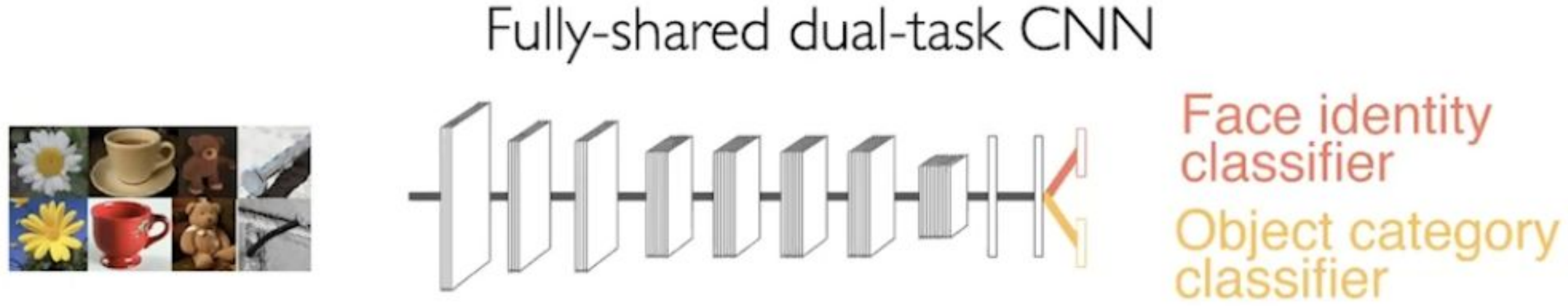
Functional Specialization using two models





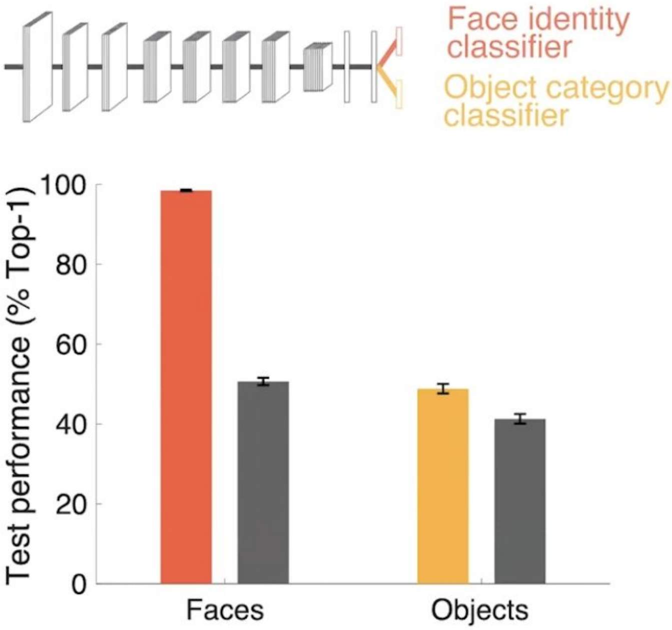
Face trained Network can’t see object very well and vice visa

What happens if we use a shared networks?

