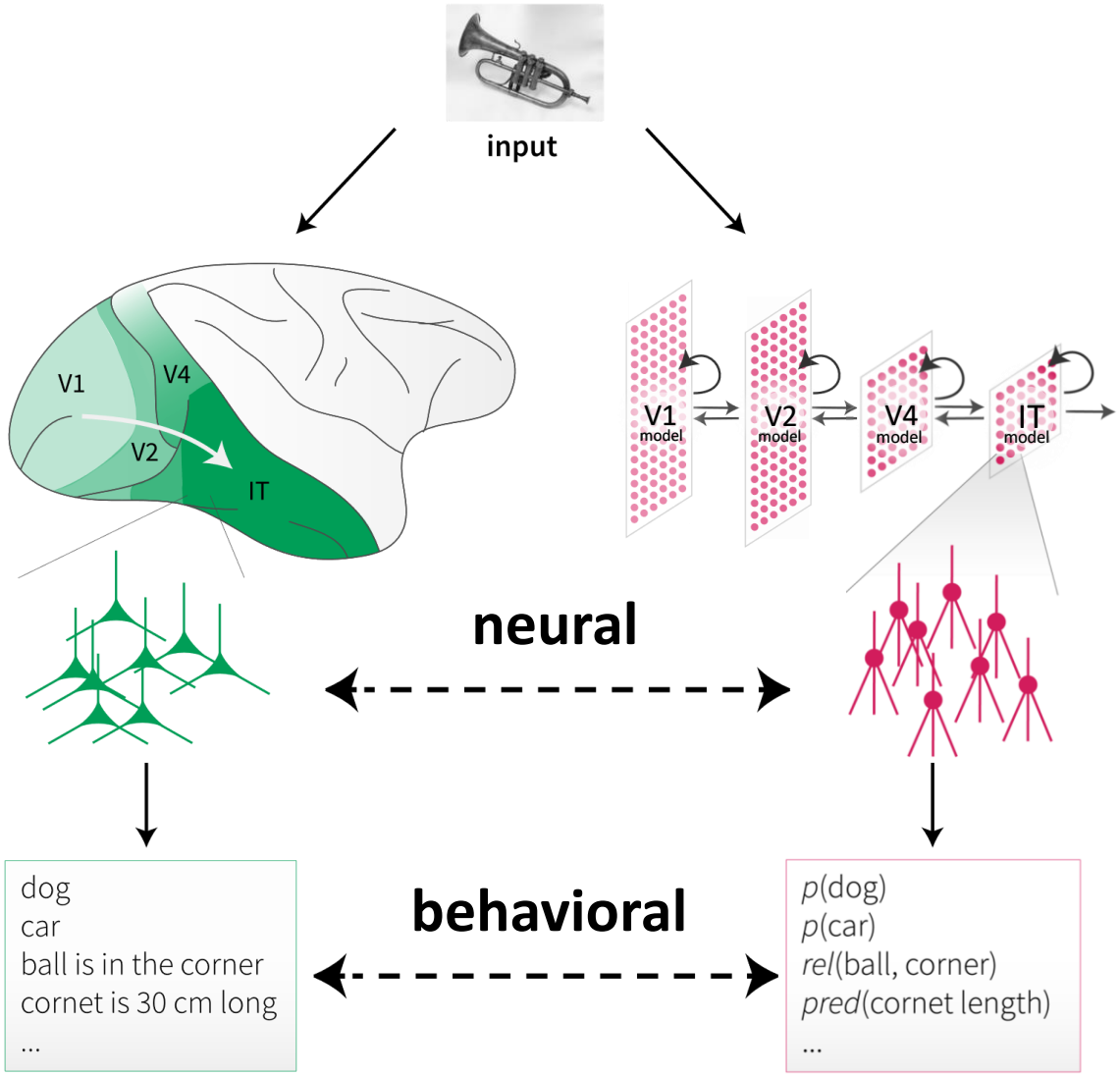
Brain-Like Object Recognition with High-Performing Shallow Recurrent ANNs



Martin Schrimpf*

Jonas Kubilius*

Kohitij Kar
Ha Hong
Najib Majaj
Elias Issa
Pouya Bashivan
Kailyn Schmidt
Jonathan Prescott-Roy
Rishi Rajalingham
Franziska Geiger
Aran Nayebi
Daniel Bear
Daniel Yamins
James DiCarlo

** equal contribution*

MIT, KU Leuven, Bay Labs, NYU, Columbia, Stanford

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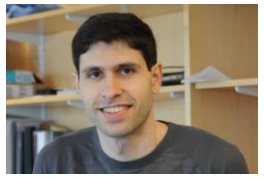

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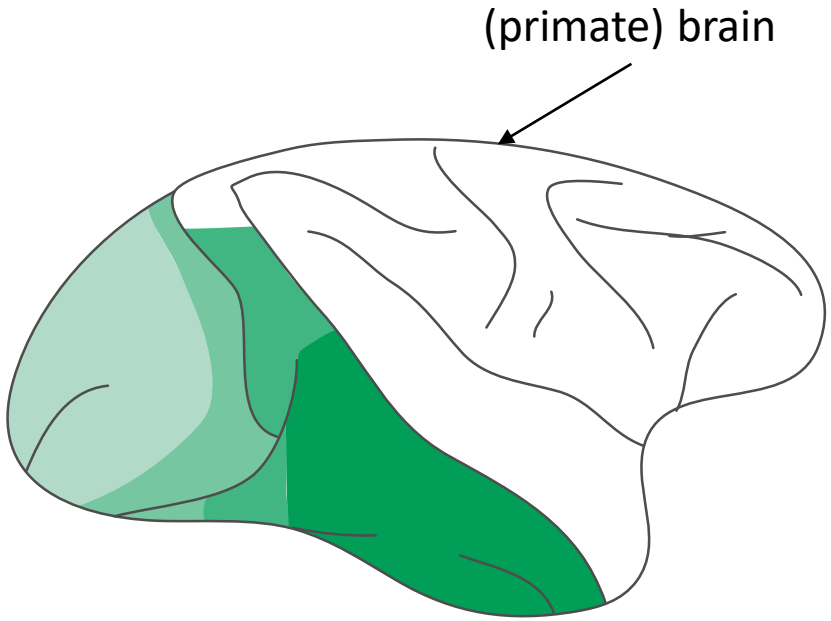
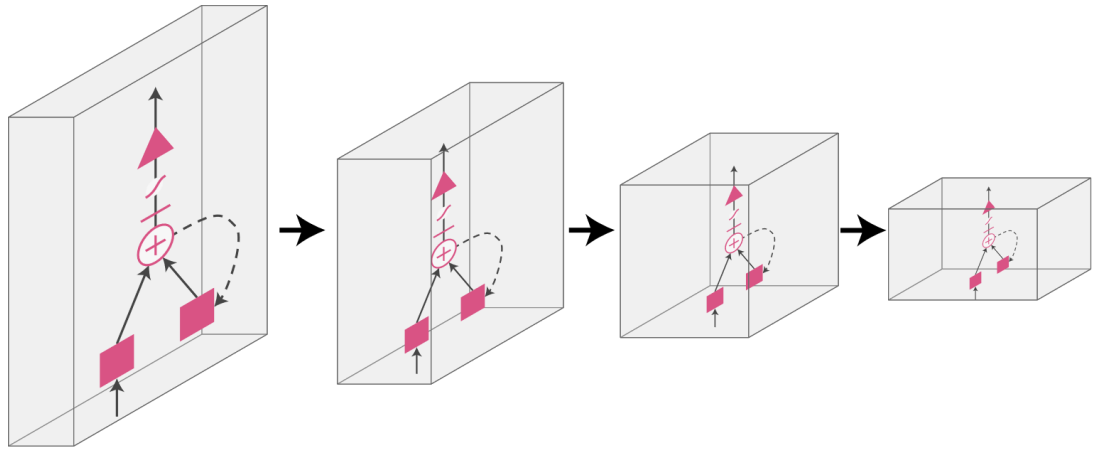
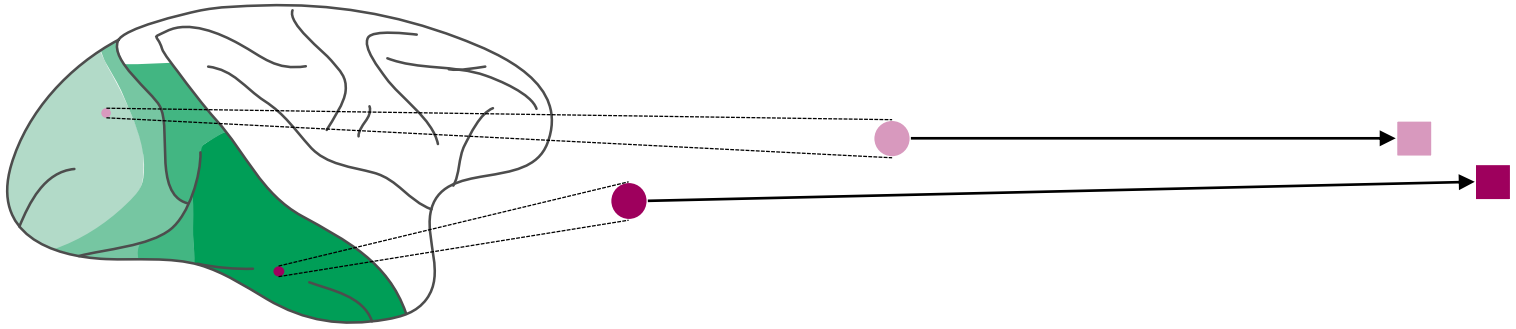
Modeling the brain





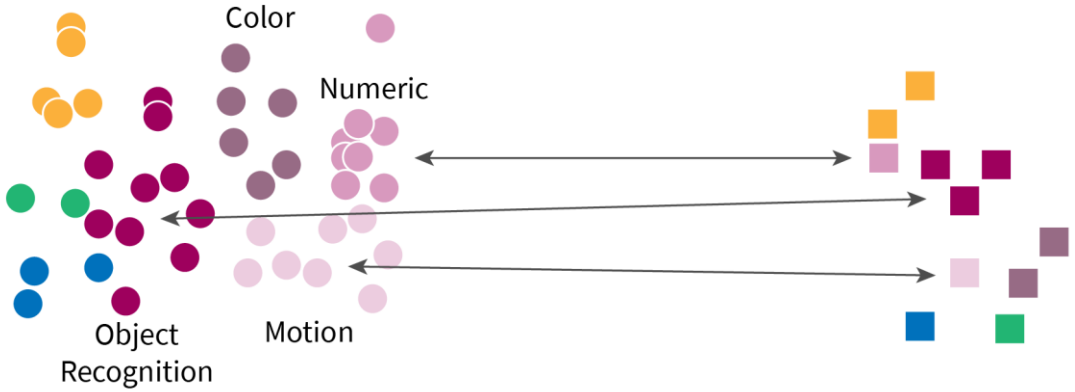
Piecewise Efforts



Isolated Data

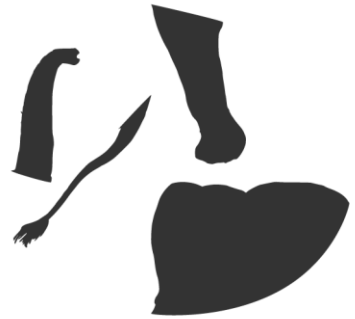
Isolated Models

Piecewise Efforts



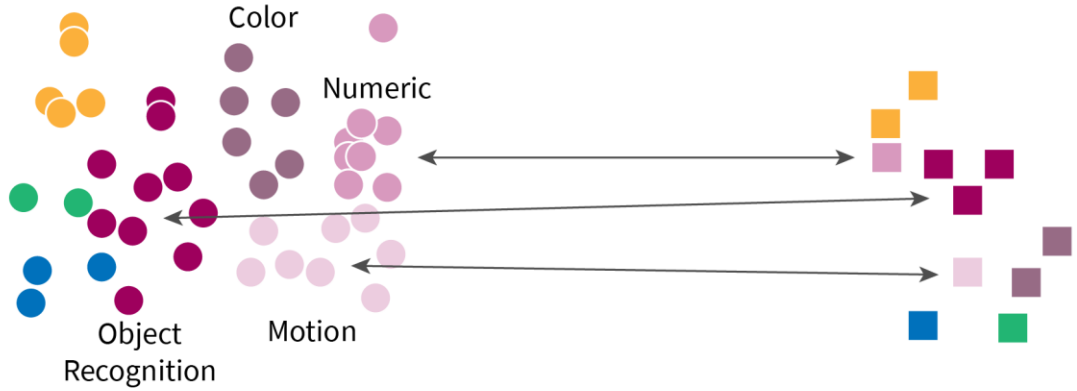
Isolated Data

Isolated Models



These are necessary first steps! But insufficient for a unified model by themselves

