Cortical organization as optimization under distance-dependent constraints

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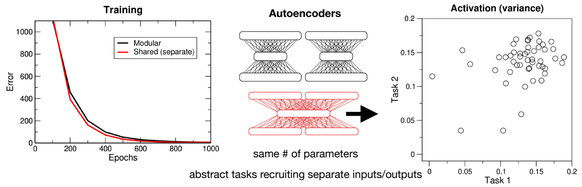
Introduction

- **Why do high-level visual representations show a substantial degree of domain-level topographic specialization?**
- Modular theories claim that this reflects optimality of segrated representation for unrelated tasks, and possibly innate mechanisms for implementing such segregation [1]
- However, graded topographic specialization might arise from domain-general distance-dependent constraints, such as connectivity [2], and axonal conduction noise [3], (see also: topography from abstract self-organizing principles [4,6])
  - Distance-dependent constraints have yet to be explored in terms of local recurrent computation in high-performing deep neural networks
- We investigate the claim that segregation is optimal, the possibility that general spatial constraints on recurrent computation may induce topographic functional specialization in a multi-task DCNN, and whether such specialization is graded in nature.

No advantage for segregated representations of unrelated tasks

Two unrelated tasks and a shared or modular hidden representation

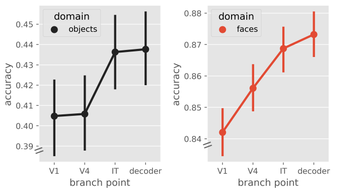


Shared training did not impair and slightly *improved* reconstruction performance (left) and resulted in multiplexing of units onto the two unrelated tasks (right).

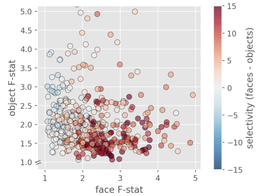
Branching architecture for objects+faces (cf. Dobs et. al CCN 2019)

Modified to use:
- Fixed number of filters across architectures (modular brains don't get double the neurons)
- CORnet-Z architecture [5], which has fewer parameters than AlexNet.
- Fully interleaved mini-batches during training

branching models performance



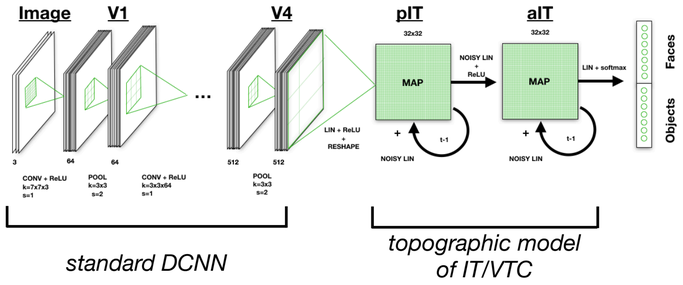
shared model responses



- Sharing representations doesn't hurt and may slightly help performance
- Graded domain specialization emerges naturally in the shared model
  - Most units have information for both tasks, as in the brain

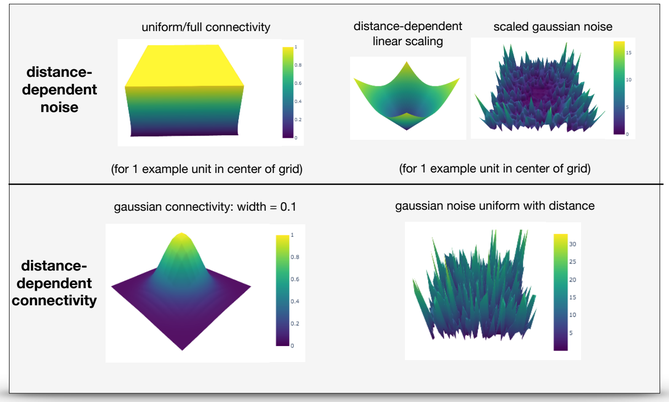
Graded topographic organization arises from domain-general distance-dependent constraints on communication

Architecture and method



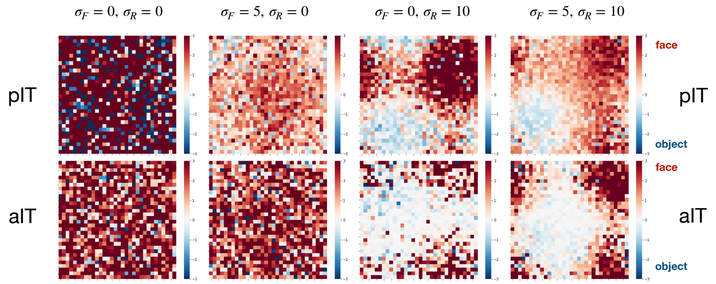
- CORnet-Z V1/V2/V3/V4 CNN backbone with 2 map-like RNN layers (pIT, aIT) to investigate high-level functional organization
- Map-layers process static V4 inputs for 5 time steps
- Jointly learn to recognize 584 object (ImageNet) categories and 1882 face (VGGFace2) identities (matched in total # of images)
- Impose one of two **distance-dependent constraints on communication** for units arranged uniformly in a fixed location on a 2D grid**:** (see Box 1):
  - **Noise**: nearby units communicate with less noise than farther units (wrap-around Euclidean distance). Noise is *multiplicative* with weights.
  - **Connectivity**: nearby units have higher probability of connectivity than farther units, using a Gaussian probability distribution over distance.