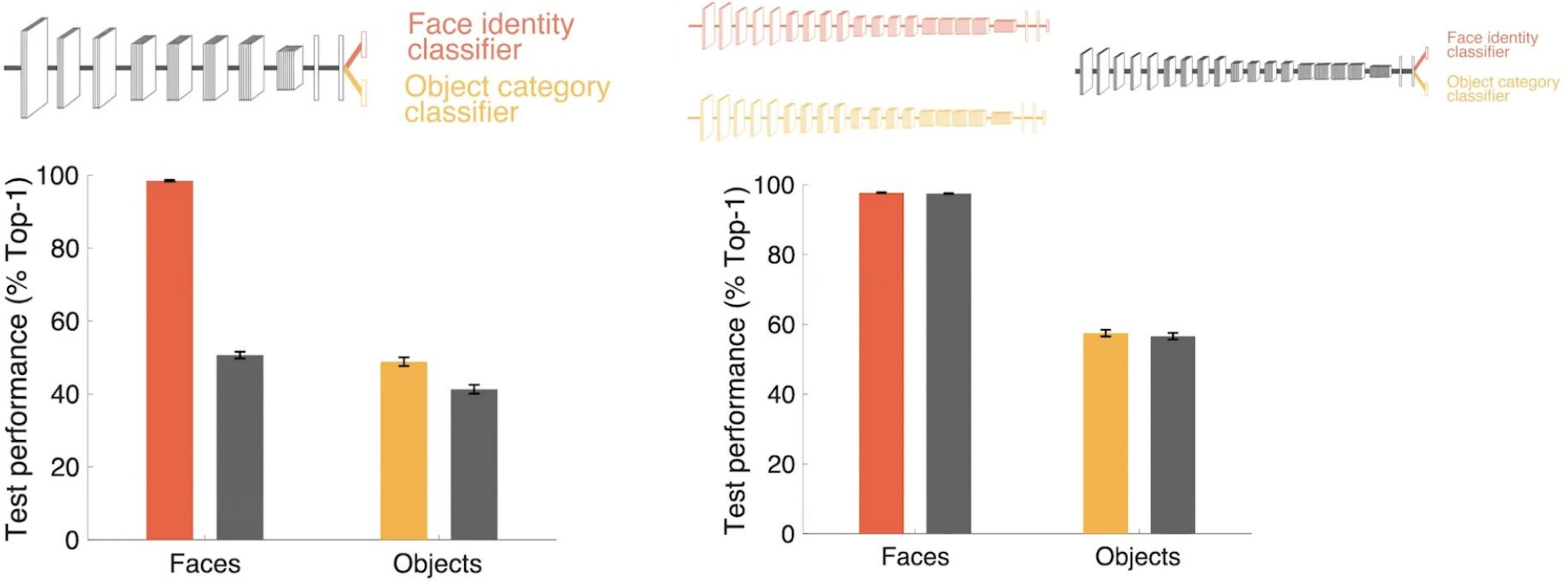


This is expected to perform worse than the separation specialists

Experiments on shared networks

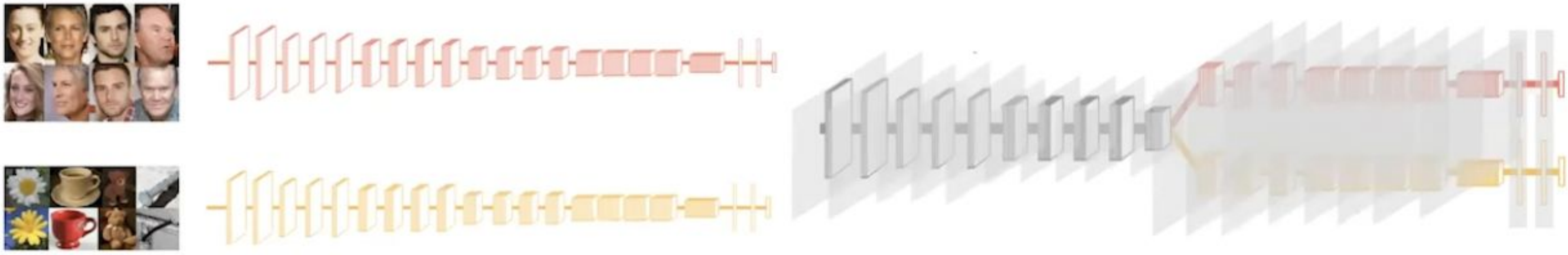


Experiments on shared networks



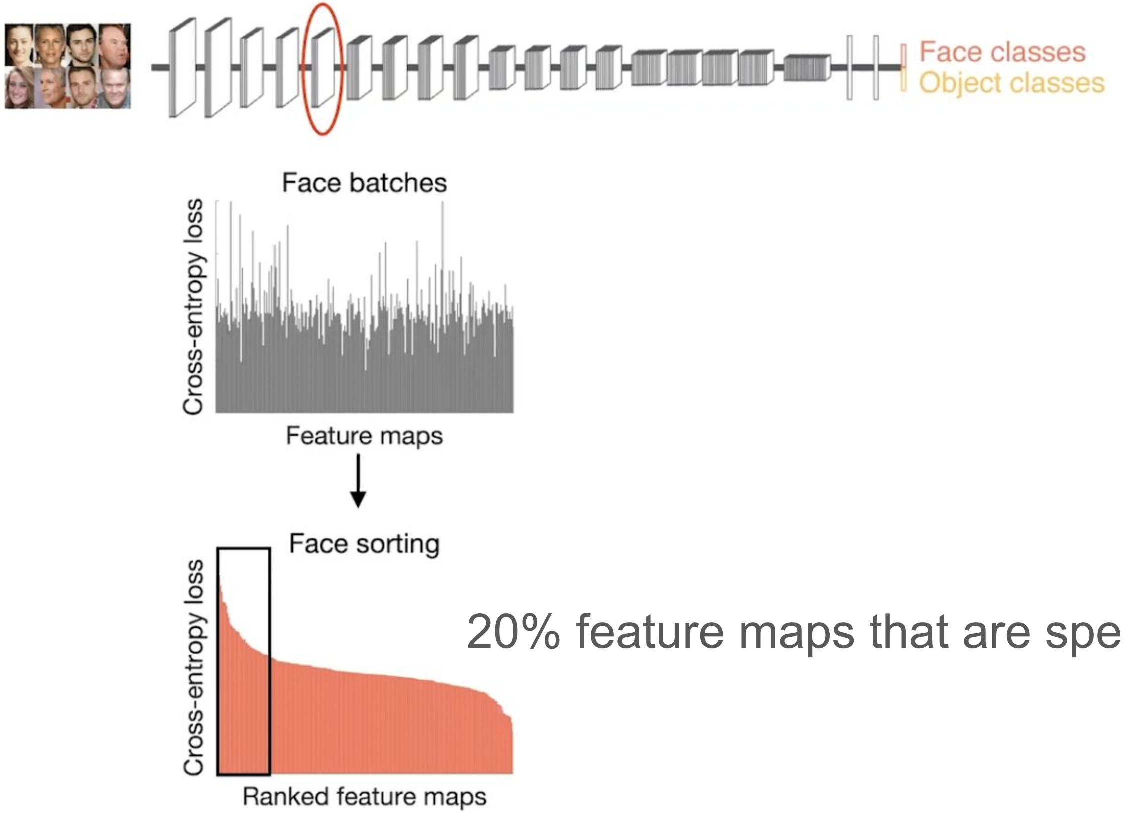
Larger networks can have better capability of incorporating both tasks

Can functional separation achieved automatically?