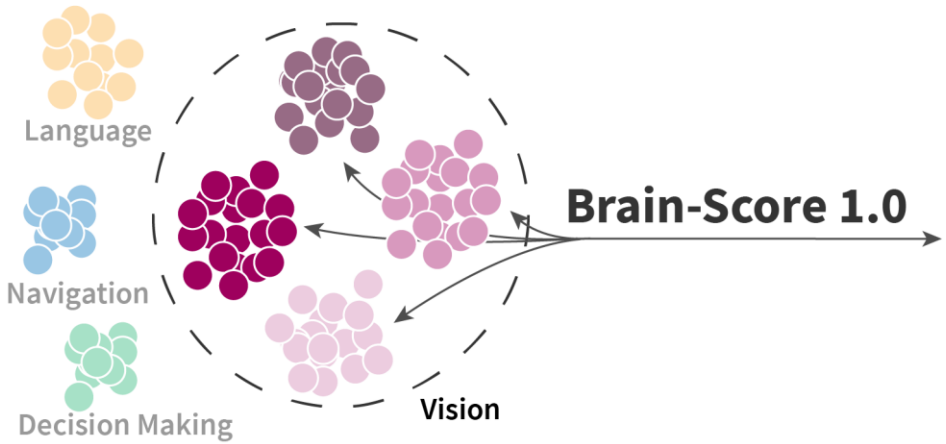
Piecewise Efforts

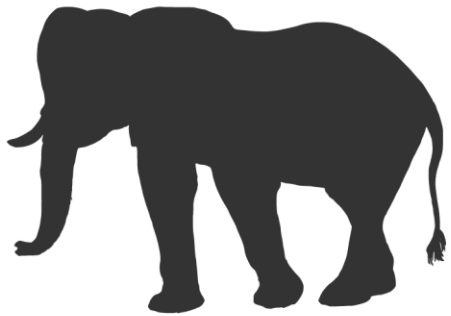


Isolated Data

Isolated Models

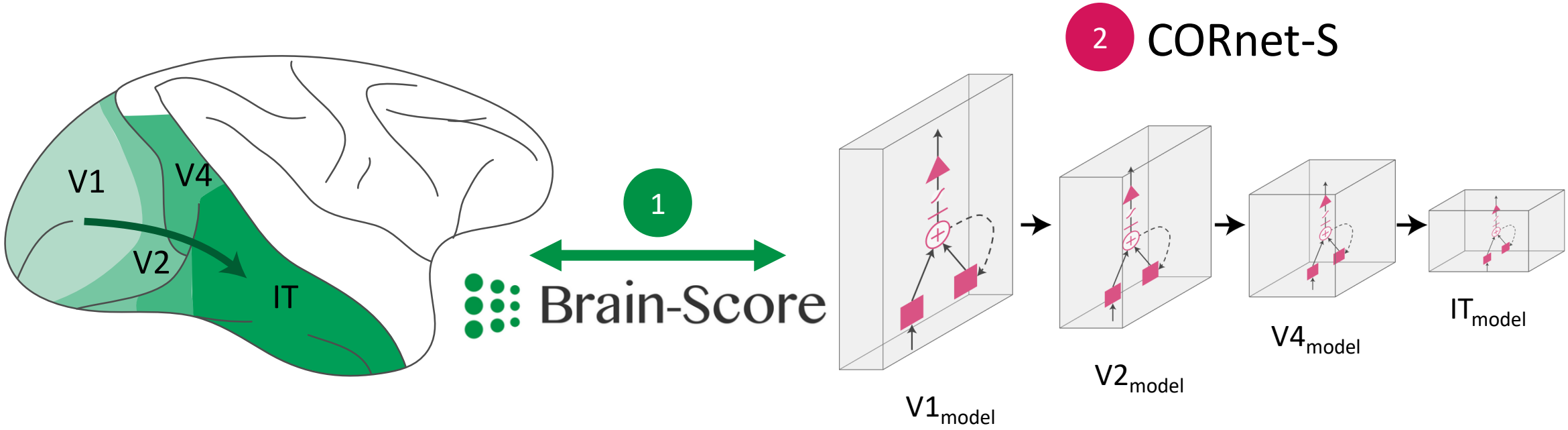
Integrative Benchmarking





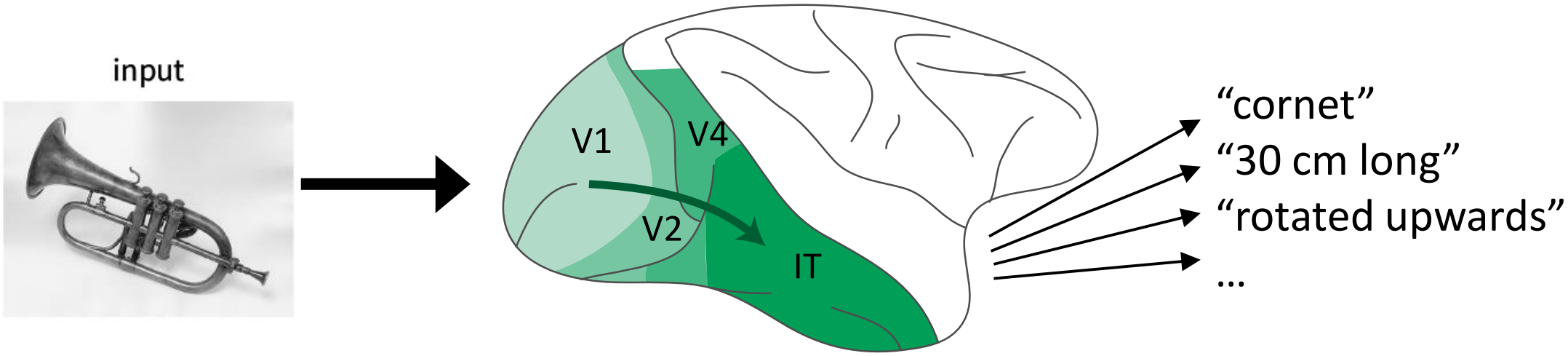
Integrative Models

Modeling the brain's ventral visual stream

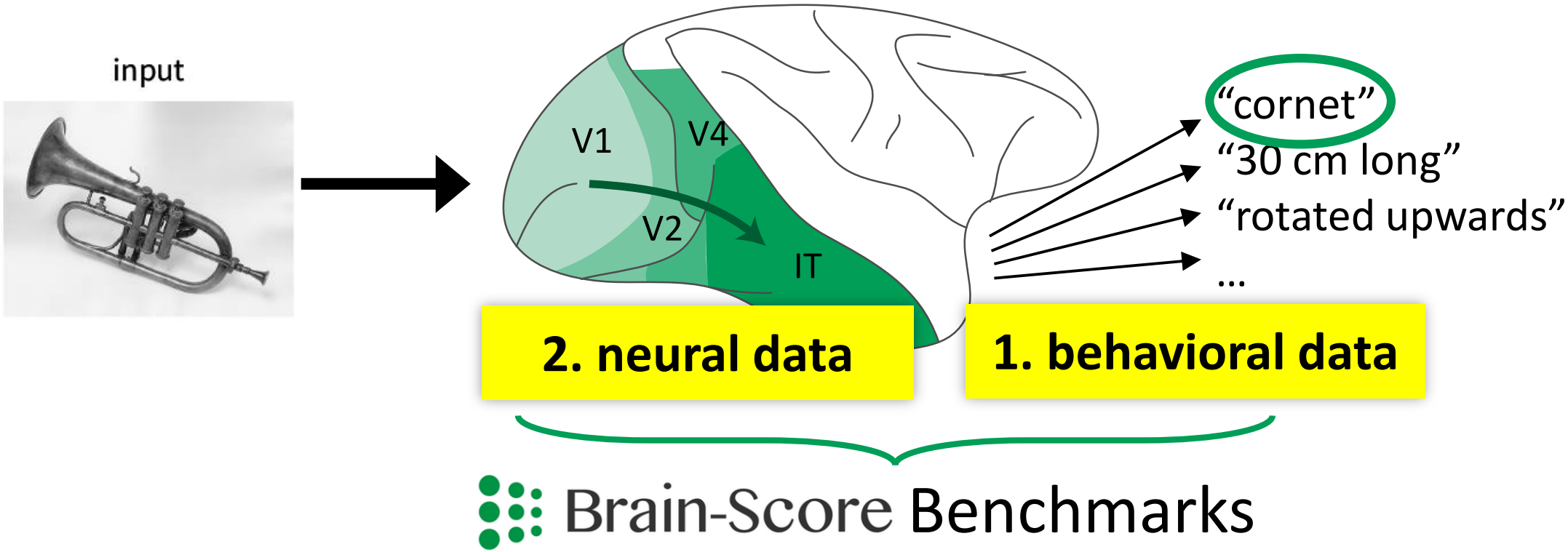


~~"your model is not like the brain"~~ **"but it's a little better than before"**

