Feedforward theories of visual cortex predict human performance in rapid image categorization

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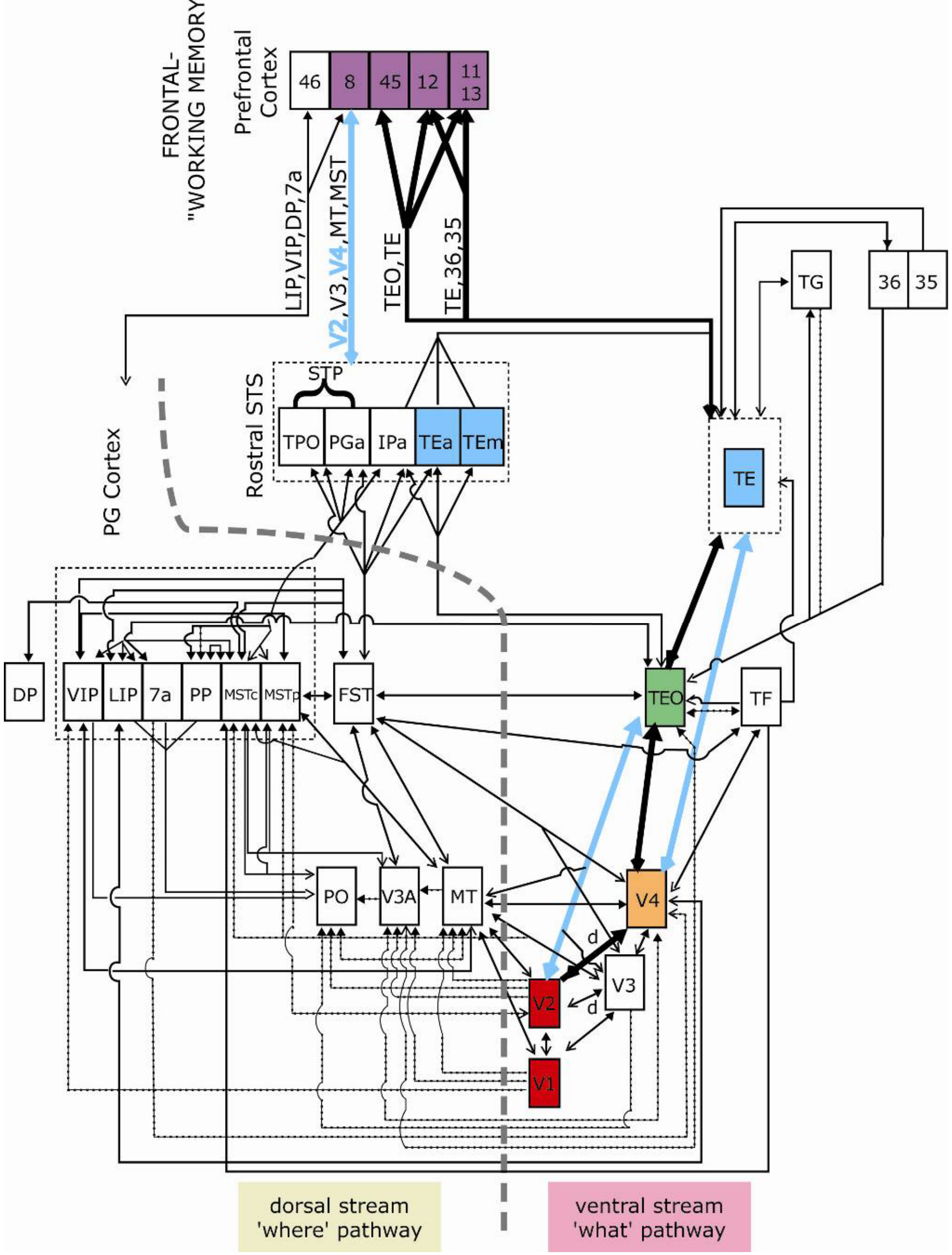
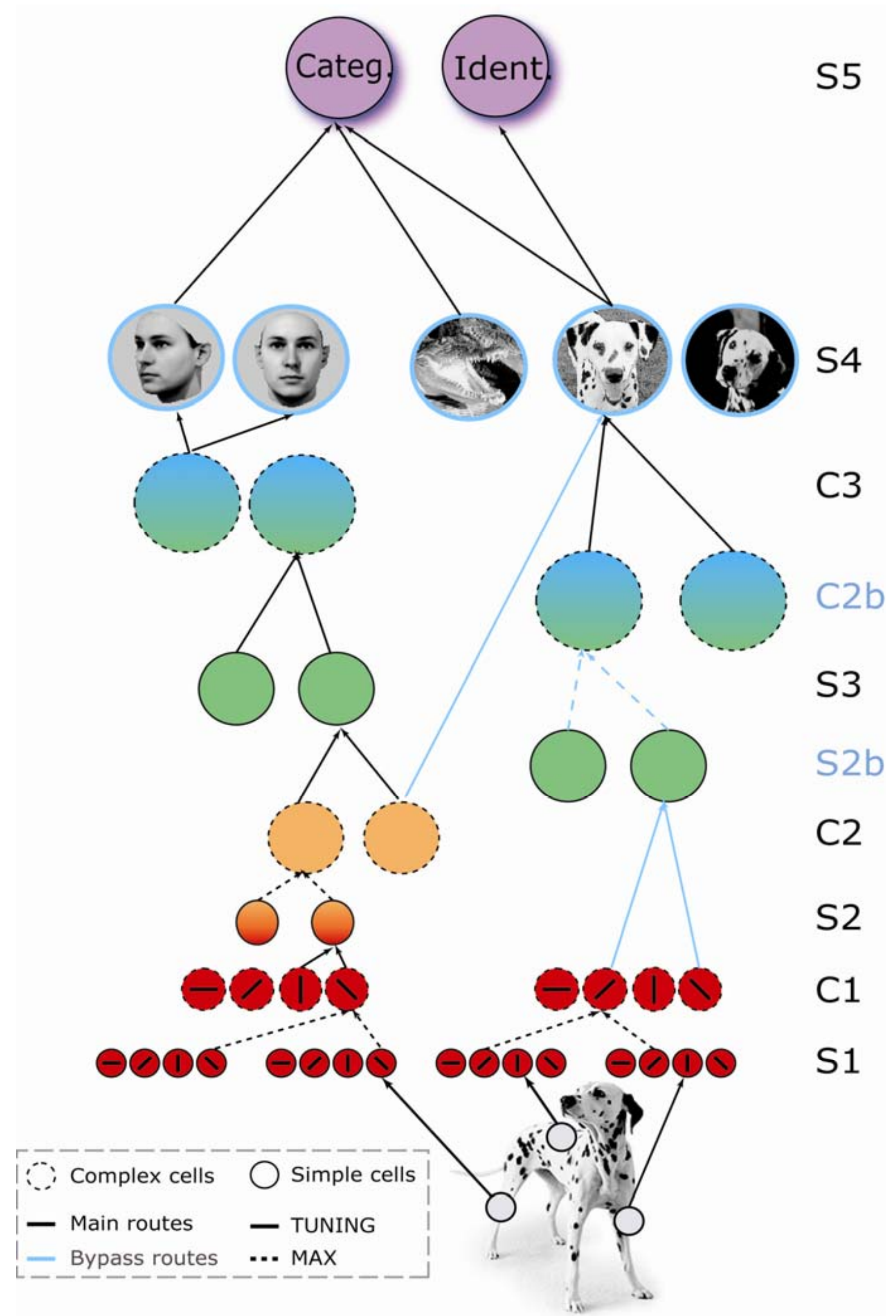