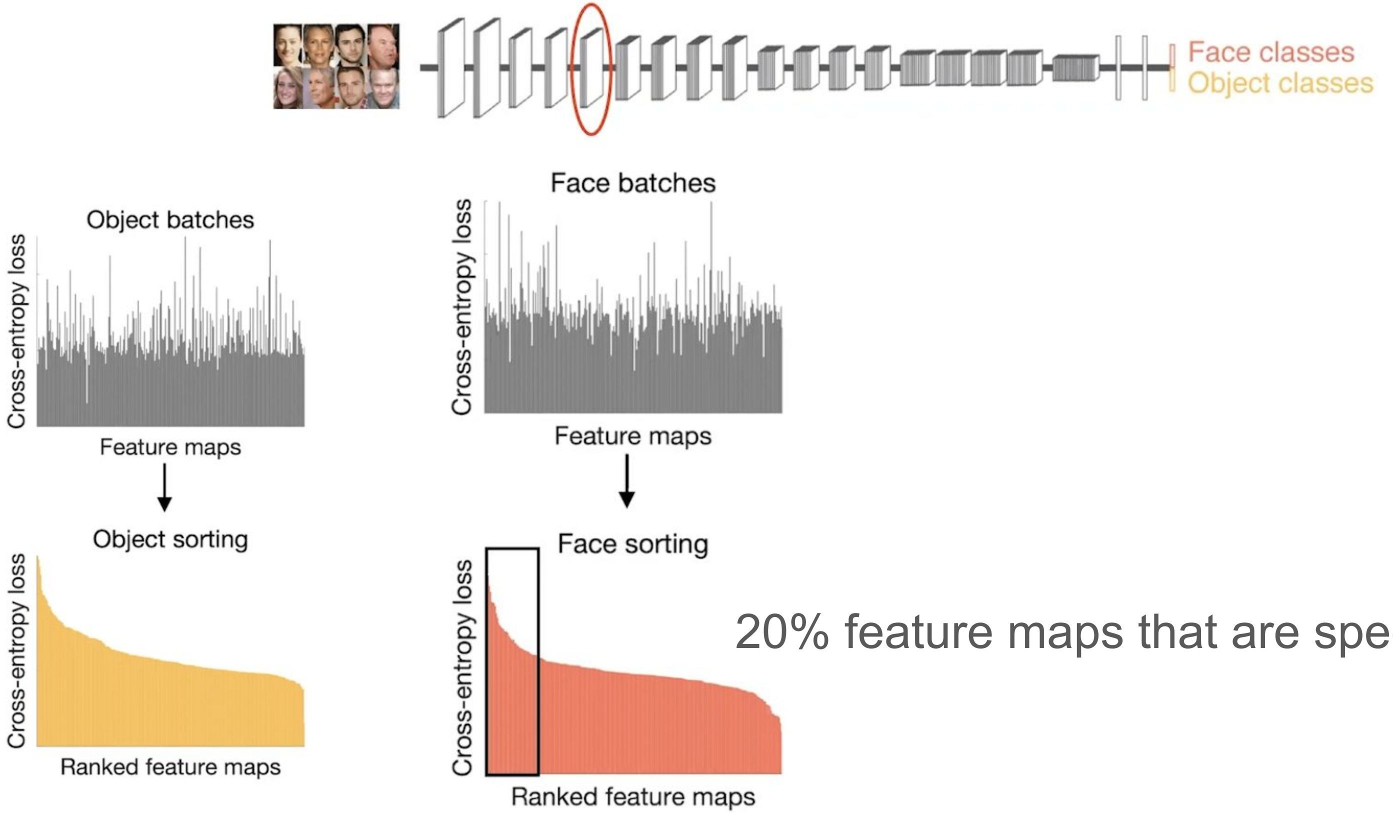
Did the network discover the segregation automatically?

Lesion test to drop specialist neurons



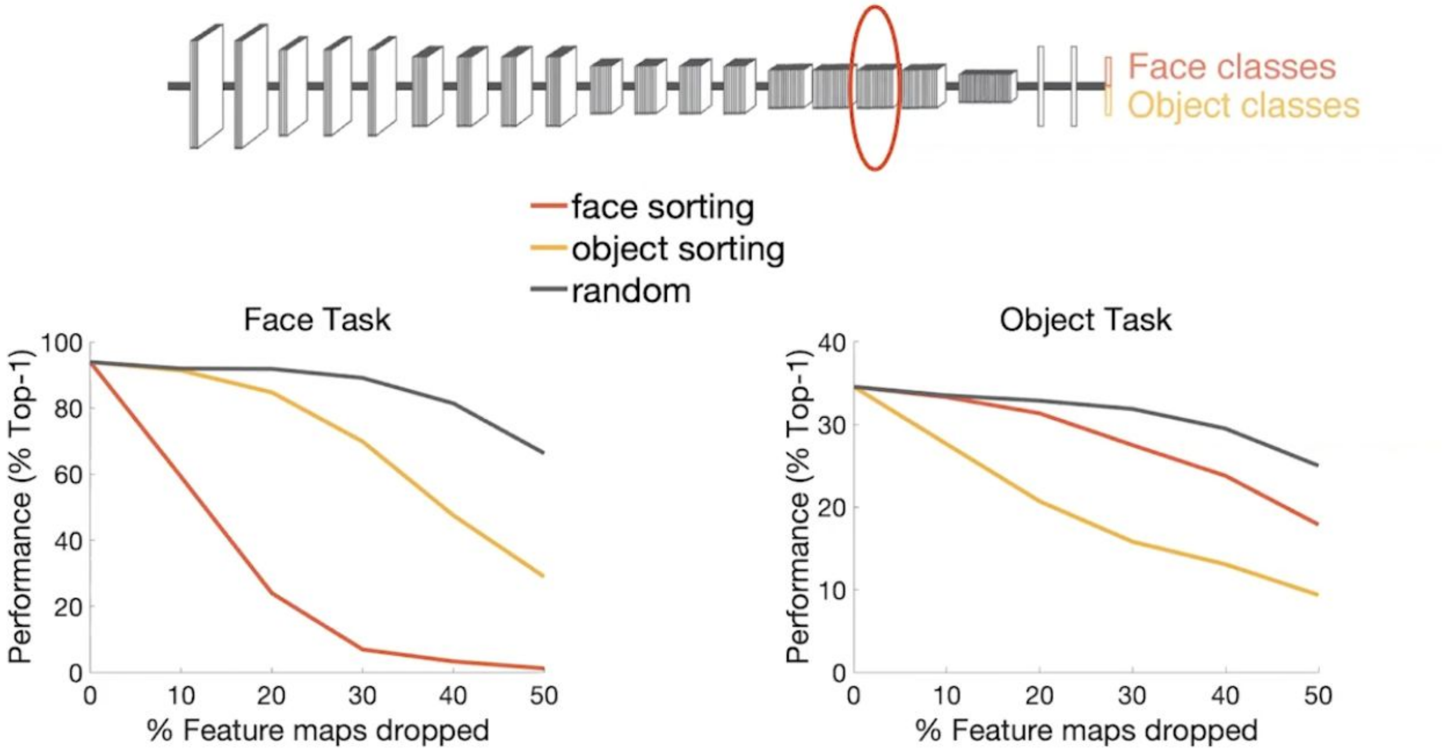
20% feature maps that are specialized to face