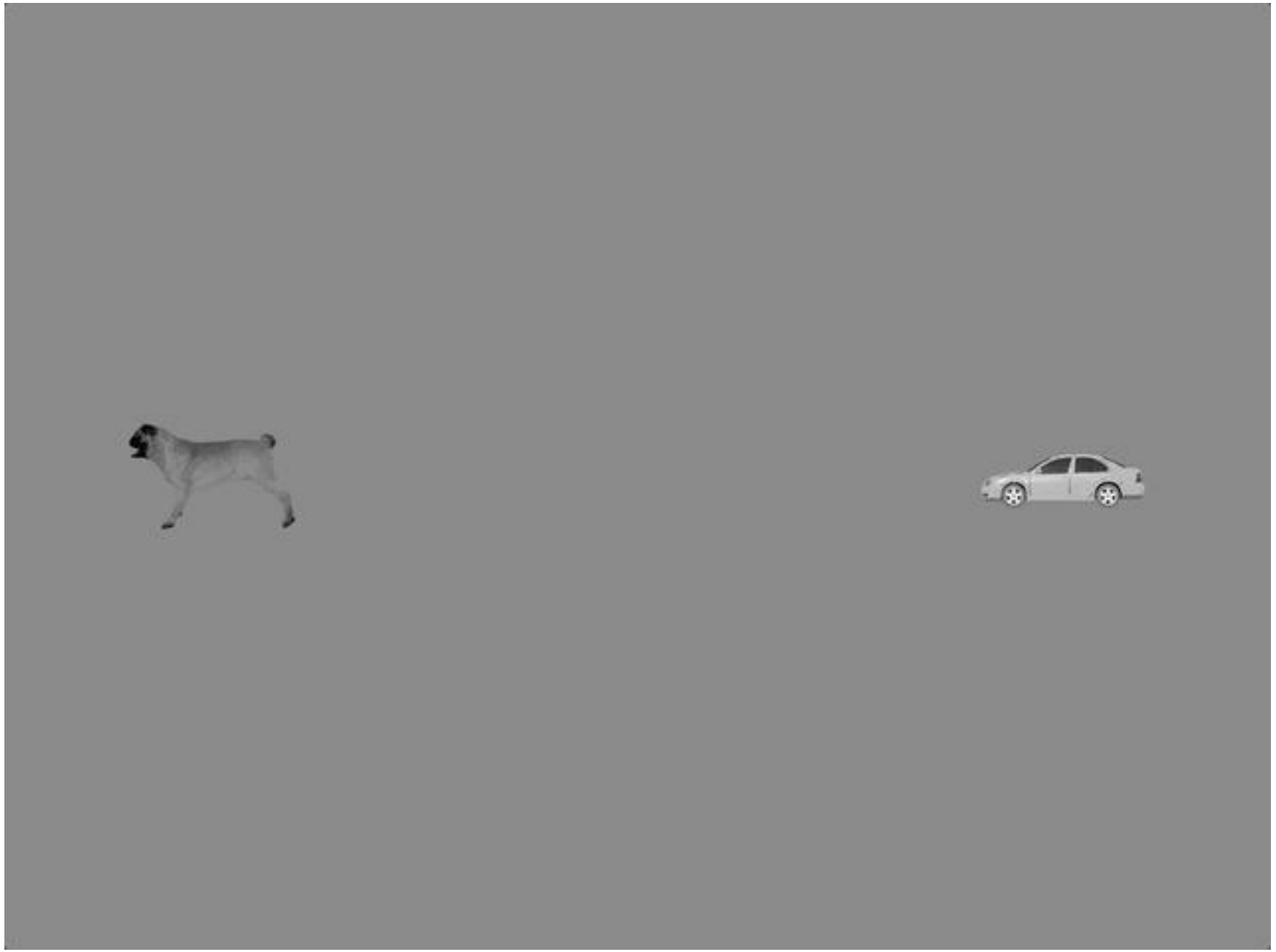
Object recognition in the brain



Comparing models to object recognition in the brain

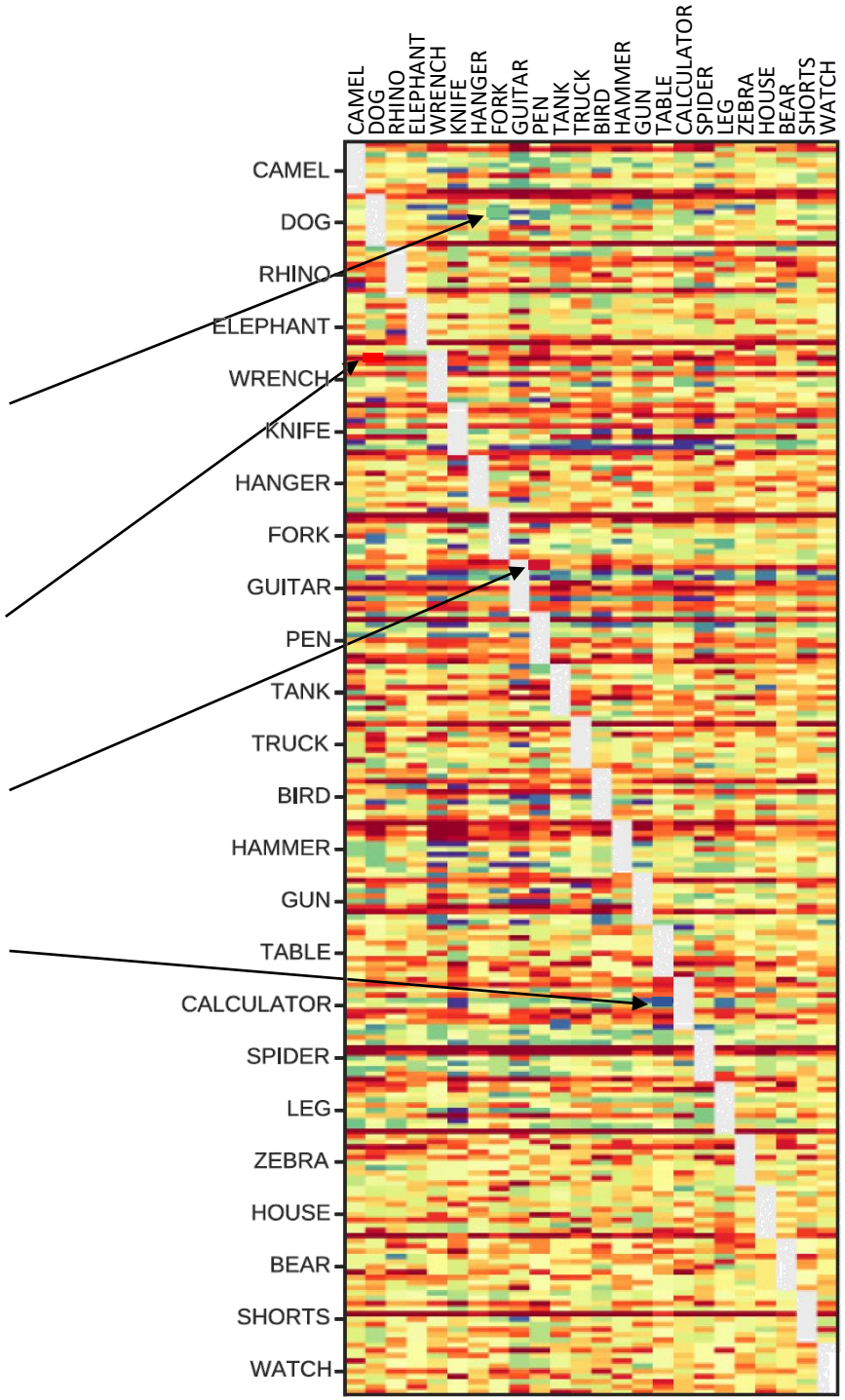


Behavioral benchmark

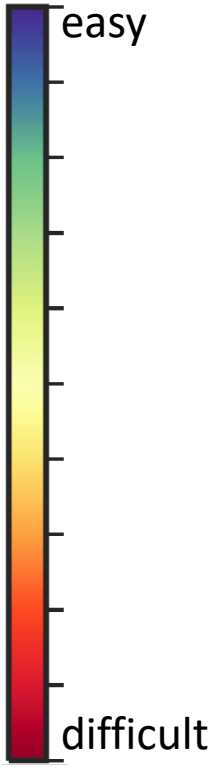


Rajalingham, Issa*, Bashivan, Kar, Schmidt, DiCarlo (JNeuro 2018)*

Behavioral benchmark



performance per binary categorization



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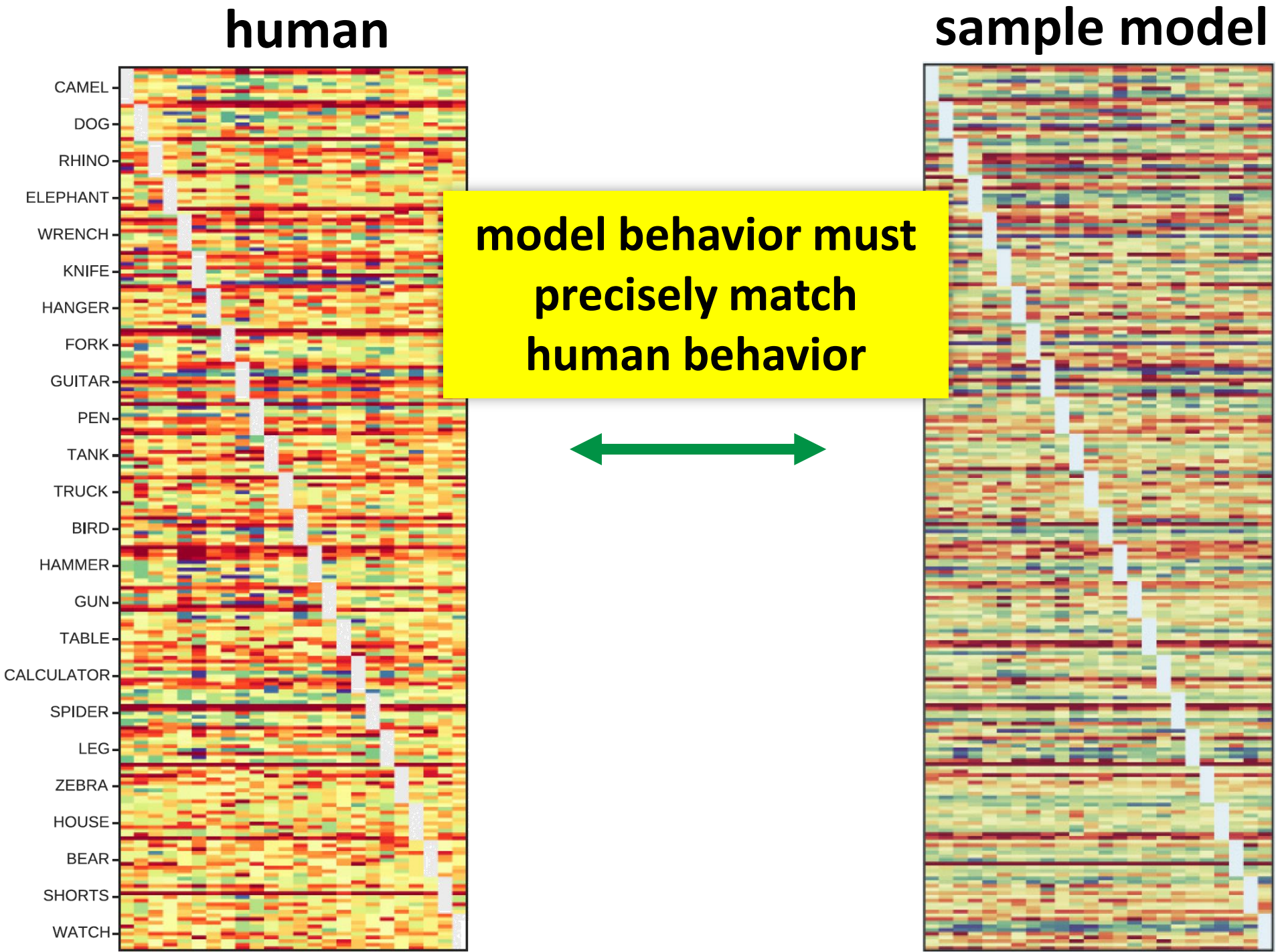
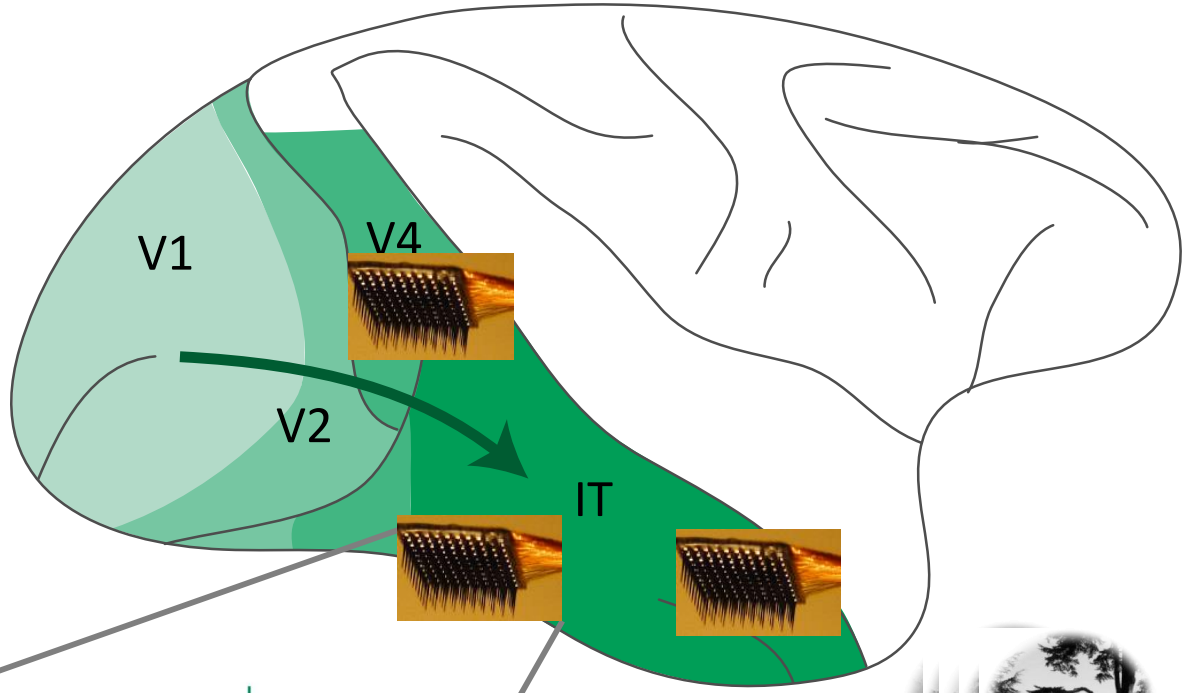
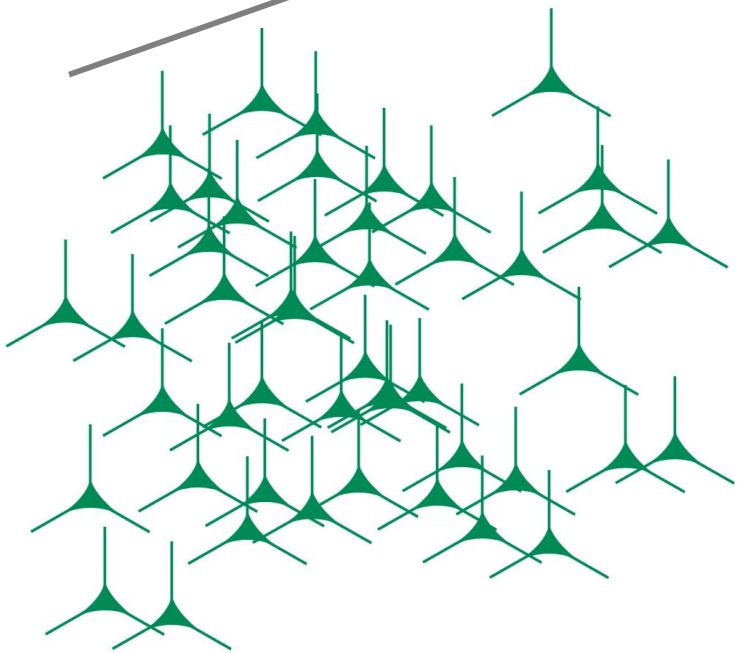
Behavioral benchmark



Neural benchmarks

Neural benchmarks

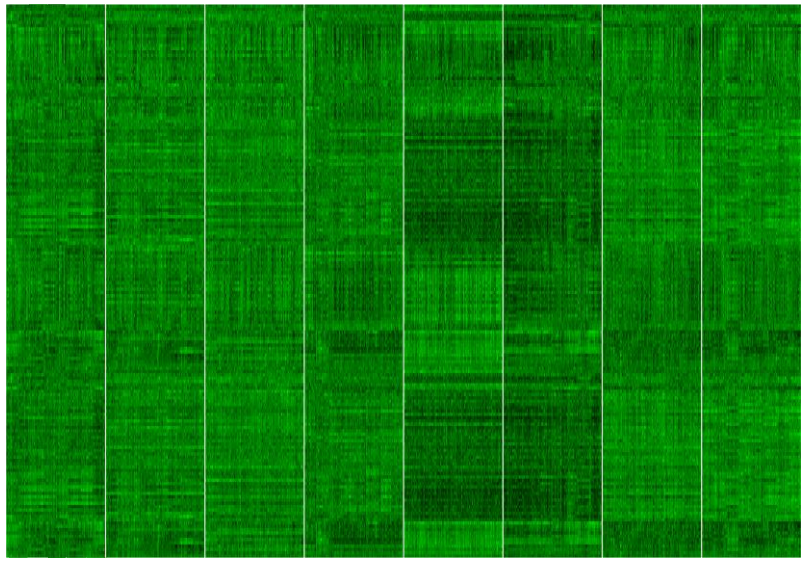




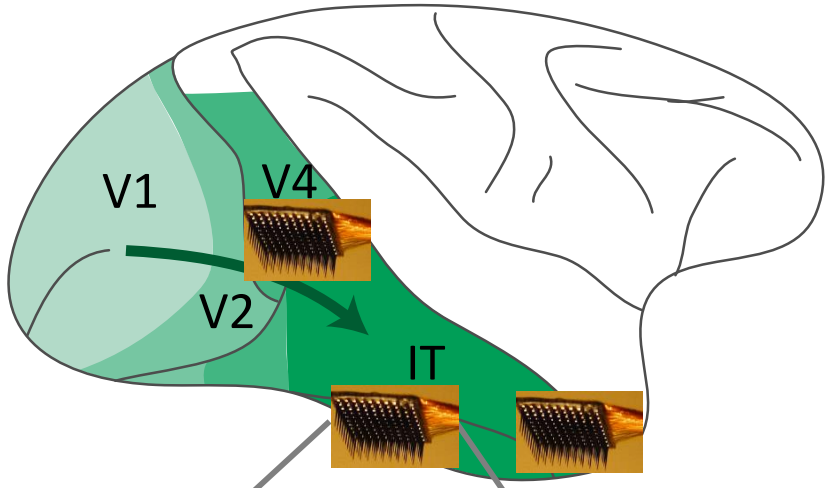
...

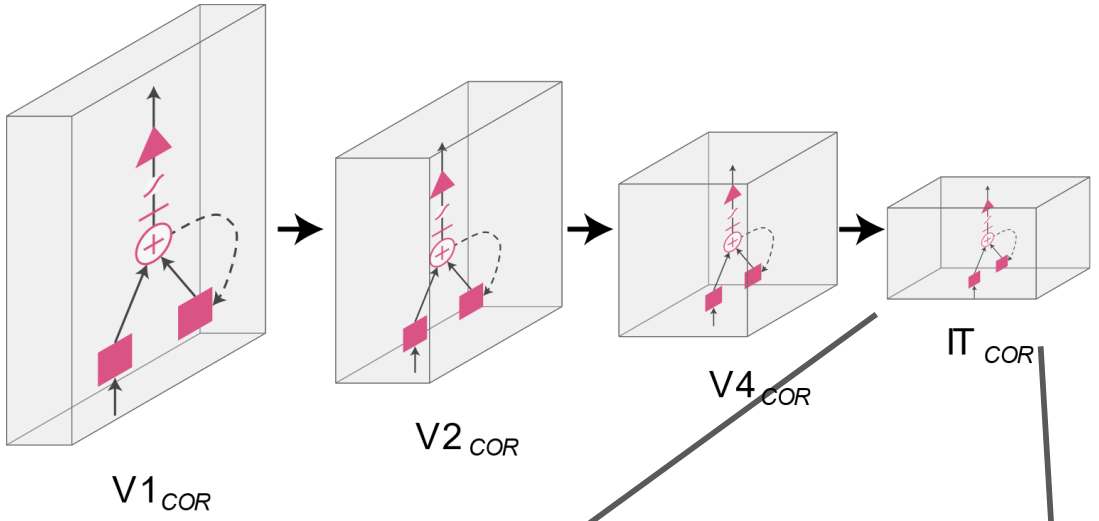
images

neurons

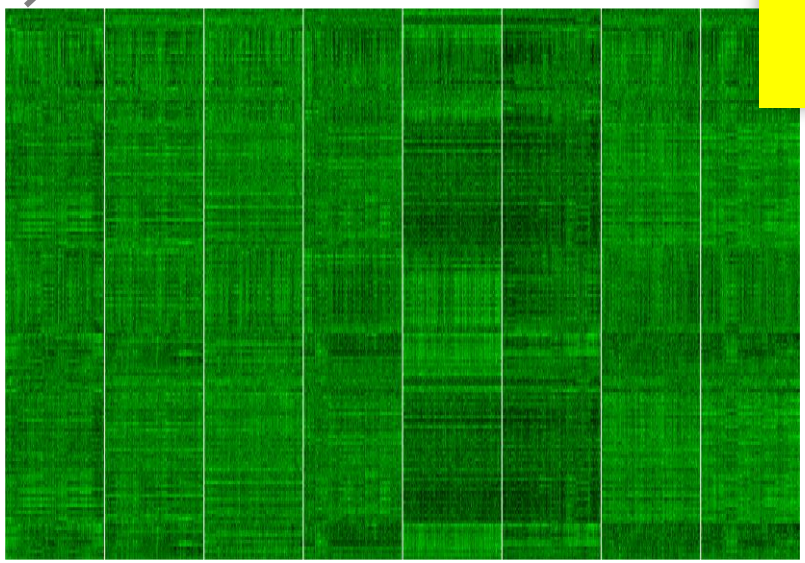


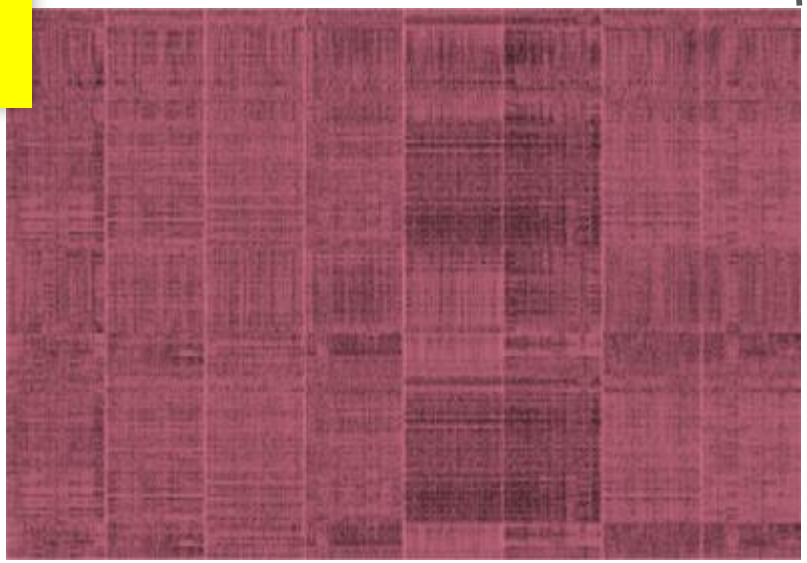
Neural benchmarks





model internals must linearly match neural spike rates

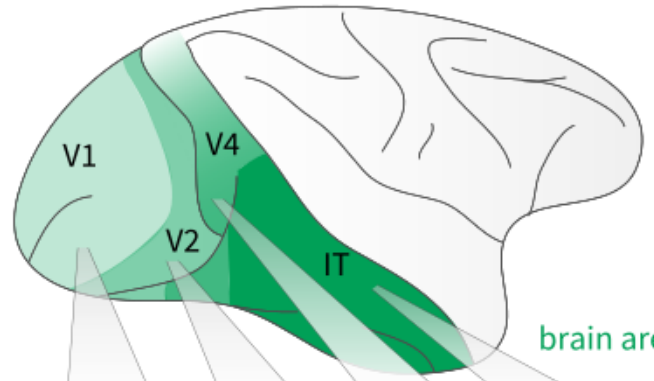




input

Brain

Brain Measures



brain areas

spike rates

behavior

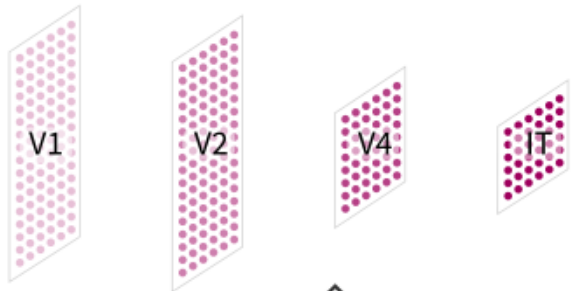
"dog"
"cornet"
"ball is in the corner"
"cornet is 30cm long"
...

Brain-Score Benchmarks

Brain Models

models that make **commitments** to the particulars of brain

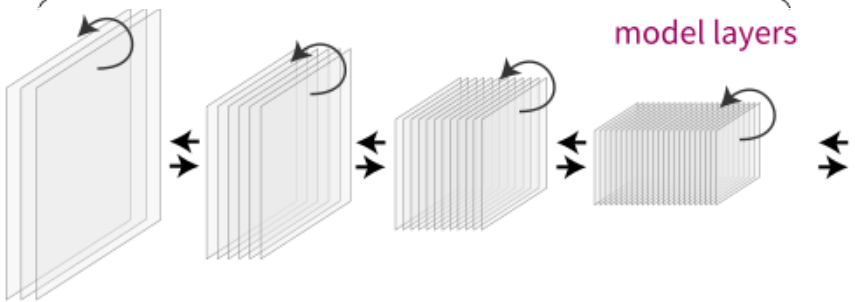
model spike rates



model behavior

"dog"
"cornet"
"ball is in the corner"
"cornet is 30cm long"
...