Modified from (Ungerleider & VanEssen)

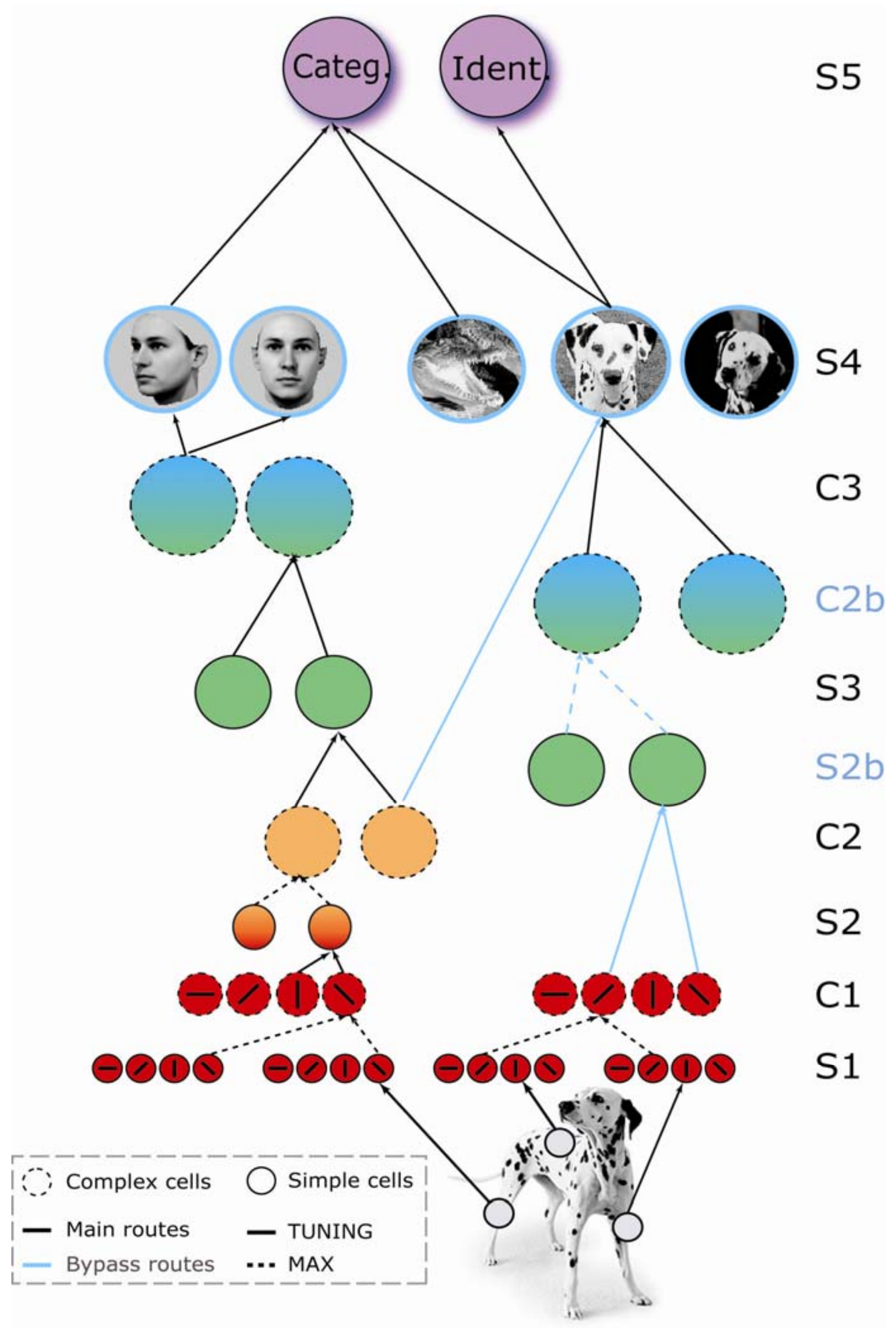


- **Builds upon previous neurobiological models**
  (Hubel & Wiesel, 1959; Fukushima, 1980; Oram & Perrett, 1993, Wallis & Rolls, 1997; Riesenhuber & Poggio, 1999)