Lesion test to drop specialist neurons

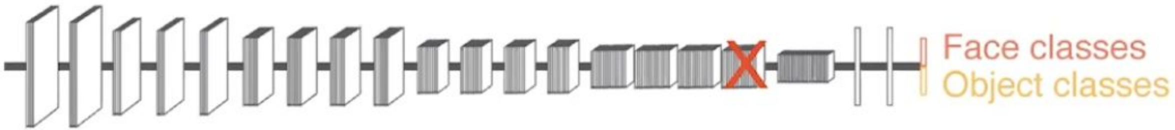


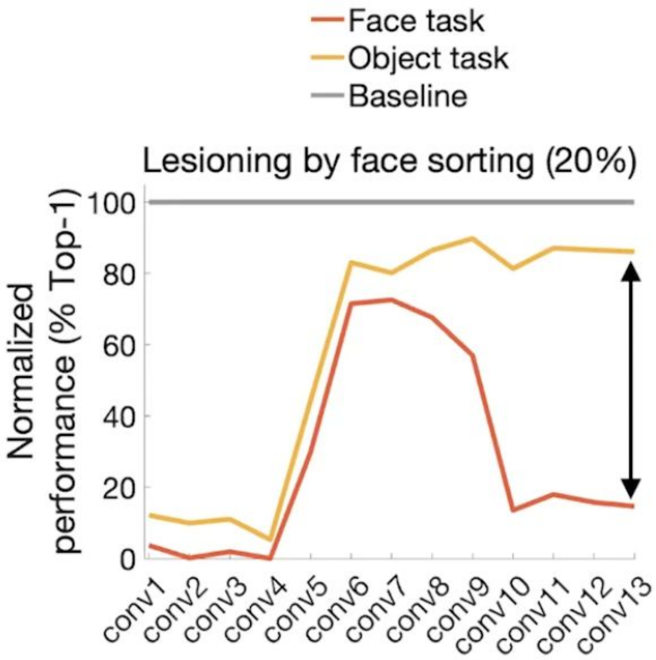
20% feature maps that are specialized to face

Functional segregation in the large networks

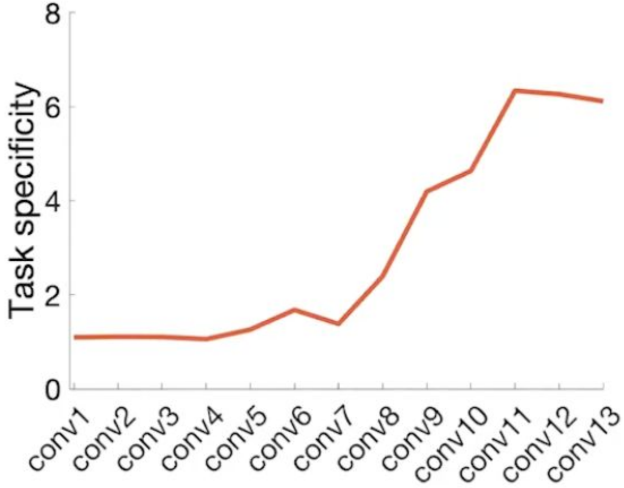


At which stage the system become specialized?