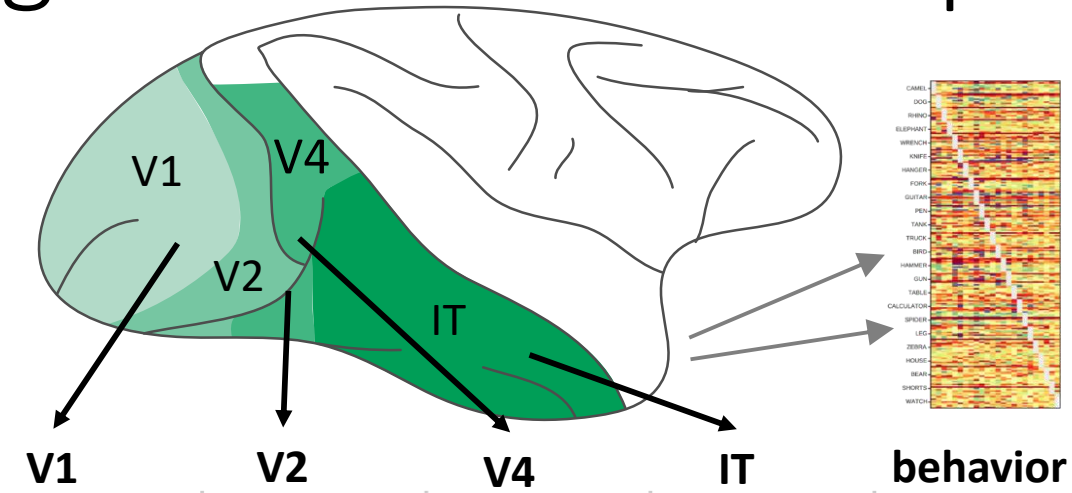
model layers



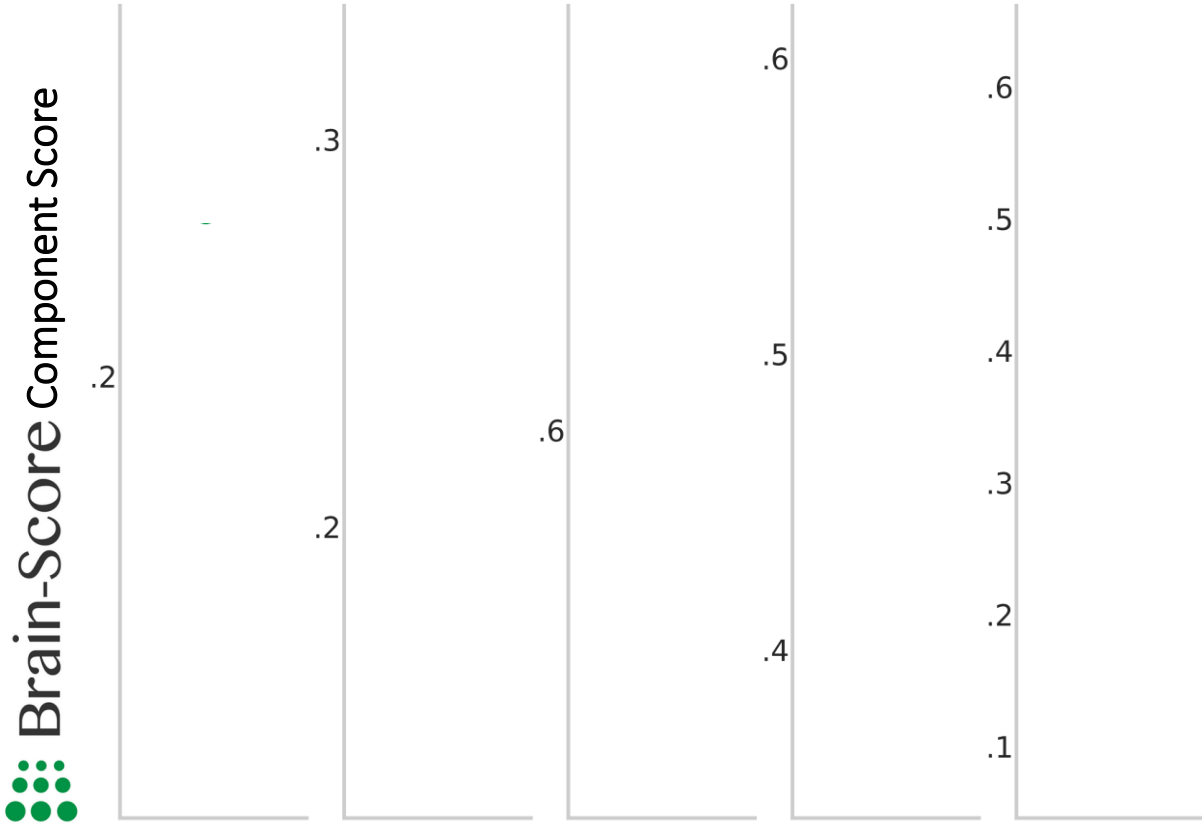
decoder

Base Models

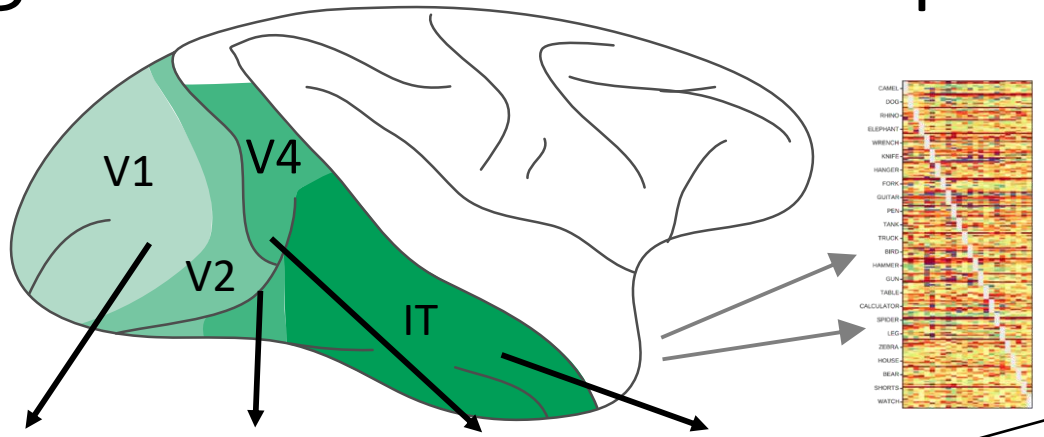
Large-scale model comparison on Brain-Score

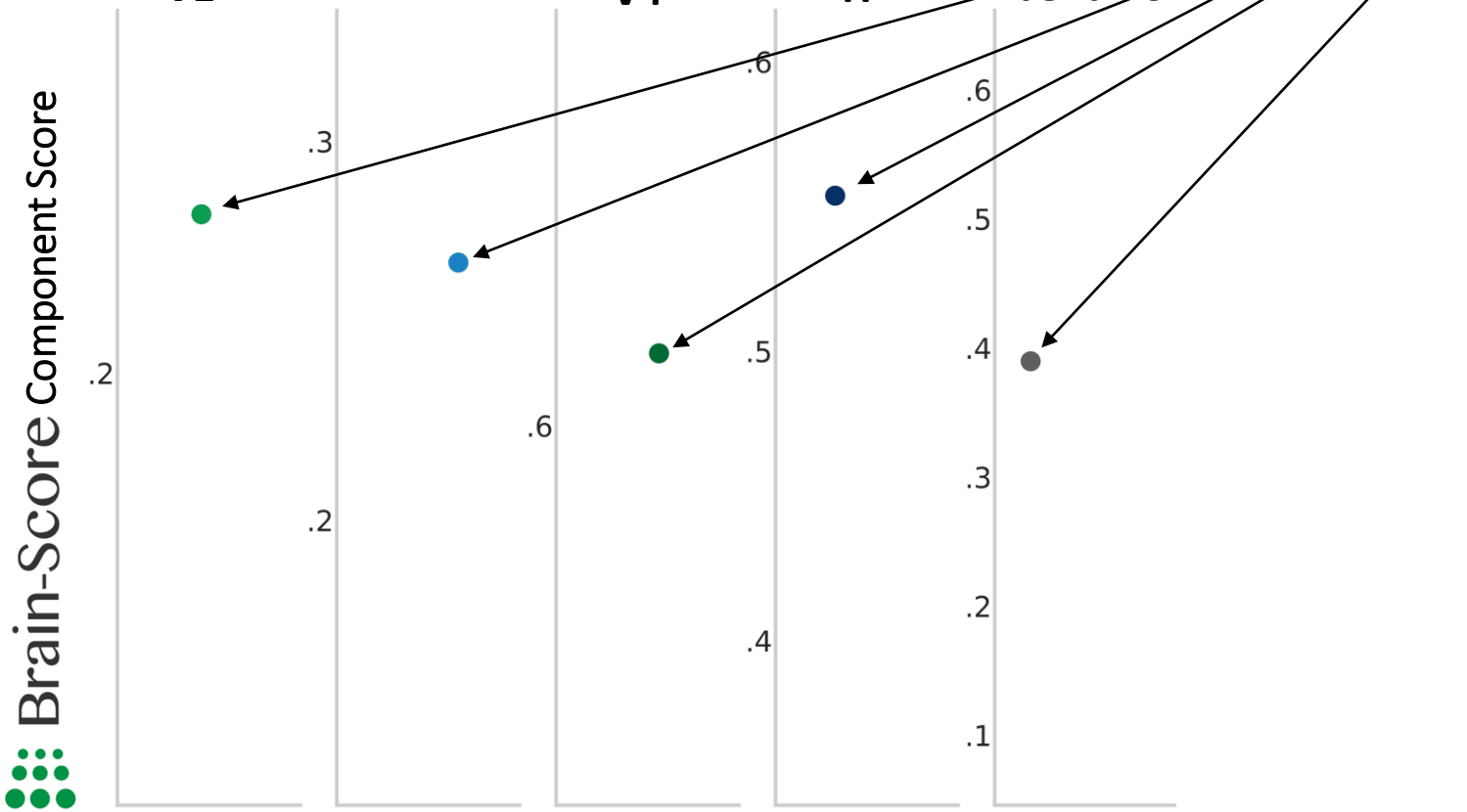


V1 V2 V4 IT behavior



Large-scale model comparison on Brain-Score



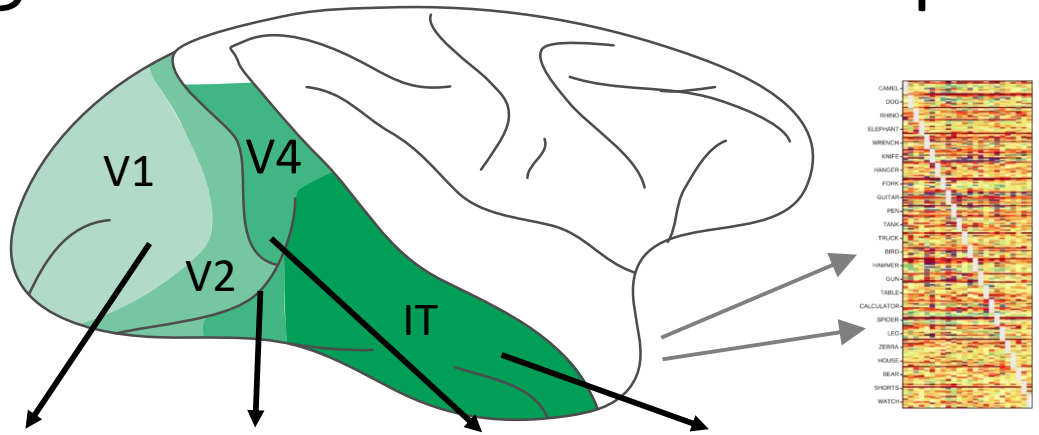


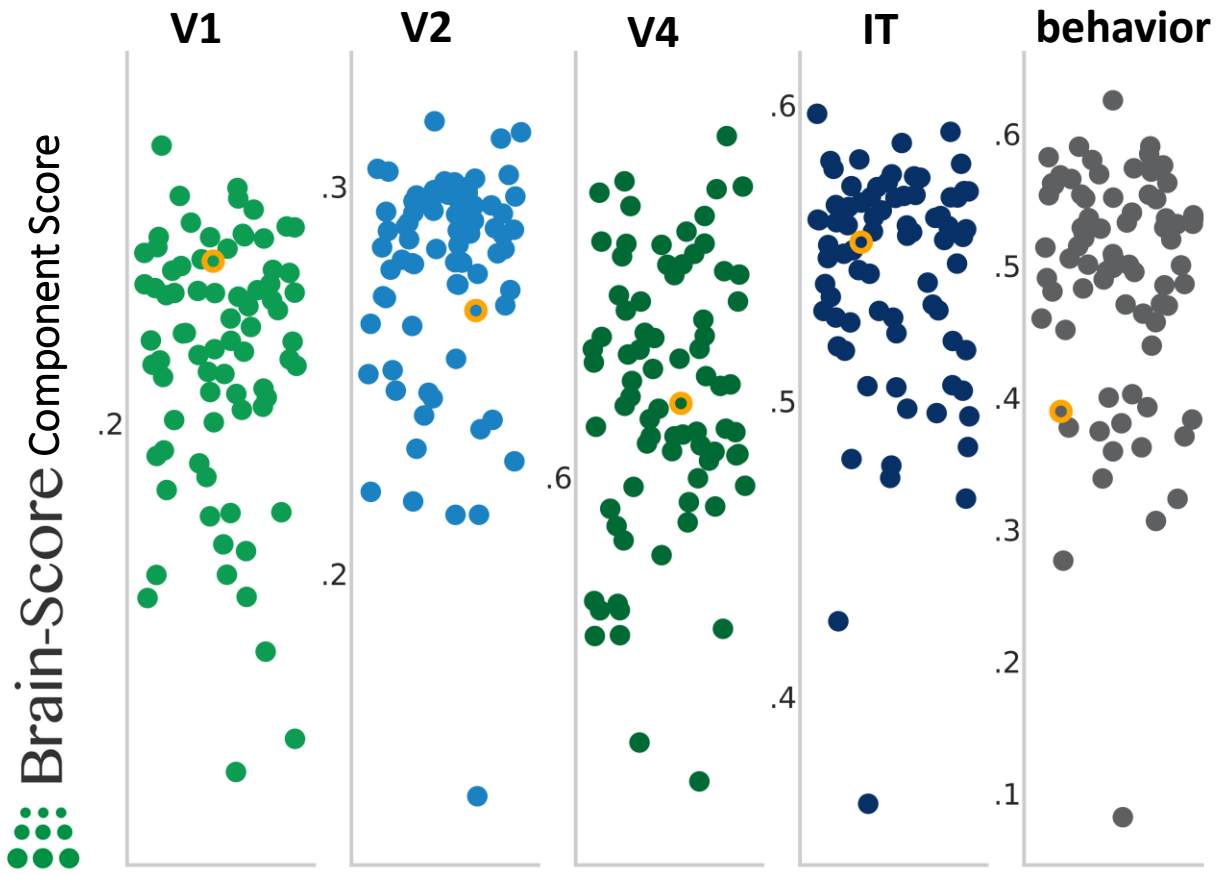
Brain Base-Model* Candidates tested:

alexnet

*translated into a “Brain Model”:
- assign layers to regions
- assign pixels to visual degrees
- …

Large-scale model comparison on Brain-Score





Brain Base-Model* Candidates tested:

alexnet

vgg-16
vgg-19
densenet-121
densenet-169
densenet-201
inception_resnet_v2
inception_v1
inception_v2
inception_v3
inception_v4
mobilenet_v1_0.25_128
mobilenet_v1_0.25_160
mobilenet_...
mobilenet_v2_1.3_224
mobilenet_v2_1.4_224

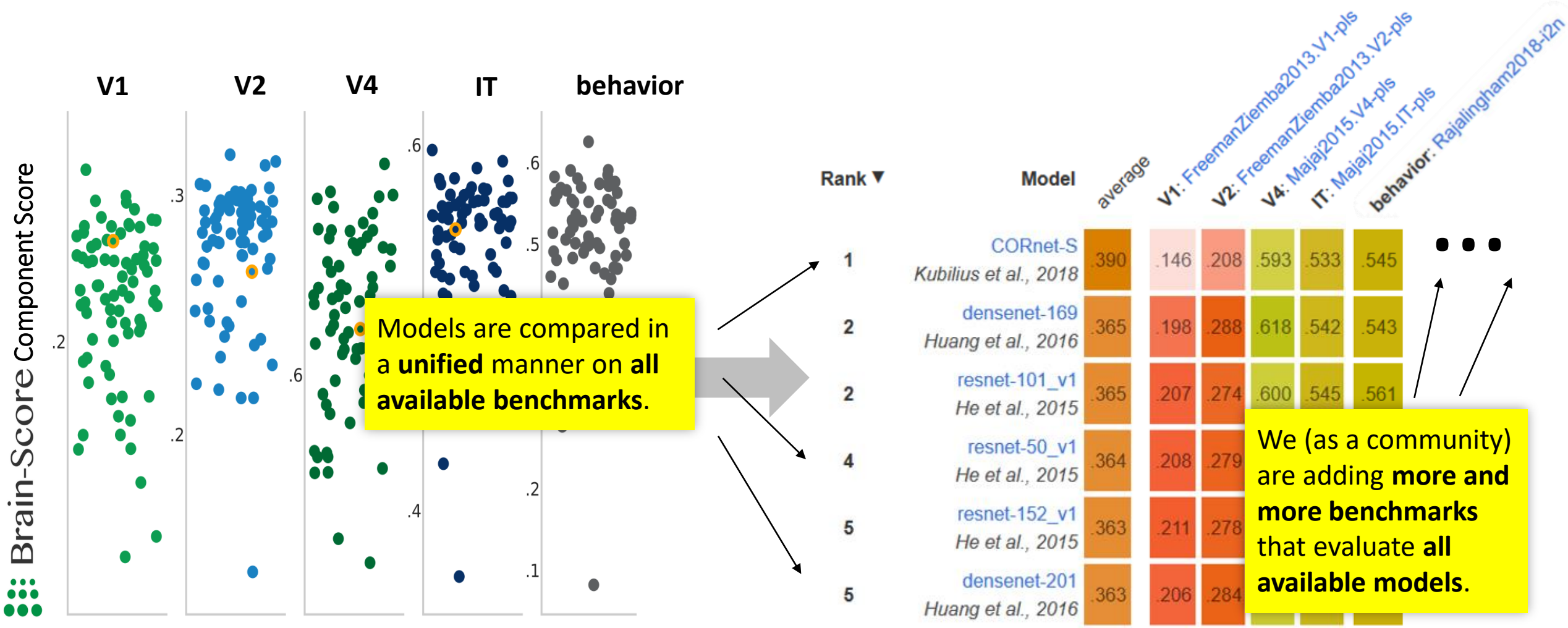
nasnet_large
nasnet_mobile
pnasnet_large
resnet-101_v1
resnet-101_v2
resnet-152_v1
resnet-152_v2
resnet-18
resnet-34
resnet-50_v1
resnet-50_v2
squeezenet1_0
squeezenet1_1
xception
...