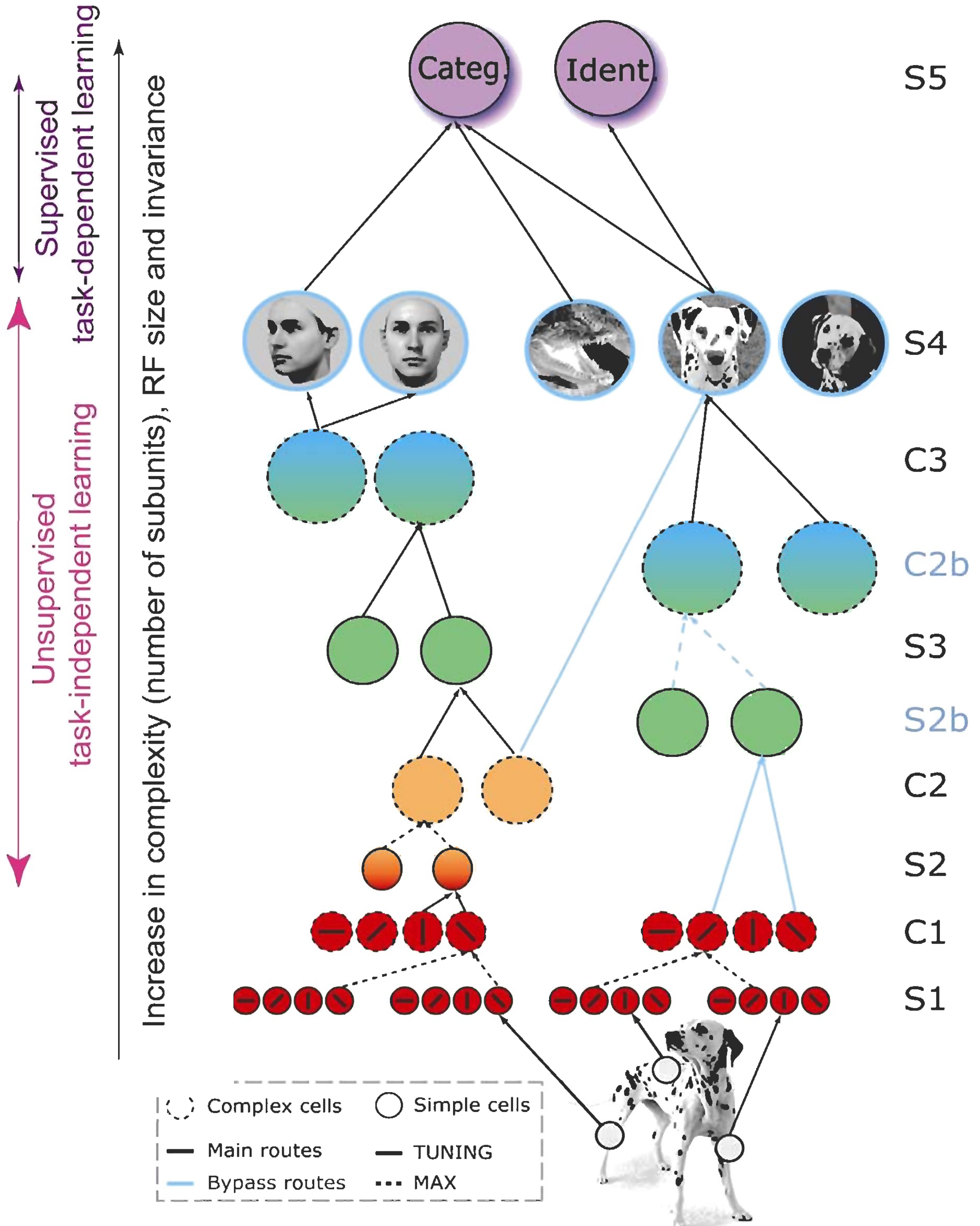
- **General class of feedforward hierarchical models of object recognition in cortex**

- **Biophysically plausible operations**

- **Predicts several properties of cortical neurons**
  (Serre, Kouh, Cadieu, Knoblich, Kreiman, Poggio, 2005)