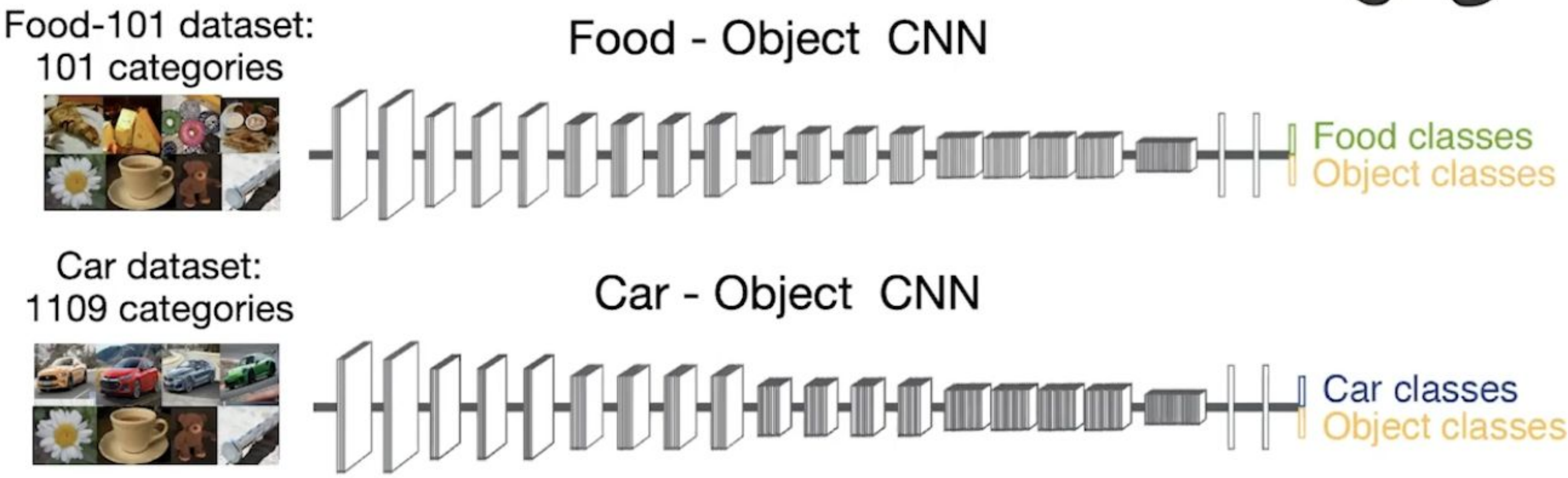




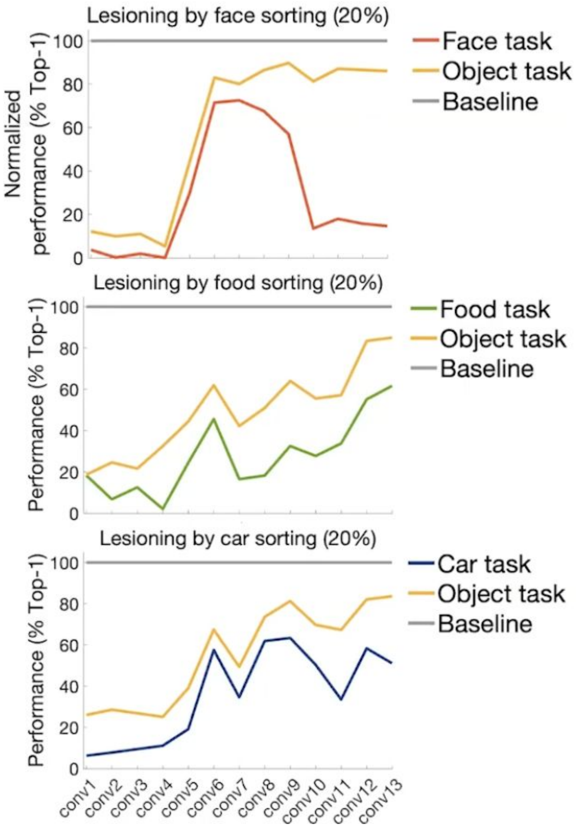
Control: replicates with matched performance!

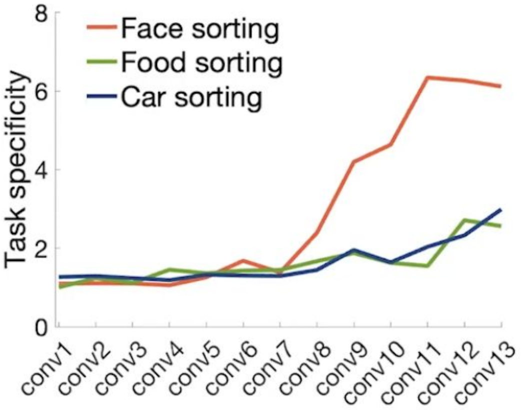


Do any two tasks requires specialization?