*translated into a "Brain Model":
- assign layers to regions
- assign pixels to visual degrees
- ...

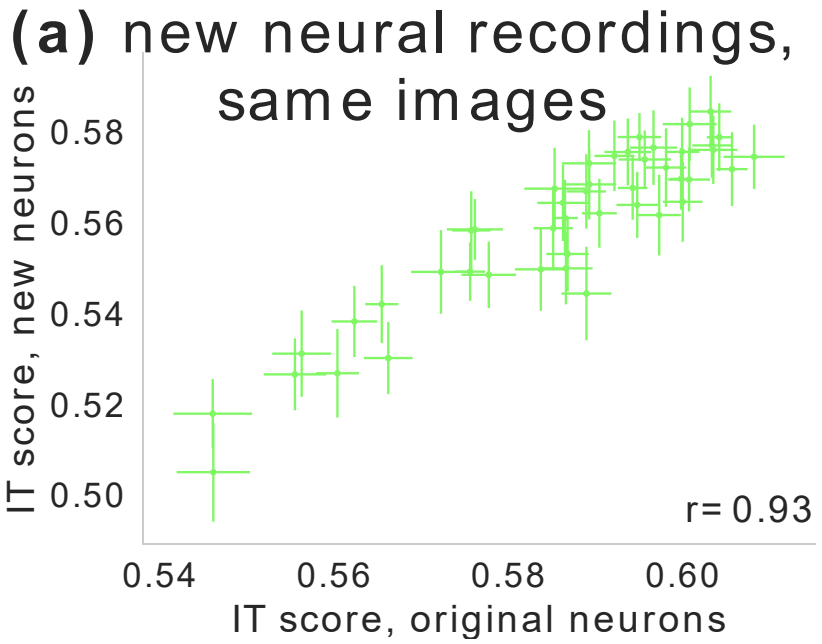
Brain-Score: Integrative Benchmarking

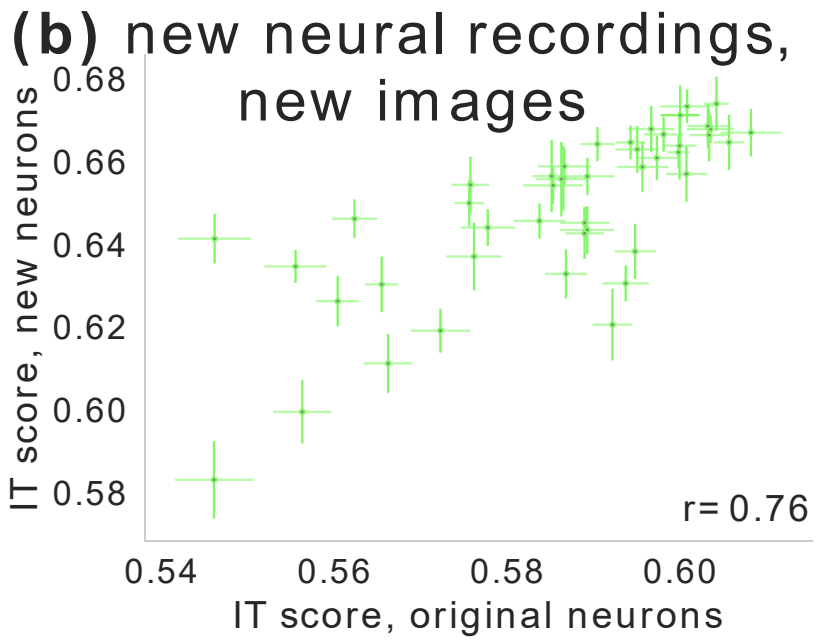
Brain-Score Leaderboard About Compare Participate

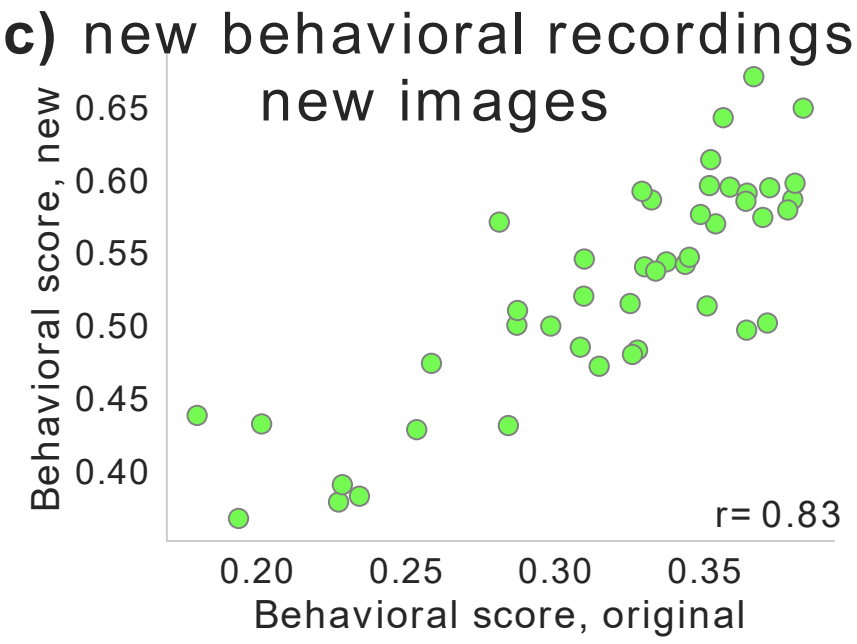
www.Brain-Score.org



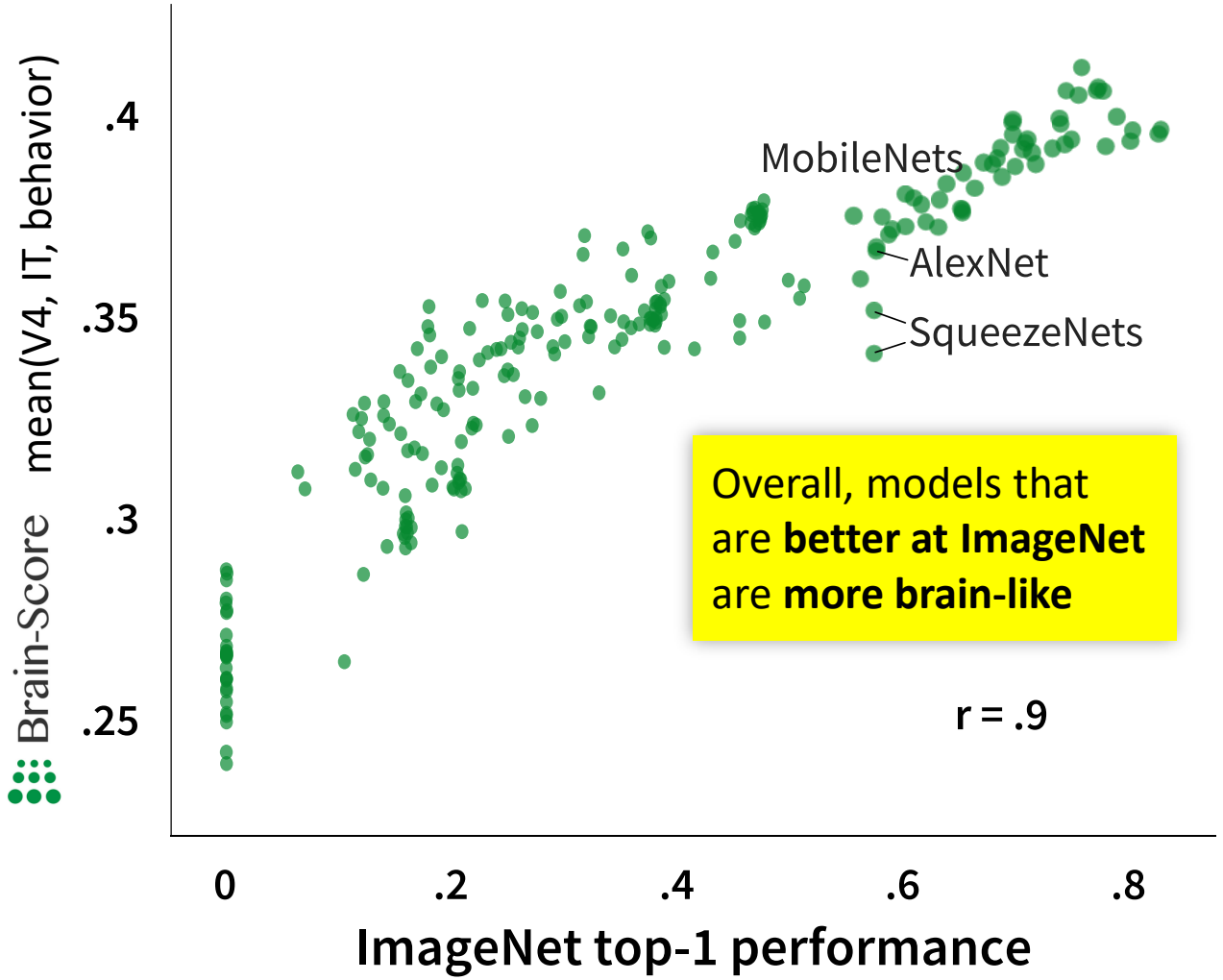
Scores generalize across subjects and stimuli



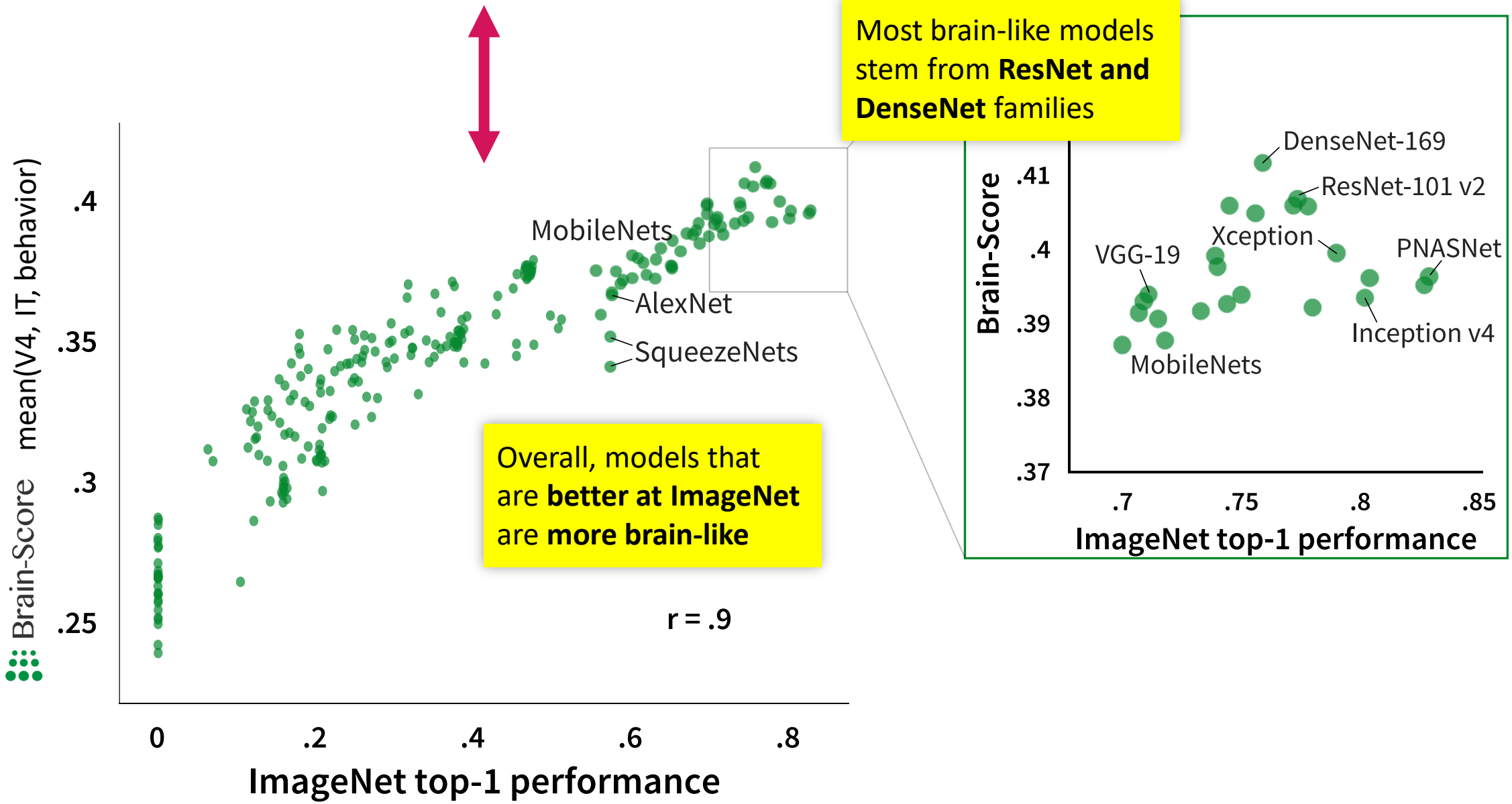




Task performance correlates with Brain-Score



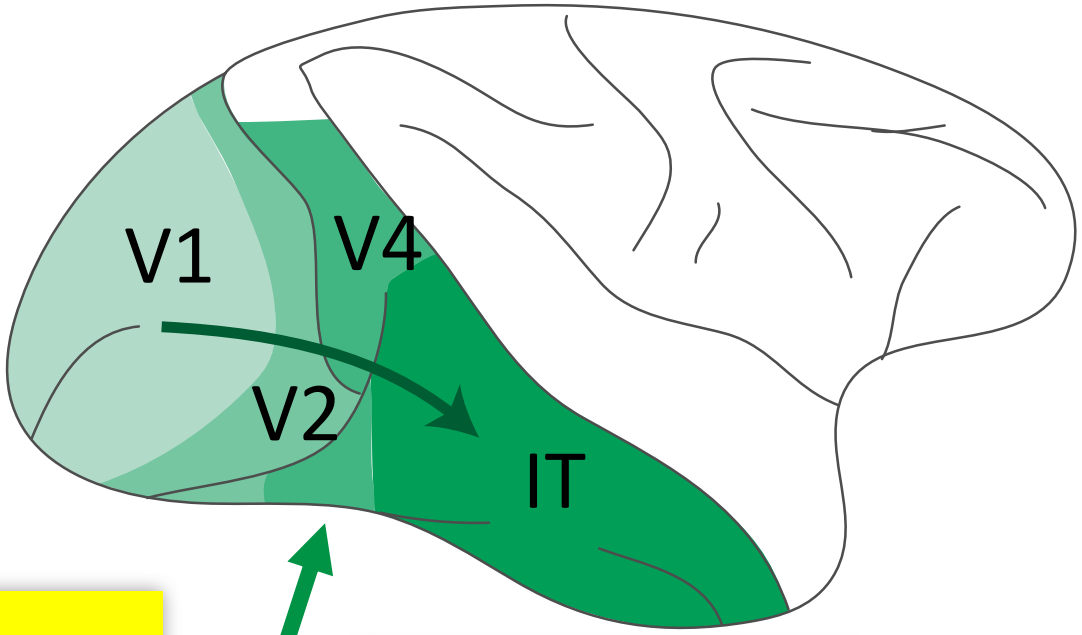
Task performance correlates with Brain-Score



- Organizes brain measurements into quantitative benchmarks
- Embraces *all* models, regardless of complexity
- Shows that some NNs are first brain approximations, but are also not there yet

Schrimpf, Kubilius*, et al. (bioRxiv 2018)*

Model-Brain mismatch: two problems



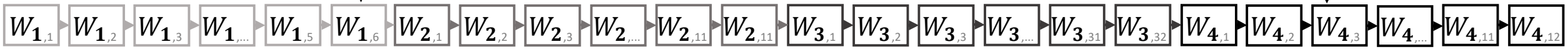
1. difficult to map anatomy

2. no temporal responses

e.g. ResNet-101

V4?