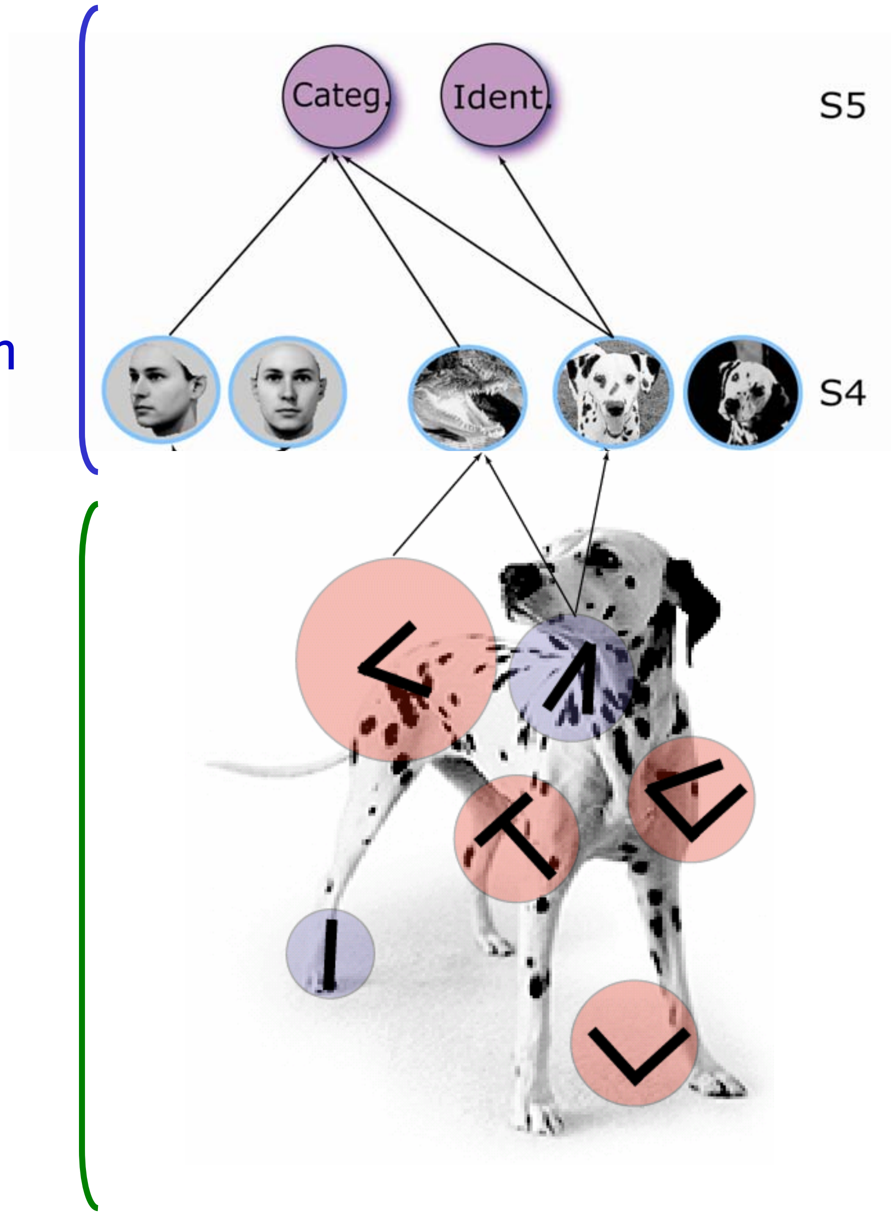


Model layers	Corresponding brain area (tentative)	RF sizes	Number units	
classifier	PFC		$1.0 \; 10^0$	
S4	AIT	$>4.4^o$	$1.5 \; 10^2$	~ 5,000 subunits
C3	PIT - AIT	$>4.4^o$	$2.5 \; 10^3$	
C2b	PIT	$>4.4^o$	$2.5 \; 10^3$	
S3	PIT	1.2^o- 3.2^o	$7.4 \; 10^4$	~ 100 subunits
S2b	V4 - PIT	0.9^o- 4.4^o	$1.0 \; 10^7$	~ 100 subunits
C2	V4	1.1^o- 3.0^o	$2.8 \; 10^5$	
S2	V2 - V4	0.6^o- 2.4^o	$1.0 \; 10^7$	~ 10 subunits
C1	V1 - V2	0.4^o- 1.6^o	$1.2 \; 10^4$	
S1	V1 - V2	0.2^o- 1.1^o	$1.6 \; 10^6$	