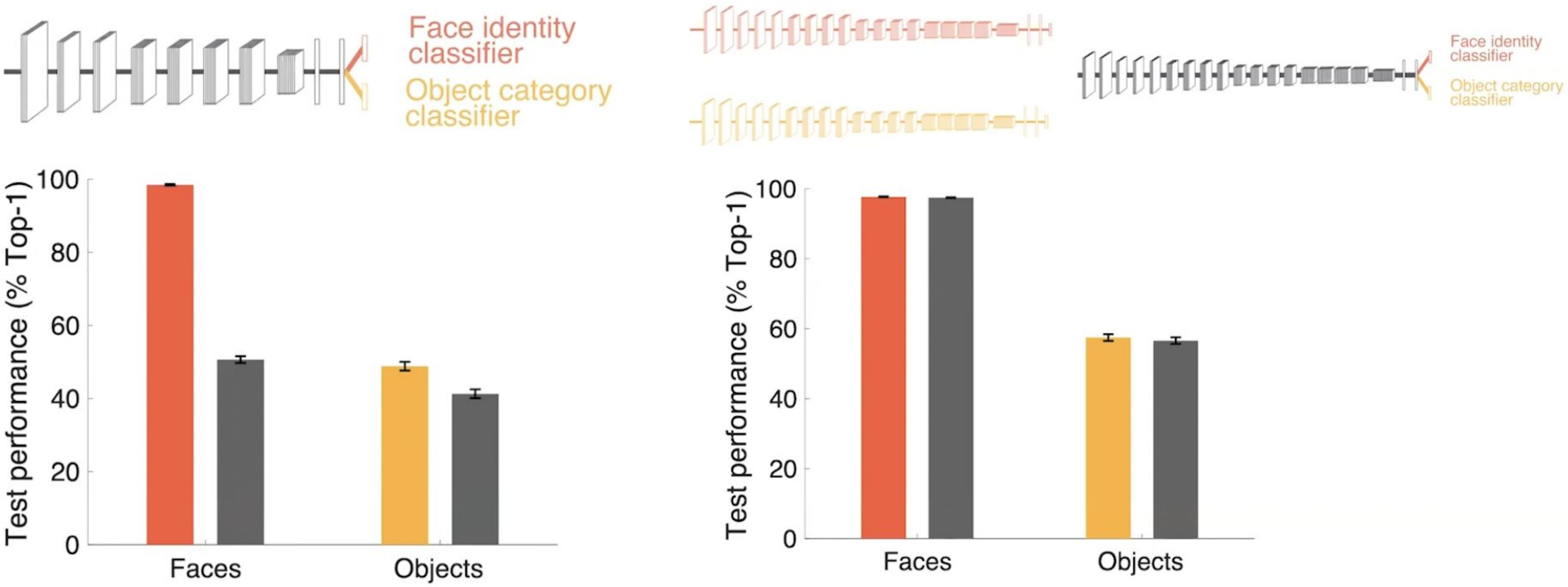


Food and Car shows less segregation than Face / Objects





Benefits of having such segregation



Having such segregation capability will boost the shared network performance

Topological Organization

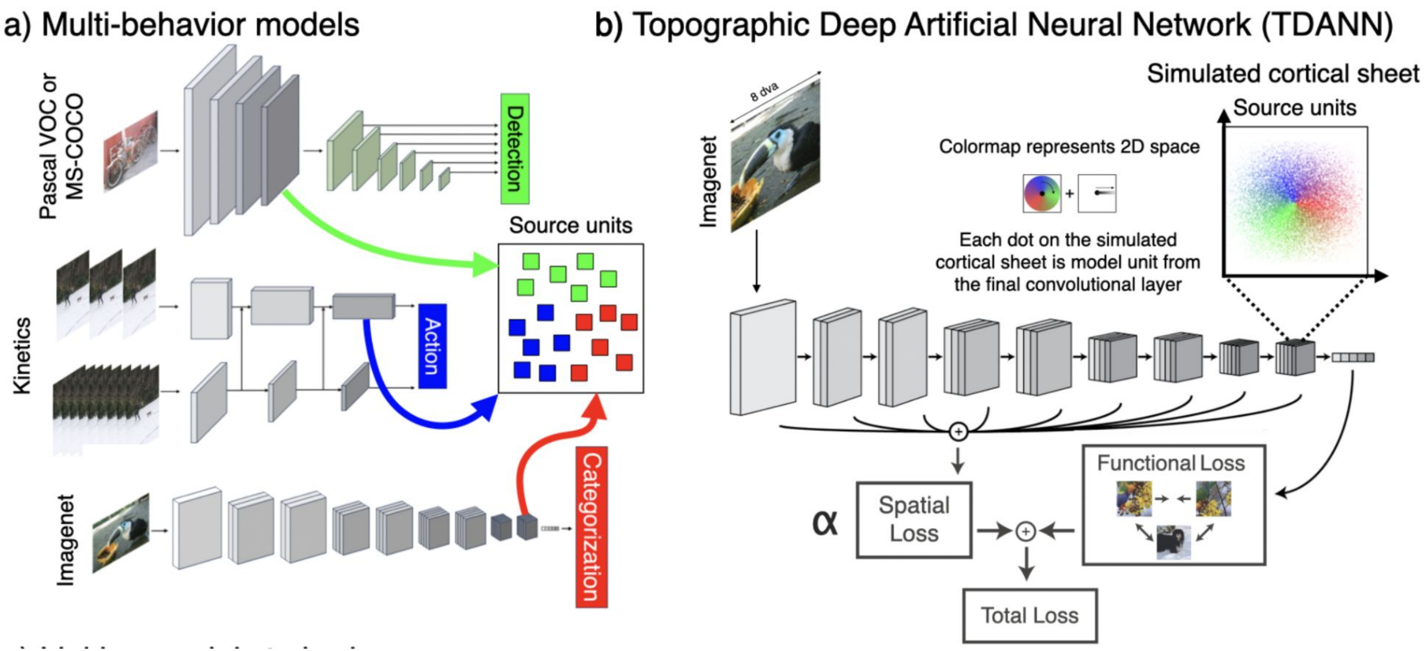
- The above experiments suggest another possible explanation for why we observe the topological organization

  They might emerge as functional segregation due to the nature of dataset

  Each region can be a specialized module for prototypical tasks

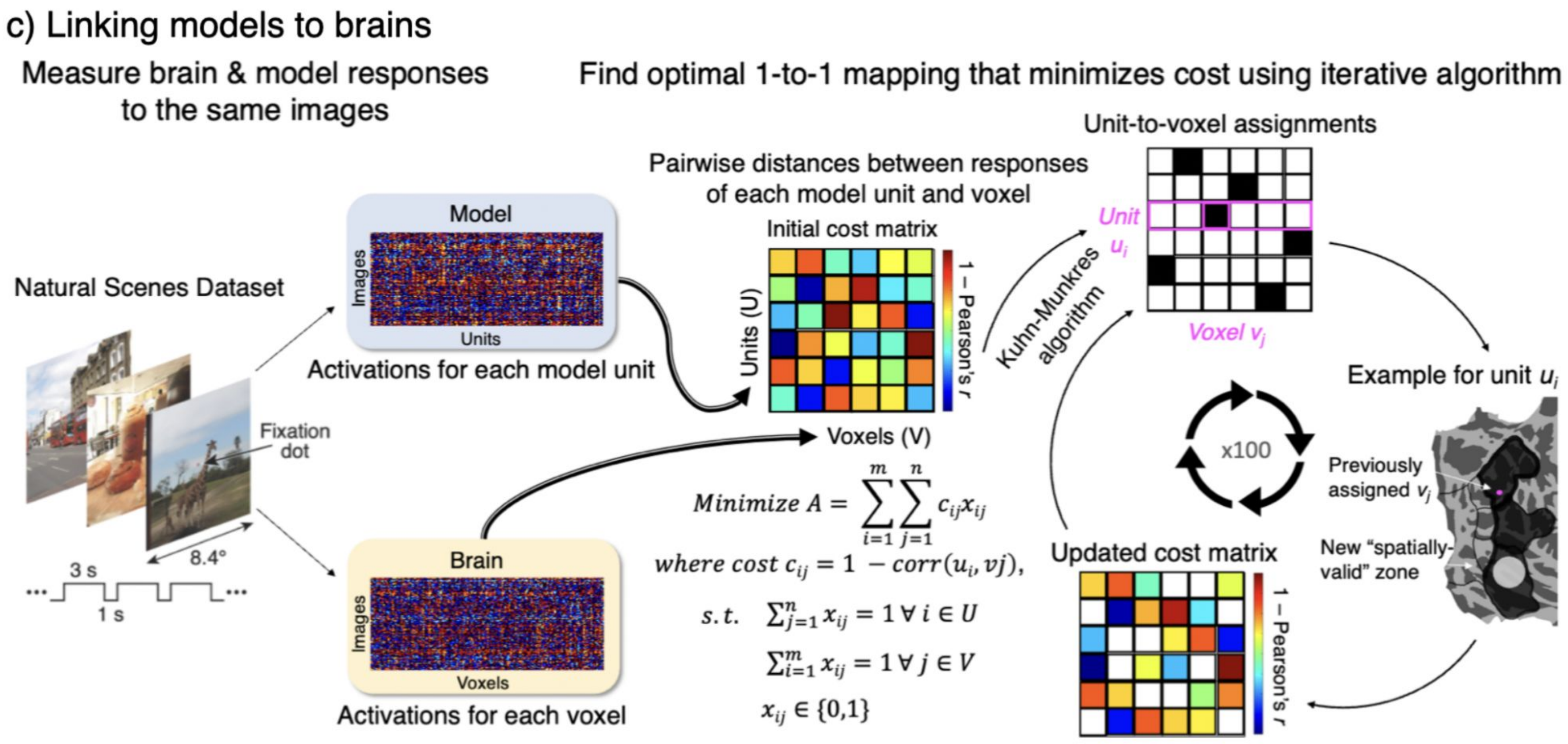
- Brings the question of the necessity of having explicit loss to enforce smooth topological structures.
- Such segregation has clear benefit of performance improvement