IT?



Solution: recurrence to re-use weights

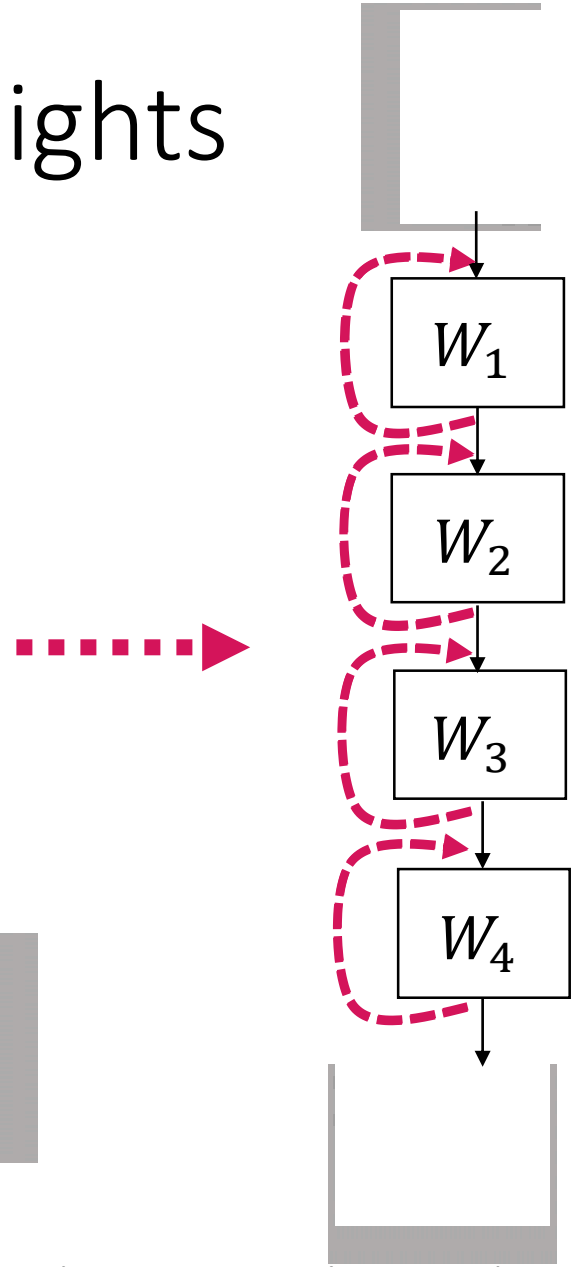
input

$W_{1,1}$ $W_{1,2}$ $W_{1,3}$ $W_{1,\dots}$ $W_{1,5}$ $W_{1,6}$

$W_{2,1}$ $W_{2,2}$ $W_{2,3}$ $W_{2,\dots}$ $W_{2,11}$ $W_{2,11}$

$W_{3,1}$ $W_{3,2}$ $W_{3,3}$ $W_{3,\dots}$ $W_{3,31}$ $W_{3,32}$

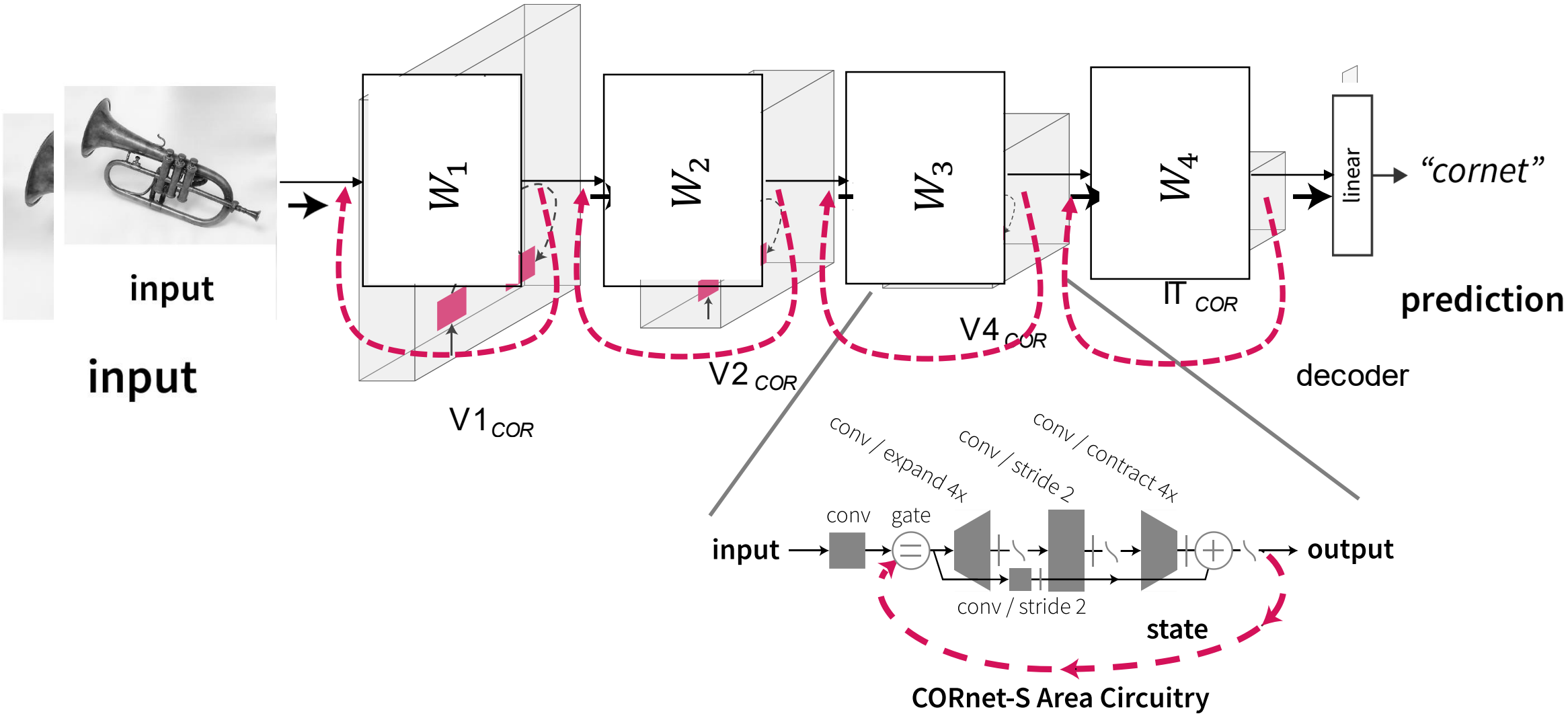
$W_{4,1}$ $W_{4,2}$ $W_{4,3}$ $W_{4,\dots}$ $W_{4,11}$ $W_{4,12}$



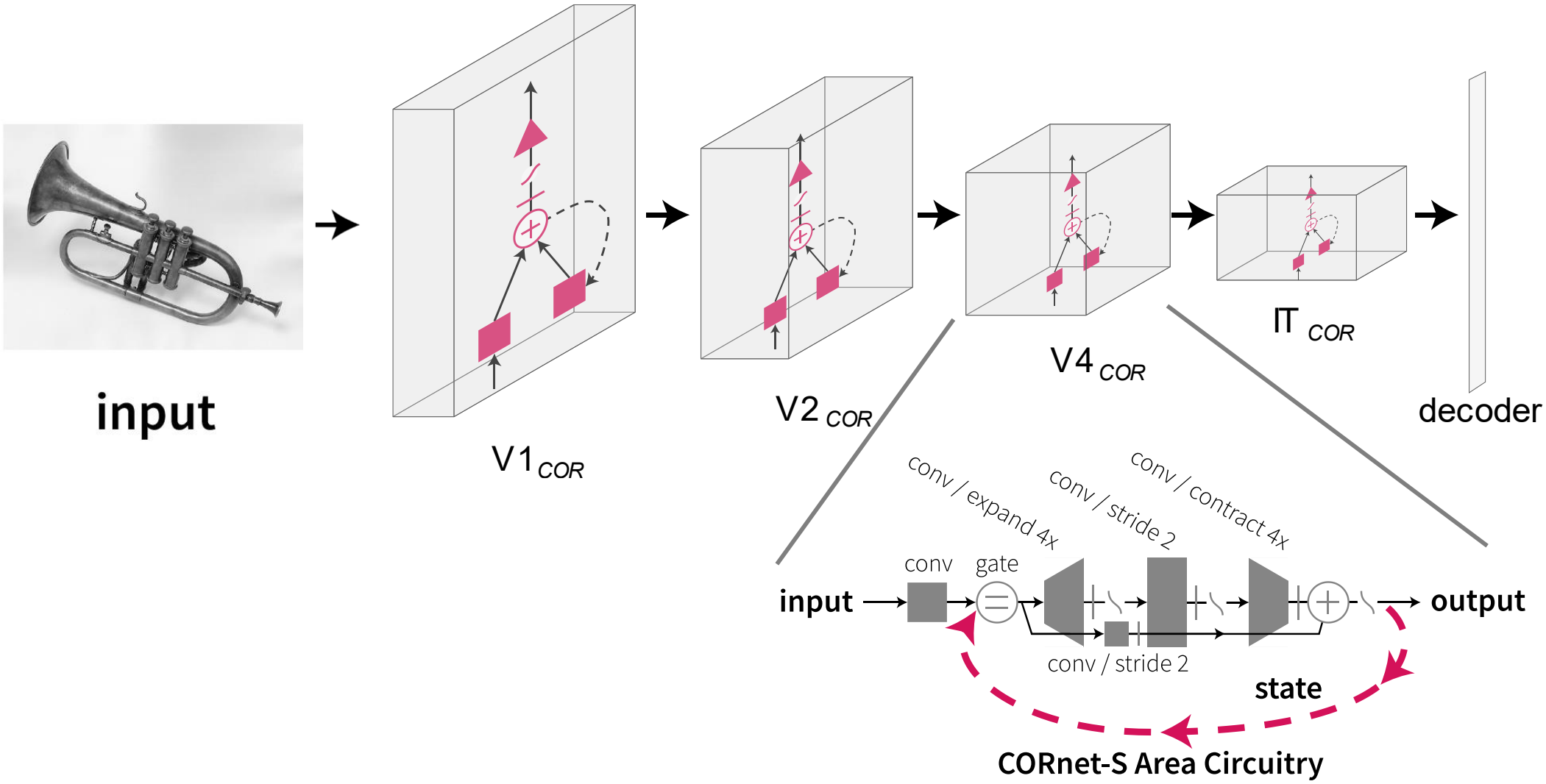
e.g. He, Zhang, Ren, Sun (CVPR 2016)
Huang, Liu, van der Maaten, Weinberger (CVPR 2017)

Liang & Hu (CVPR 2015) Liao & Poggio (arXiv 2016) Tang, Schrimpf*, Lotter* et al. (PNAS 2018) Nayebi*, Bear*, Kubilius* et al. (NIPS 2018)*