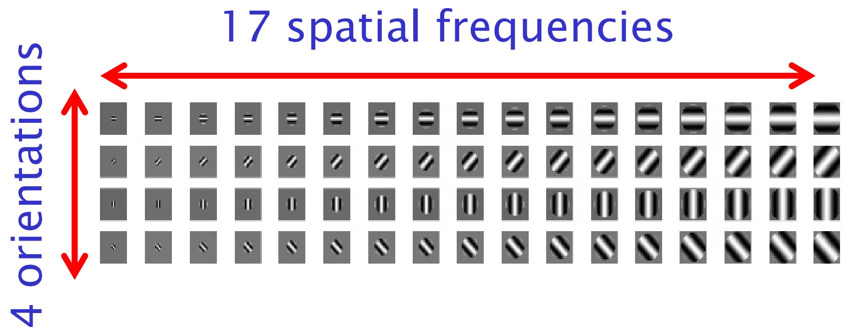


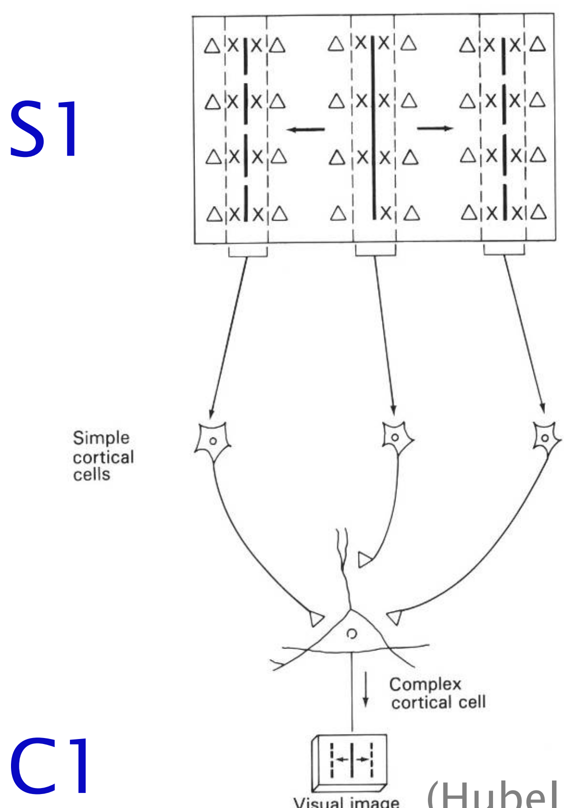
- Task-specific circuits (from IT to PFC)
  - Supervised learning
  - Linear classifier trained to minimize classification error on the training set (~ RBF net)

- Generic dictionary of shape components (from V1 to IT)
  - Unsupervised learning during developmental-like stage
  - From natural images unrelated to any categorization tasks

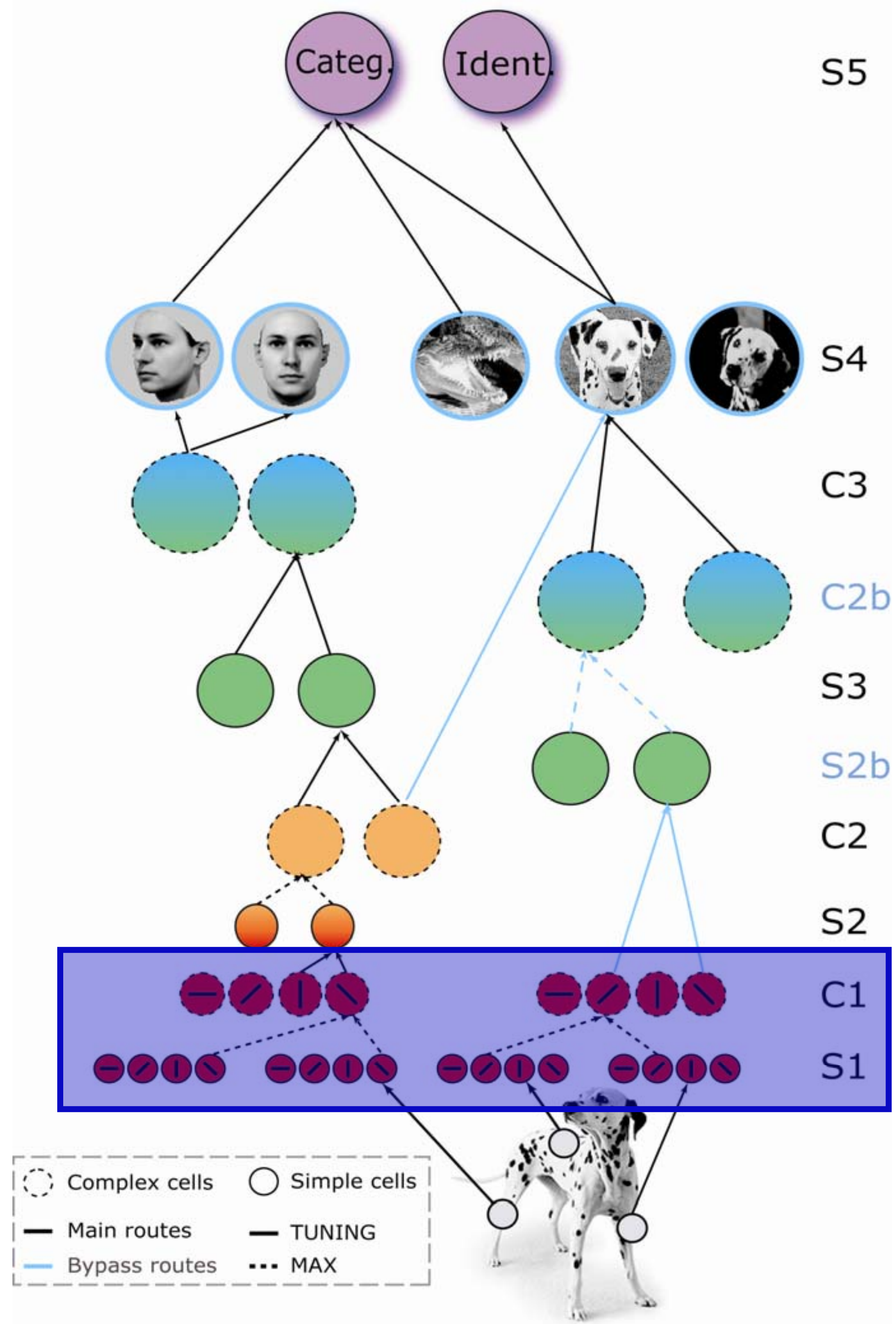


S1 and C1 units





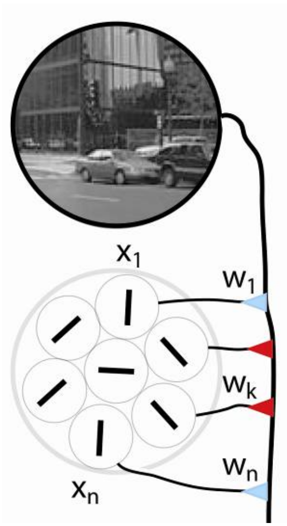
(Hubel & Wiesel, 1959)