Brain data mapping: TDANN v.s. Functional Specialists

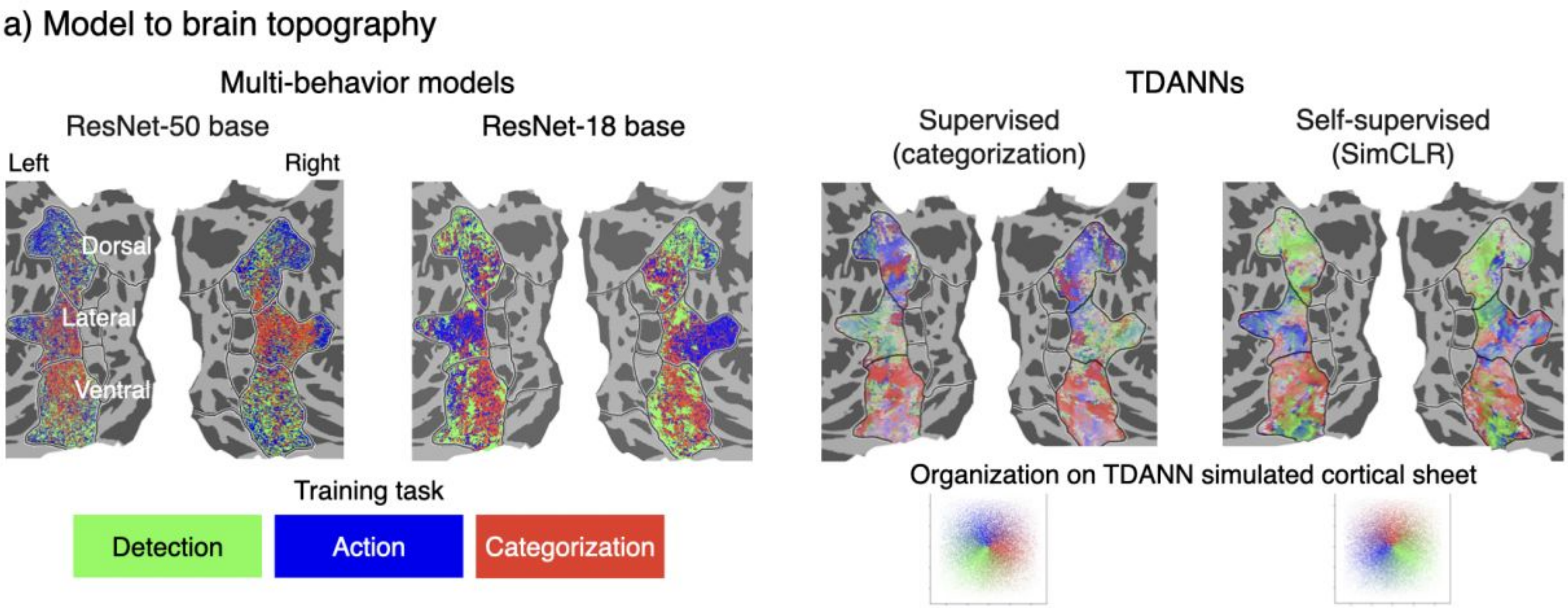


Who is better match for the brain data? (Finzi, Dawn, et al, 2023)