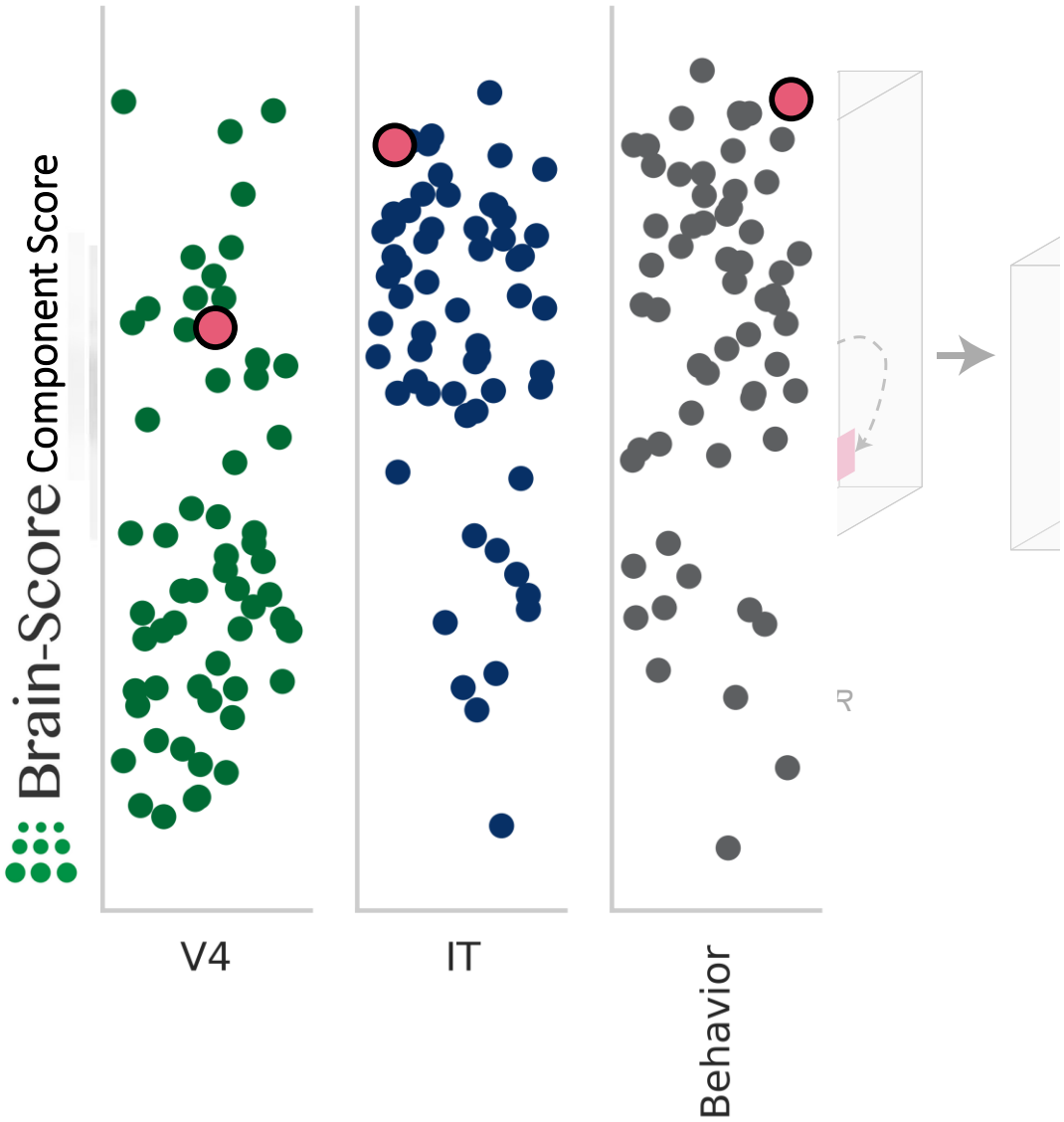
CORnet-S: shallow and recurrent



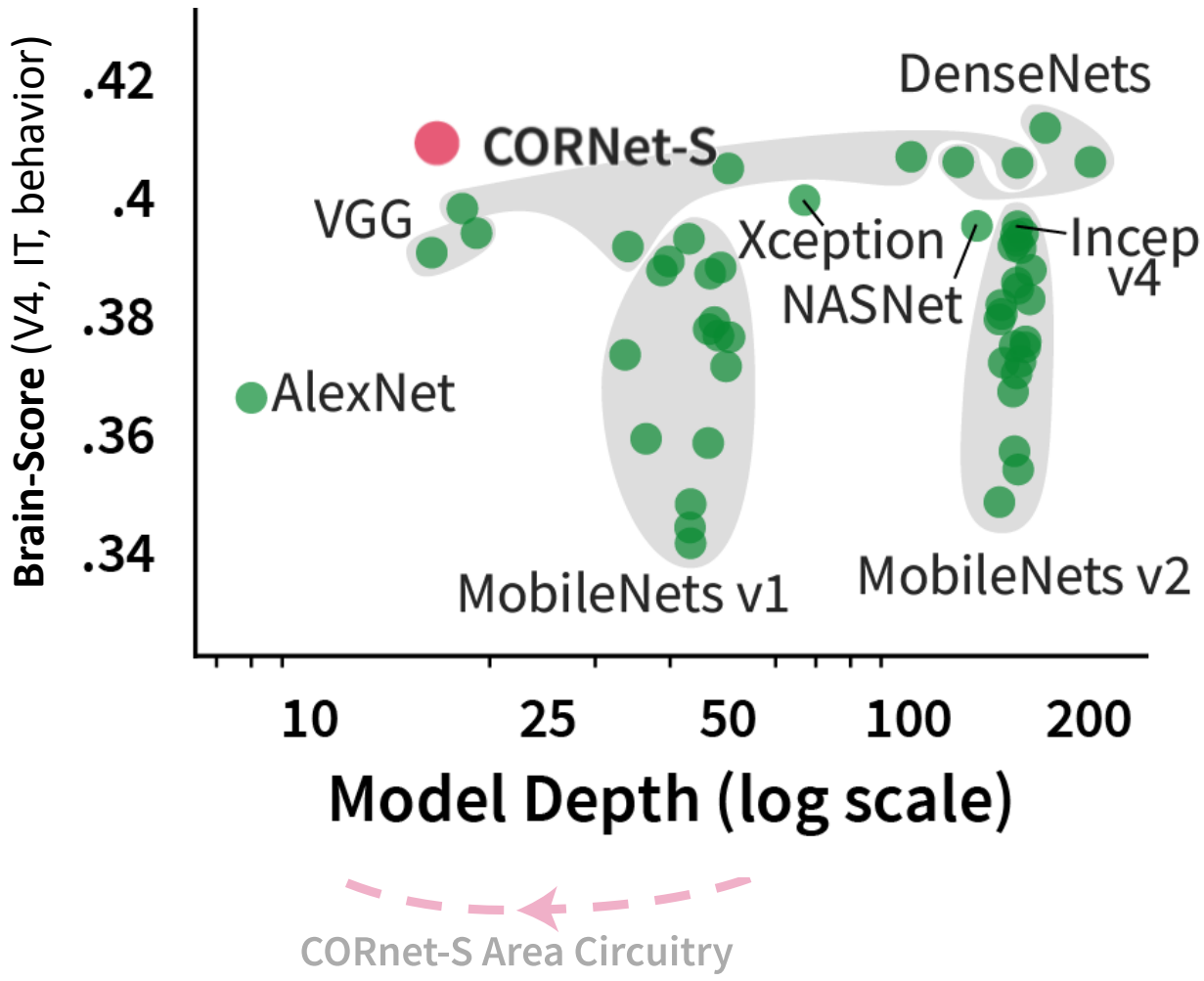
CORnet-S: shallow and recurrent



CORnet-S: shallow and recurrent rivals deep networks

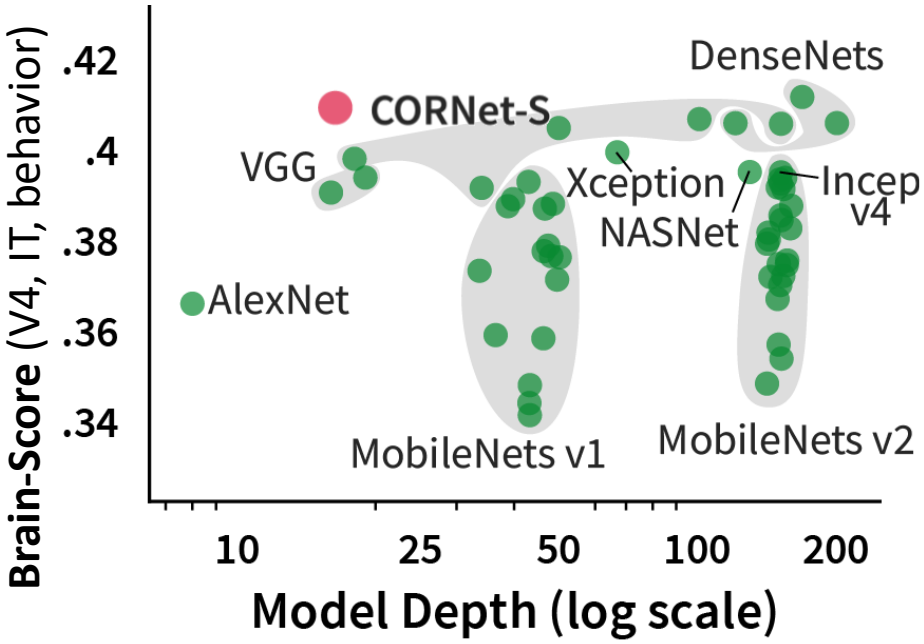


Brain-Score: ✓

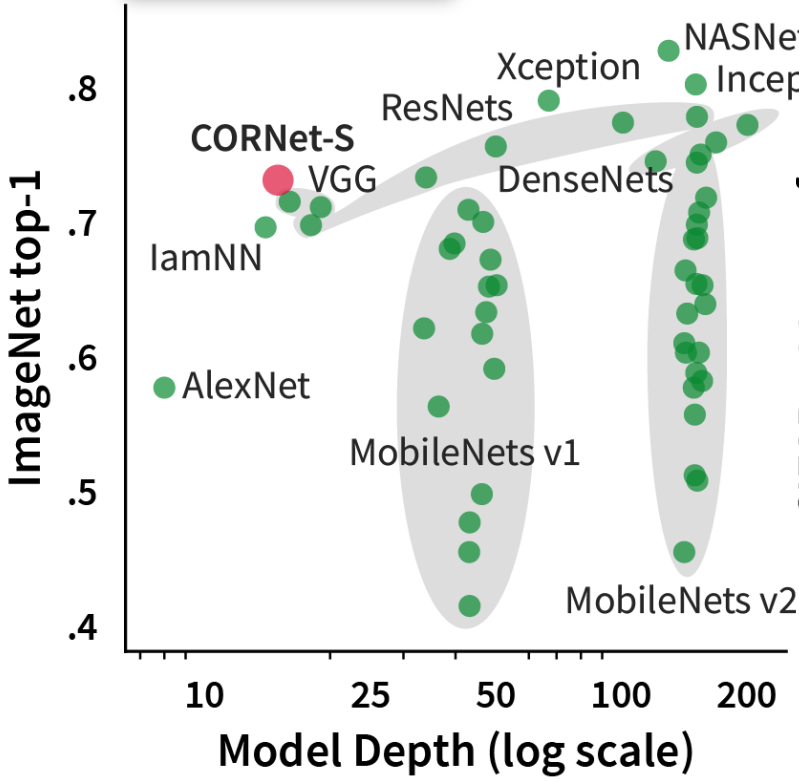


CORnet-S: shallow and recurrent rivals deep networks

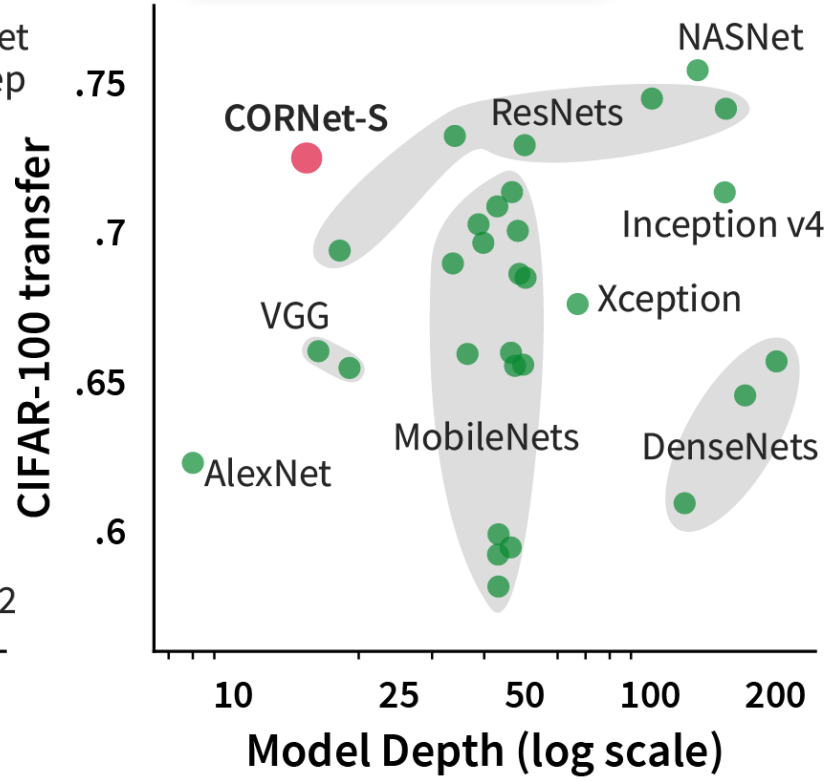
Brain-Score: ✓



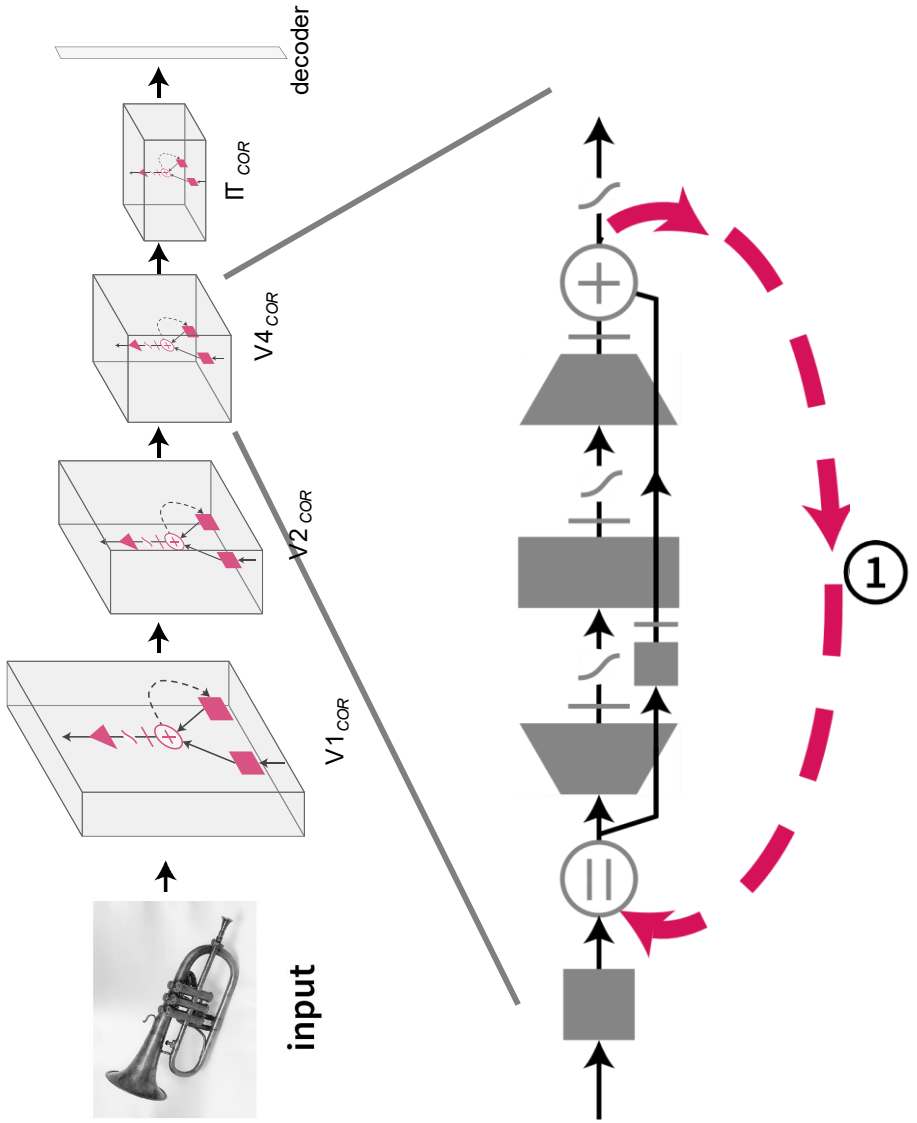
ImageNet: ✓



Generalization: +

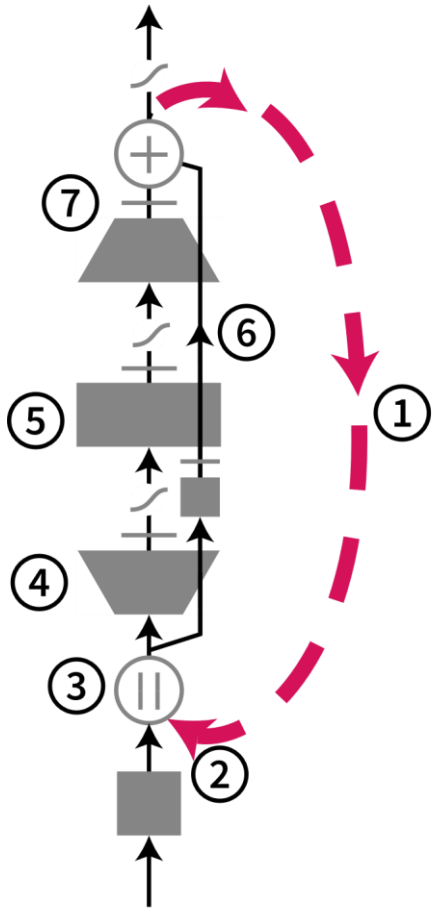


Driving factors for CORnet-S' performance



① Number of recurrent steps in V2 / V4 / IT	Δ ImageNet top-1, %	Δ Brain-Score, %
no recurrence (1/1/1)	-7	-3
2/2/2	-1	0
2/4/2	-	-
4/4/4	0	0
4/8/4	0	0
10/10/10	0	0