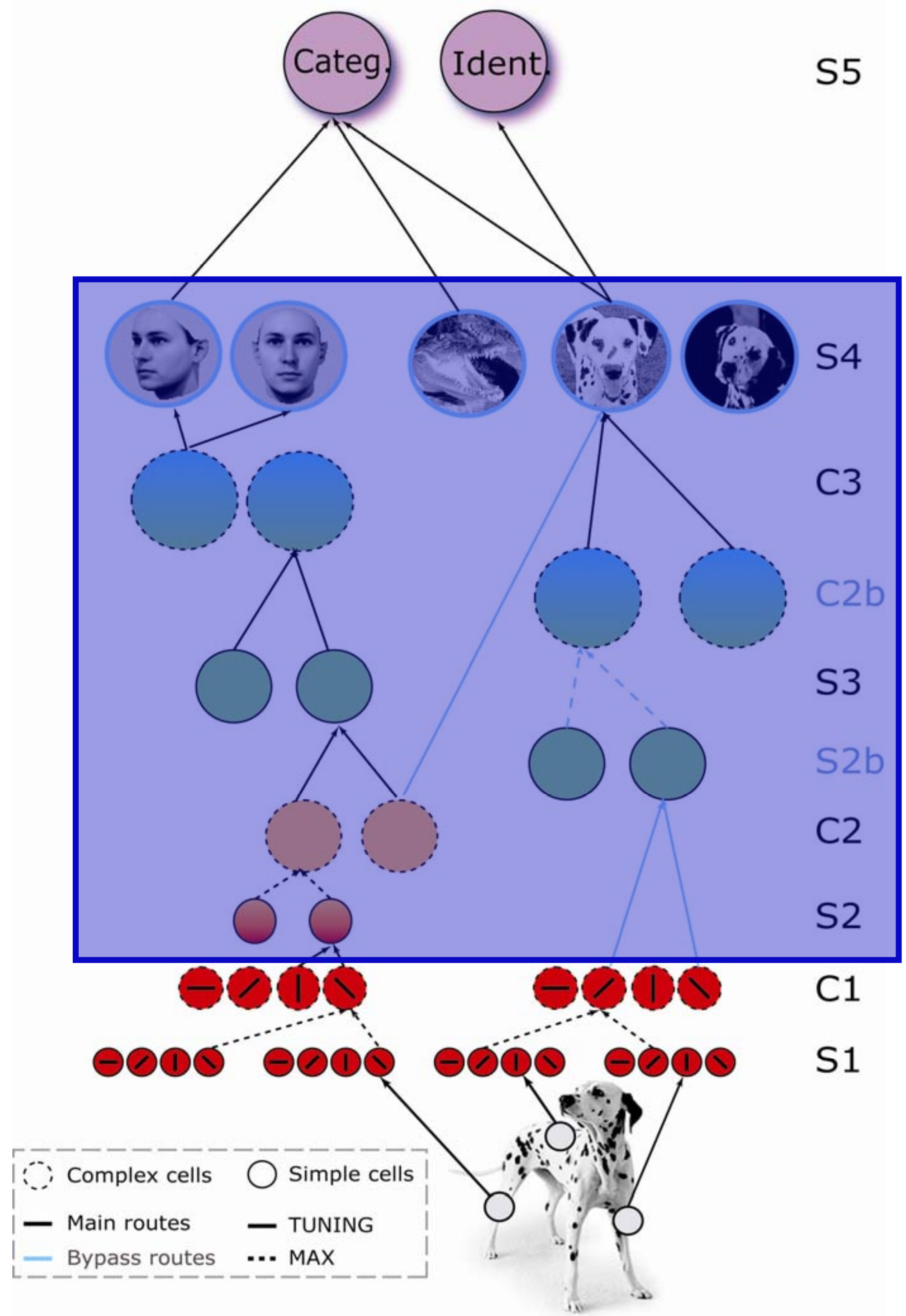


From S2 to S4

- Units are increasingly complex and invariant
- e.g, combination of V1-like complex units at different orientations