Box 1: communication constraints



Selectivity: distance-dependent noise

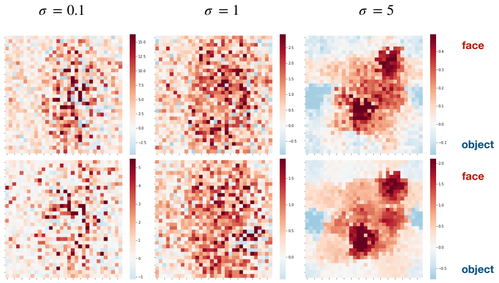
σ_F -> feedforward noise strength, σ_R -> recurrent noise strength



- Face responses tend to be stronger than object responses in all models
- Recurrent distance-dependent noise produces localized domain selectivity, especially in pIT
- Feedforward distance-dependent noise binds selective regions across grids, but does not reliably develop them in the absense of recurrent noise

Selectivity: distance-dependent connectivity

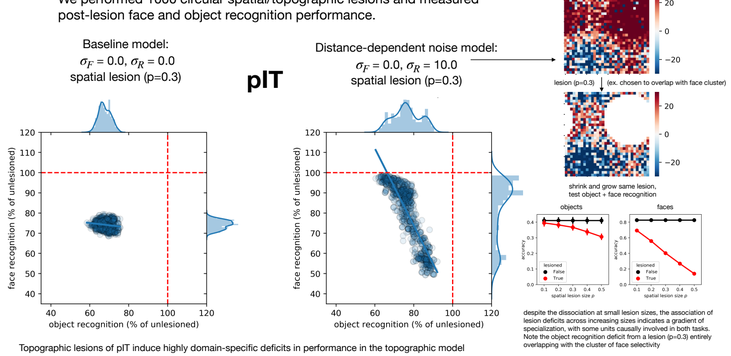
σ -> feedforward/recurrent noise strength



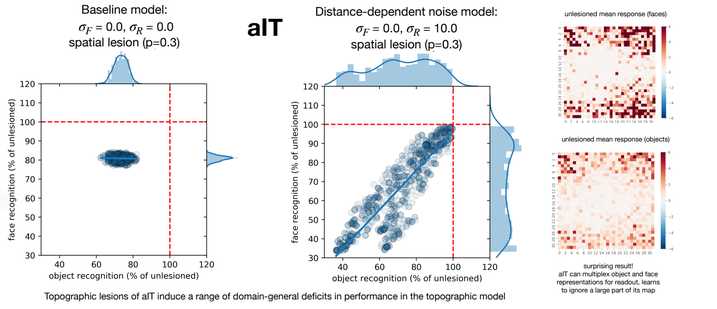
- Spatially Gaussian connection probabilities increased object and face-selective topography but only in the presence of strong noise
- Size of selective patches likely related to Gaussian connectivity width

Lesion experiments

We performed 1000 circular spatial/topographic lesions and measured post-lesion face and object recognition performance.



Topographic lesions of pIT induce highly domain-specific deficits in performance in the topographic model



Topographic lesions of aIT induce a range of domain-general deficits in performance in the topographic model

Conclusions

- We found no evidence for optimality of segregated representations across unrelated tasks, even in an abstract case of orthogonal task domains
- Object and face recognition can easily coexist in a DCNN and graded specialization naturally emerges to process both domains
- Distance-dependent constraints on recurrent computation give rise to smooth domain organization in deep layers of a DCNN
- Constraints on feedforward communication may explain the emergence of a "stream" of multiple face selective areas in IT/VTC
- Some distance-dependent constraint combined with recurrent computation seems to be the key to topographic organization
  - Distance-dependent noise is effective and biologically plausible
  - Distance-dependent connection probability is also highly plausible and produces topography in the presence of uniform noise
- Lesions of pIT indicate strong but graded topographic domain specialization whereas lesions of aIT indicate surprisingly overlapping domain representations
- In sum, **we find no functional advantage for segregated representations, and instead ascribe graded topographic organization to domain-general constraints on communication in biological neural networks**

Discussion

- Our approach is complementary to a recent approach which develops topography by maximizing local correlations [6], with greater focus on biological plausibility. In future work we hope to compare these approaches along with Kohonen-like self-organization [4].
- A greater exploration of hyper-parameter space is still necessary, along with further fine-tuning of the distance-dependent constraints with respect to biology (distance scaling, connectivity width, multiple constraints, etc.)
- In ongoing work, we include scenes and see further domain-level specialization. We are also investigating the link between functional specialization and retinotopy, and are training on a dynamic task.

References

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Acknowledgments

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