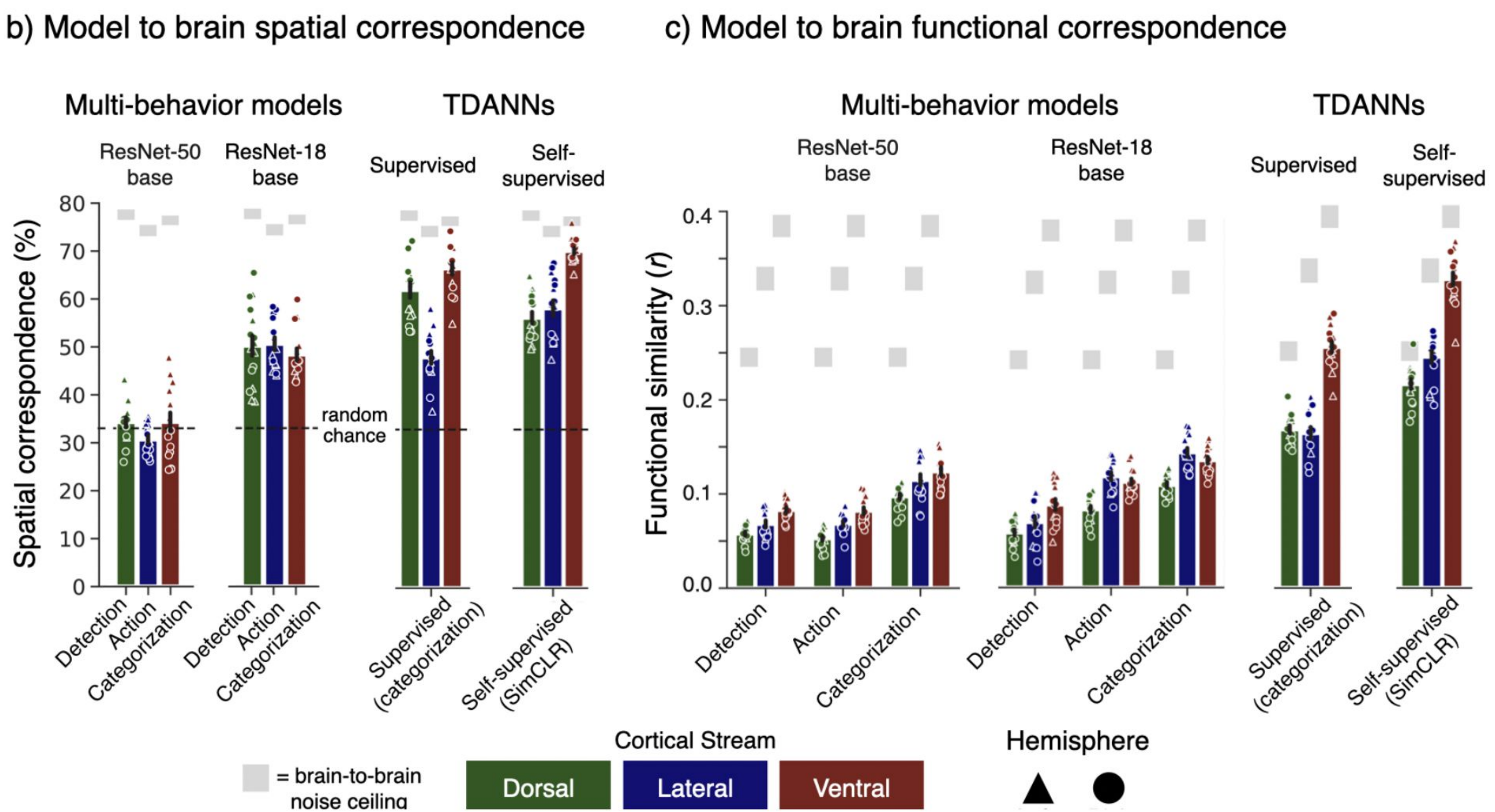
Mapping model neurons to brain voxels



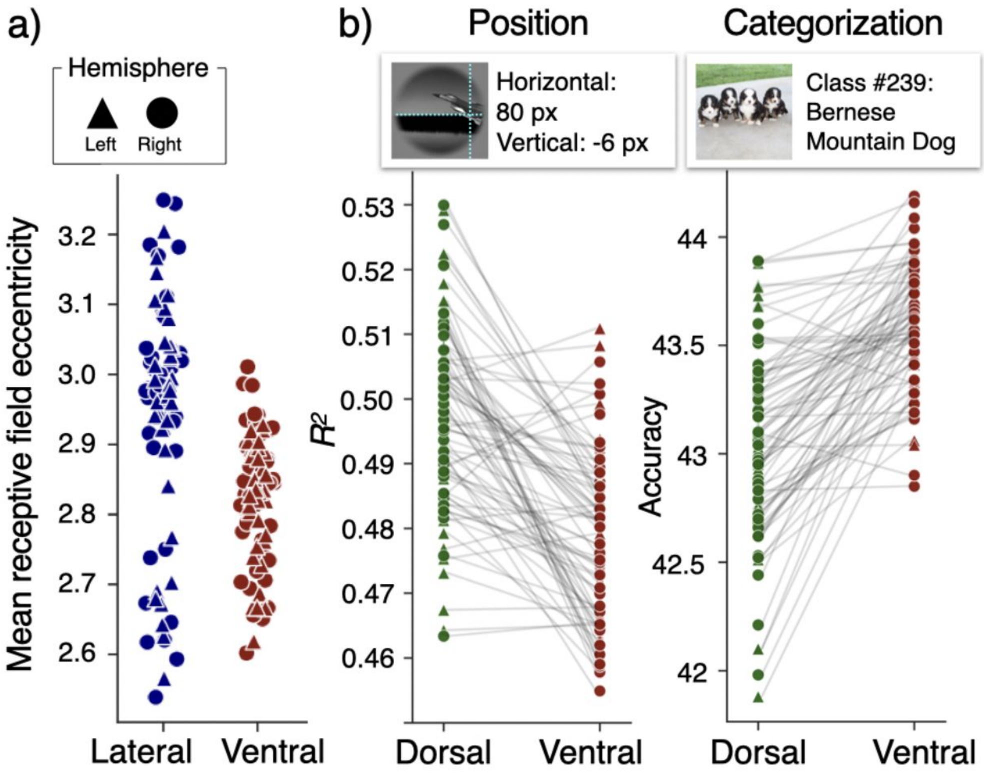
TDANN matches the brain topology better



Spatial and functional correspondence



Functional segregation emerges from the TDANN



Summary

- Two hypothesis on the emergence of topological structure.
- TDANN is most brain like
- Most of the work is not focused on the computational advantages of topological organization

Potential advantages:

- Learn faster (Convergence)
- Caching system (inference faster)

Future direction

- Closer look at the recurrent connections