Driving factor for CORnet-S' performance: recurrence

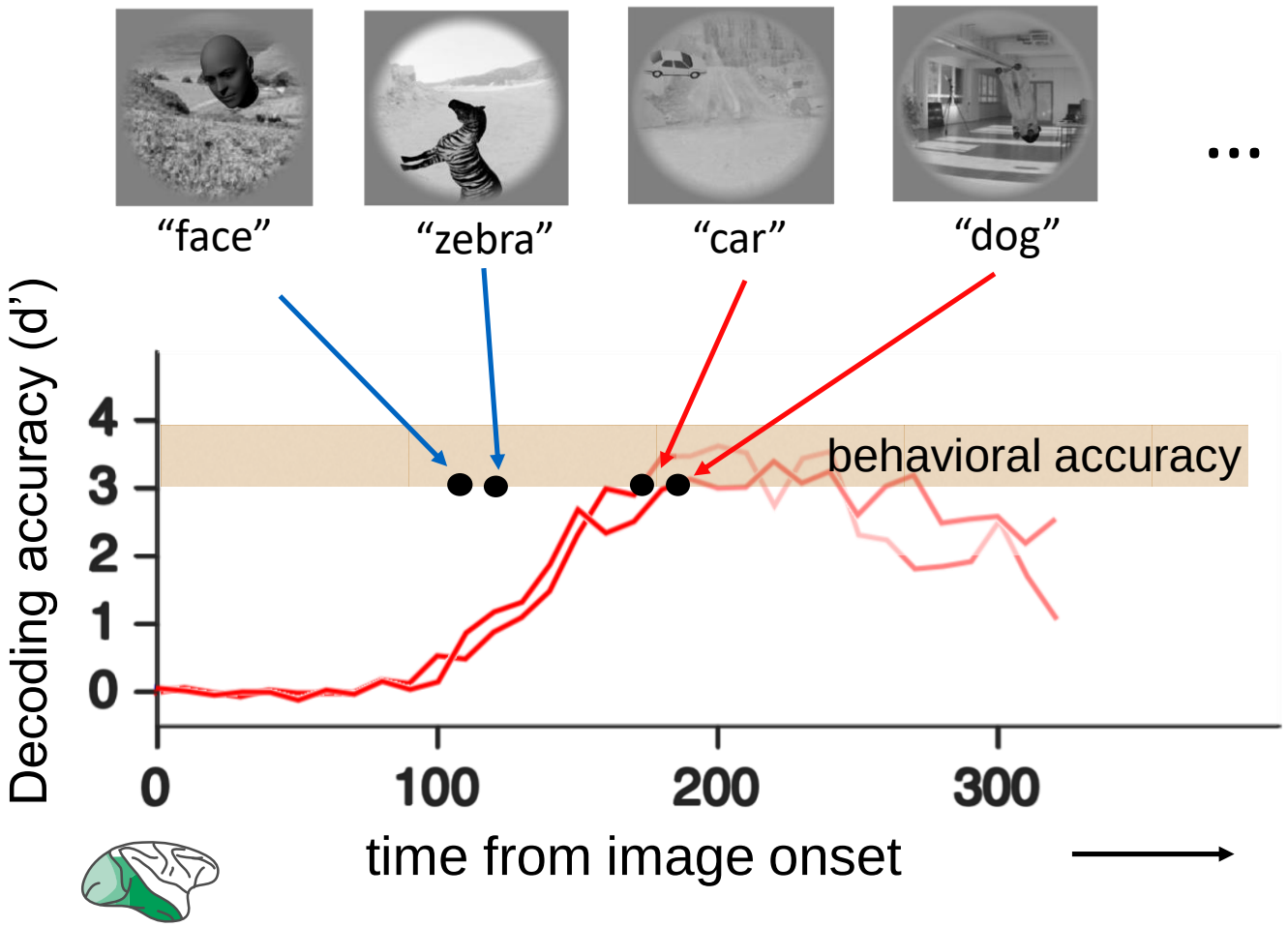


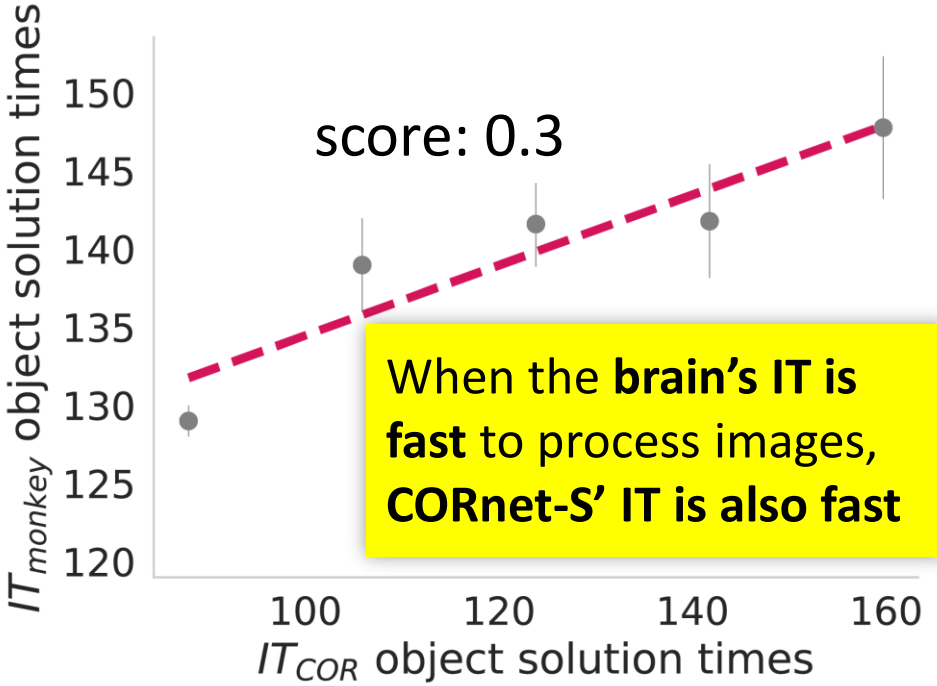
	Δ ImageNet top-1, %	Δ Brain-Score, %
① Number of recurrent steps in V2 / V4 / IT		
no recurrence (1/1/1)	-7	-3
2/2/2	-1	0
2/4/2	-	-
4/4/4	0	0
4/8/4	0	0
10/10/10	0	0
② Recurrent loop length		
from 3 to 1	-	-
from 3 to 2	-2	0

	Δ ImageNet top-1, %	Δ Brain-Score, %
③ Gating		
hard gate: input blocked at t > 0	-	-
soft gate: *sigmoid*(input + state)	0	0
④ Bottleneck size		
1x	-8	-1
2x	-4	-1
4x	-	-
6x	+1	0
⑤ Convolutional layers		
2nd and 3rd	-3	0
1st, 2nd, and 3rd	-	-

	Δ ImageNet top-1, %	Δ Brain-Score, %
⑥ Skip connection		
present	-	-
absent	-2	-1
⑦ Normalization		
Batch Normalization	-	-
Group Normalization	-1	0
Number of model areas		
4	-	-
5	-1	0

Stronger test of recurrence: temporal dynamics





When the **brain's IT is fast** to process images, **CORnet-S' IT is also fast**

Unlike feedforward models, CORnet-S can **predict neural responses over time**.

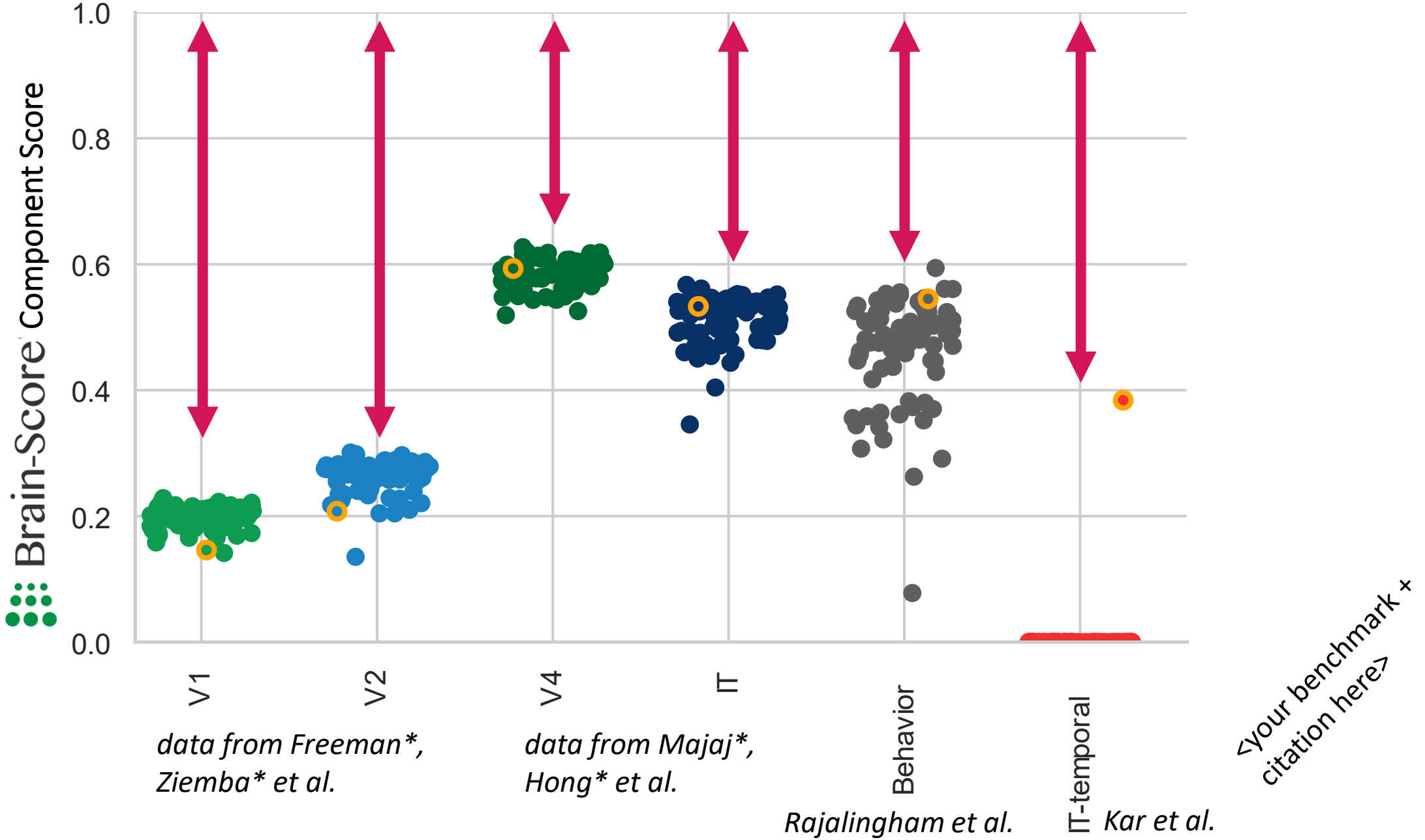
Kar, Kubilius, Schmidt, Issa, DiCarlo (Nature Neuroscience 2019)

CORnet-S

- Is more shallow than comparable models
- Maintains high performance through recurrent processing
- Predicts temporal dynamics in the brain's ventral stream

Kubilius, Schrimpf*, et al. (NeurIPS 2019)*

Lots of work to do

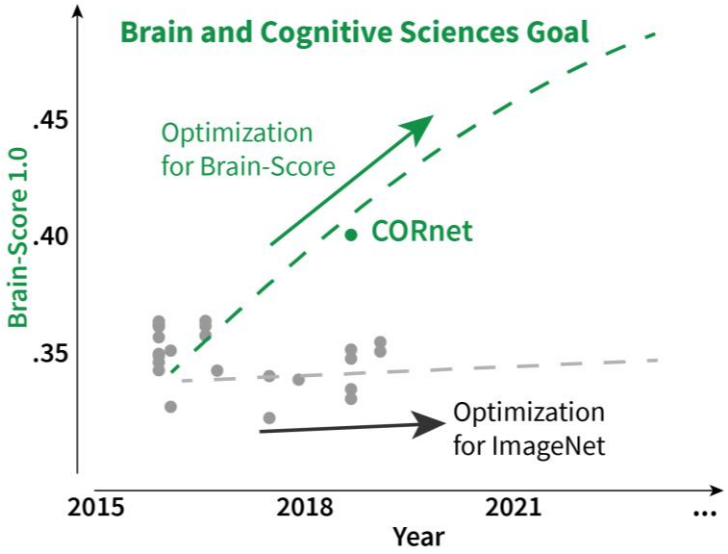


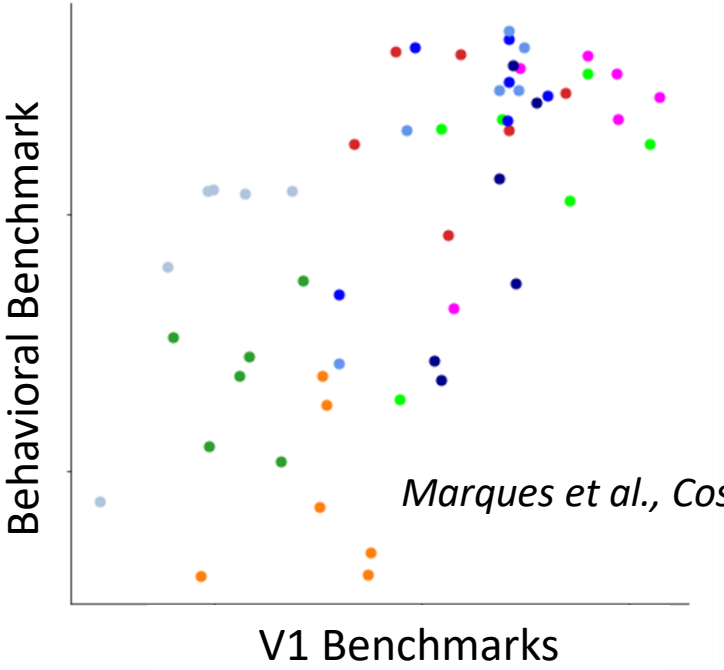
What we hope Brain-Score will enable

1. **Build ever more accurate models of the brain**

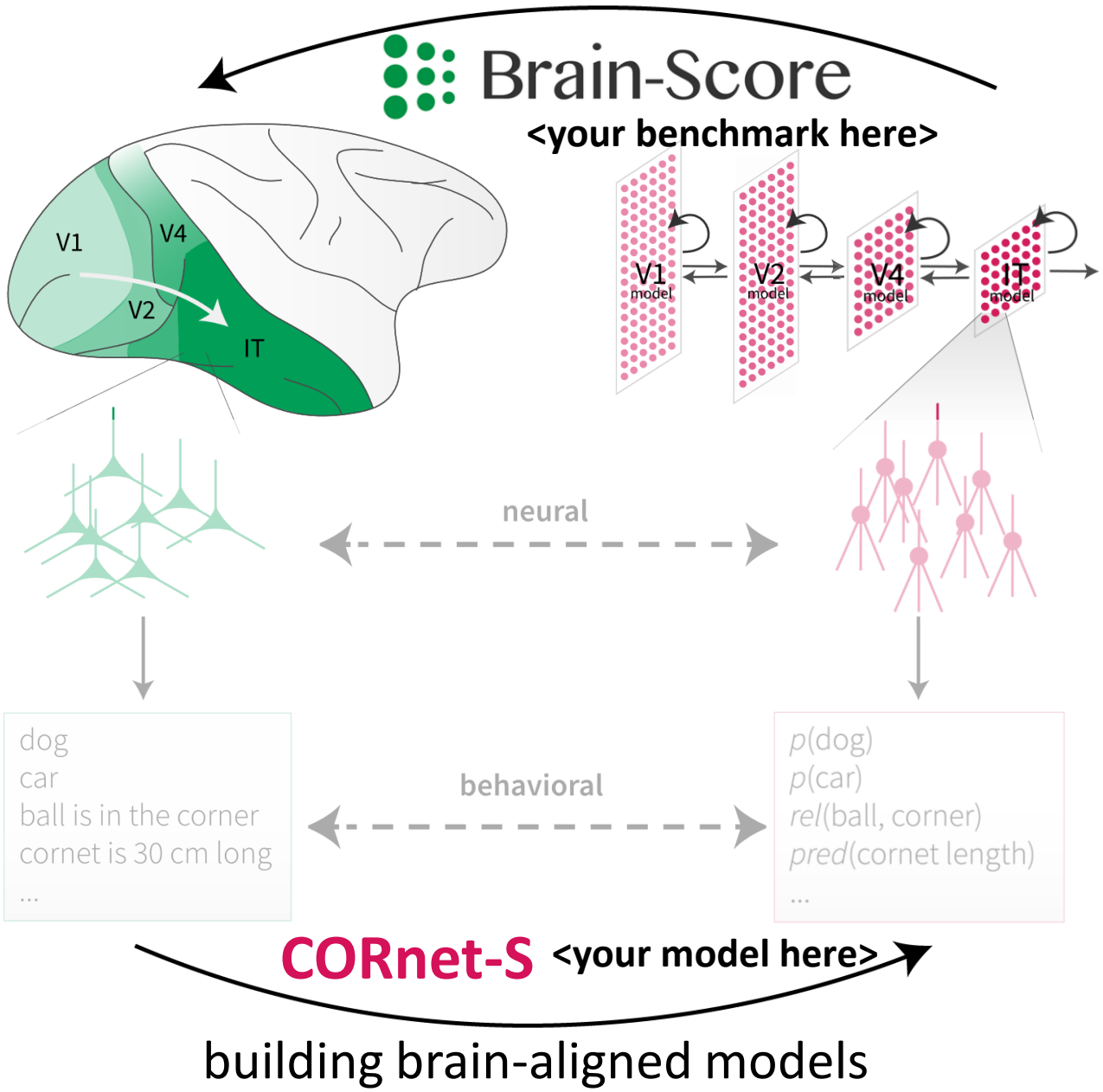
2. **Relate brain benchmarks to one another.**
   E.g. improve V1 component of model
   → improve behavior

3. **Relate brain benchmarks to engineering desiderata**
   E.g. more brain-like
   → improved energy efficiency





Marques et al., Cosyne 2020



Schrimpf, Kubilius*, et al. (bioRxiv 2018)*

Kubilius, Schrimpf*, et al. (NeurIPS 2019)*

github.com/dicarlolab/neurips2019

github.com/dicarlolab/cornet

Brain-Score.org

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