S2
unit

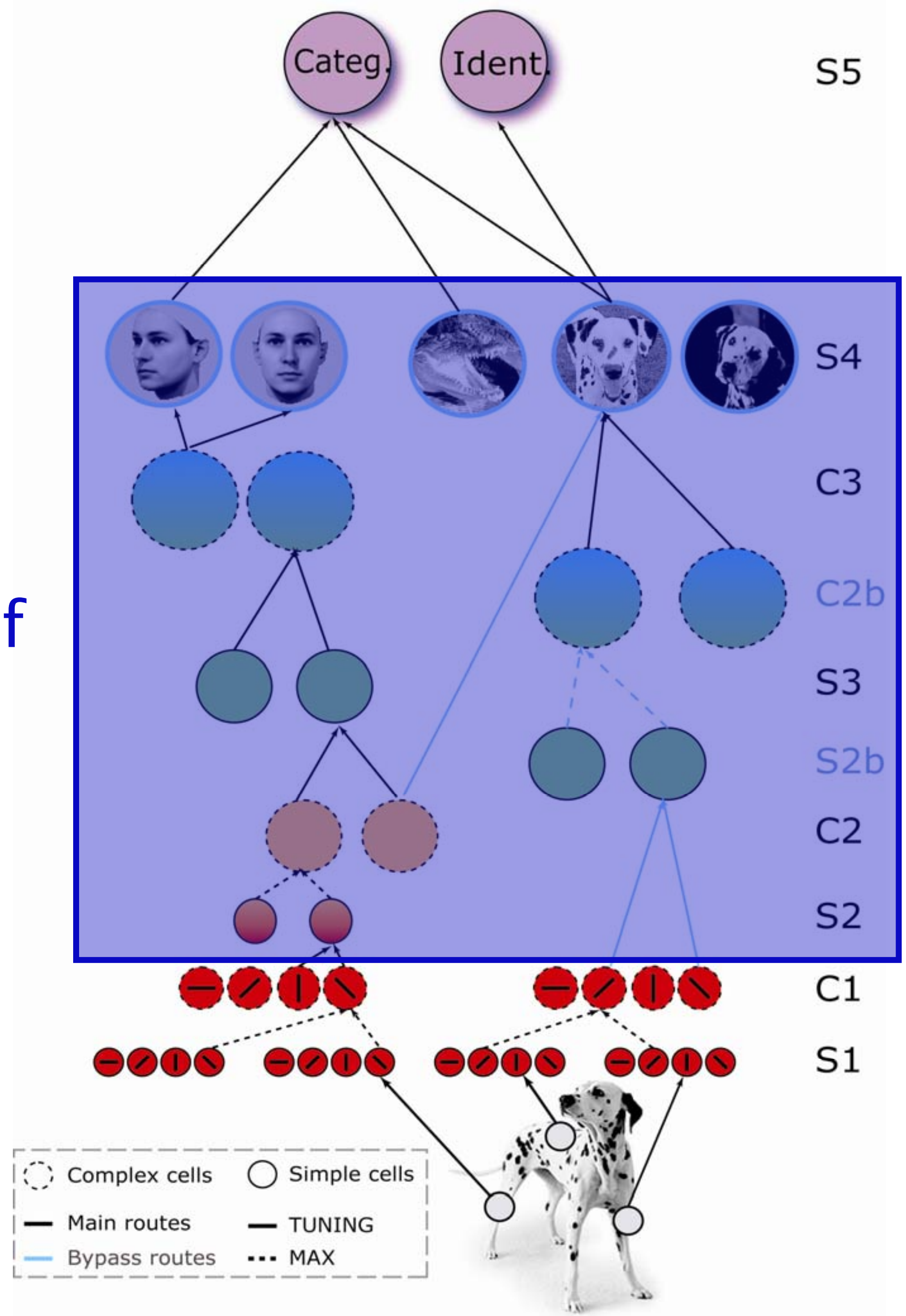




From C2 to S4

- 2,000 "features" at the C3 level ~ same number of feature columns in IT
  (Fujita et al, 1992)

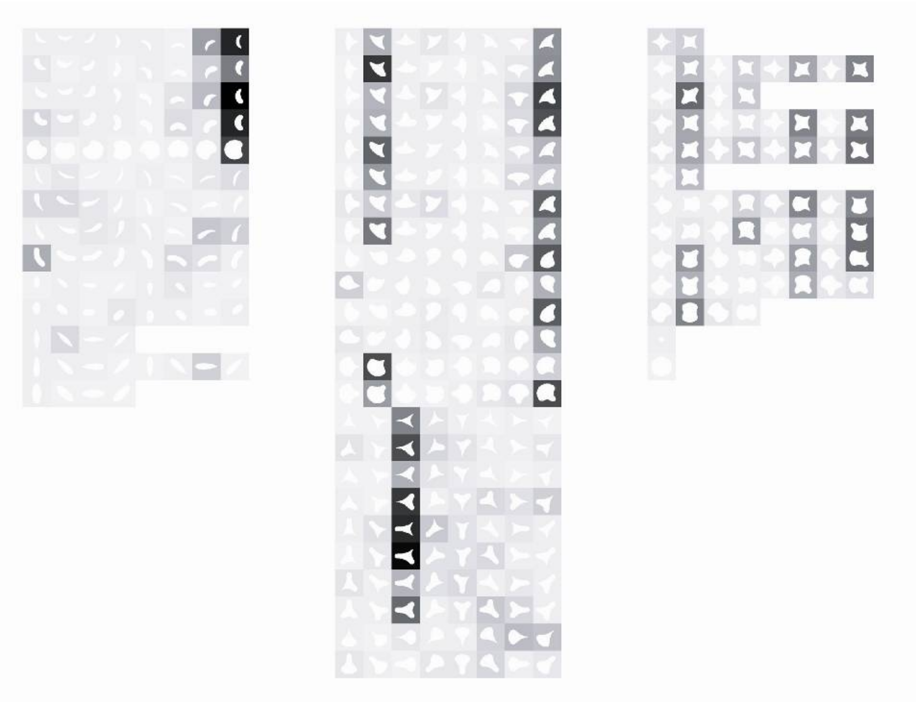
- Total ~6,000 types of features with various levels of complexity and invariance



The model predicts several properties of cortical neurons

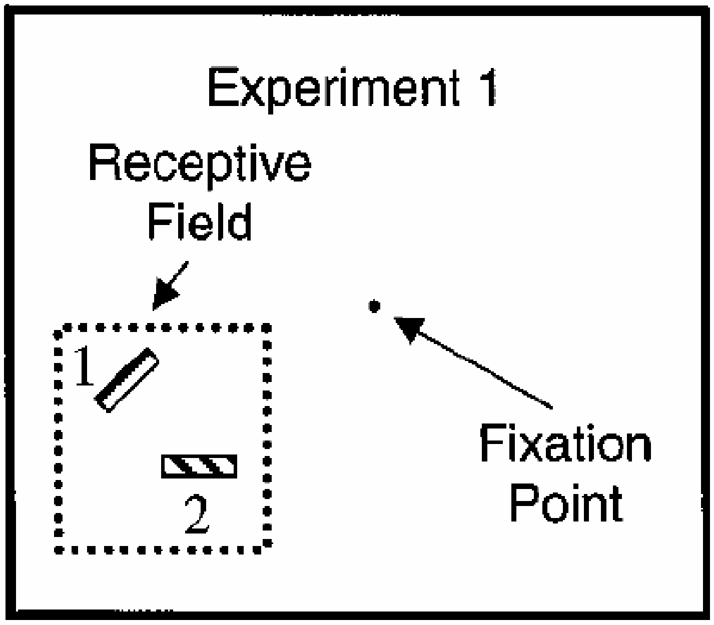
- In various cortical areas
- Examples from V4

Tuning for boundary conformation



(Pasupathy & Connor, 2001)

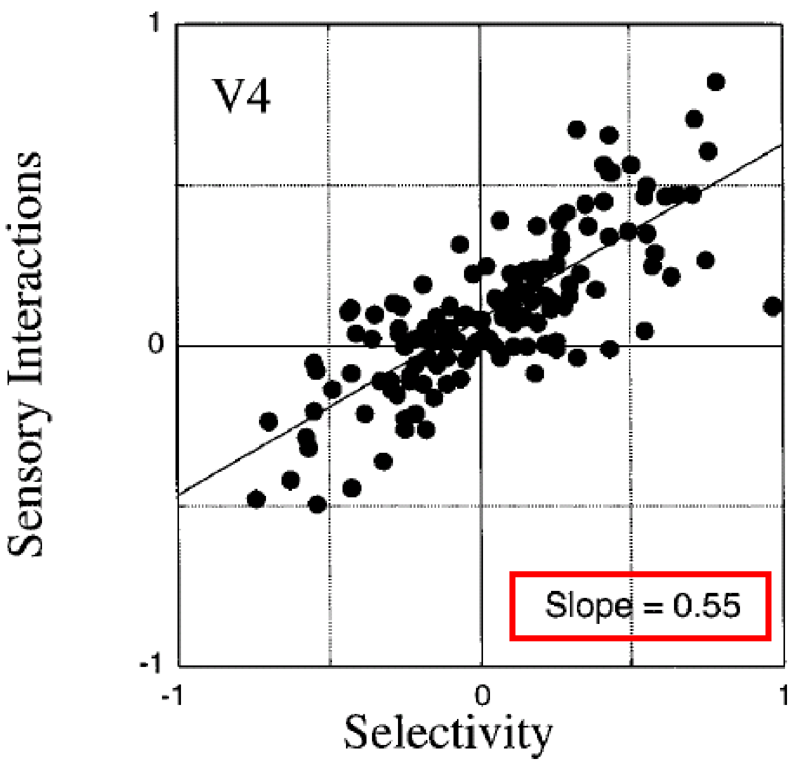
Tuning for two-bar stimuli



(Reynolds, Chelazzi and Desimone, 1999)

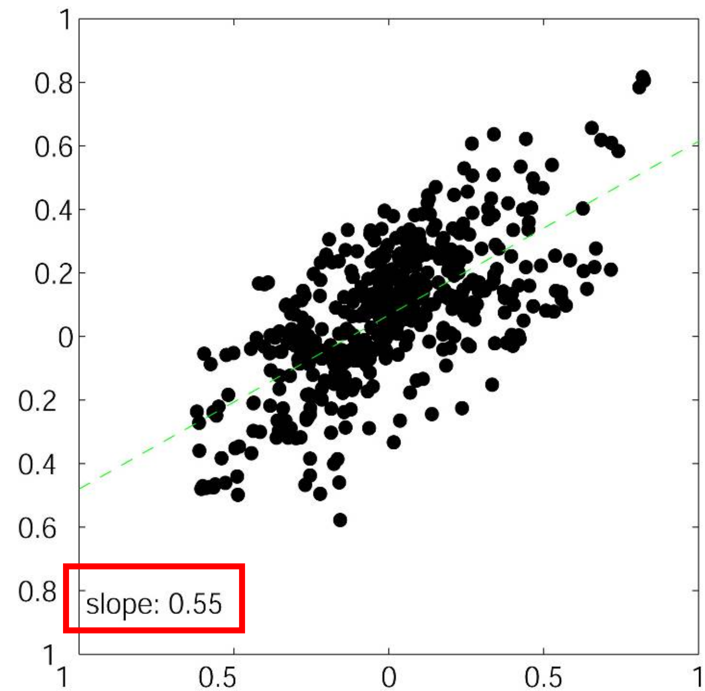
Prediction: Response of the pair is predicted to fall between the responses elicited by the stimuli alone

V4 neurons
(with attention directed away from receptive field)



(Reynolds , Chelazzi and Desimone, 1999)

C2 units



(Serre, Kouh, Cadieu, Knoblich, Kreiman and Poggio, 2005)

The model can perform complex recognition task very well

- At the level of some of the best computer vision systems
- e.g, constellation models
  (Leung et al, 1995; Burl et al, 1998; Weber et al., 2000; Fergus et al, 2003; Li et al, 2004)

rear-car airplane frontal face motorbike leaf

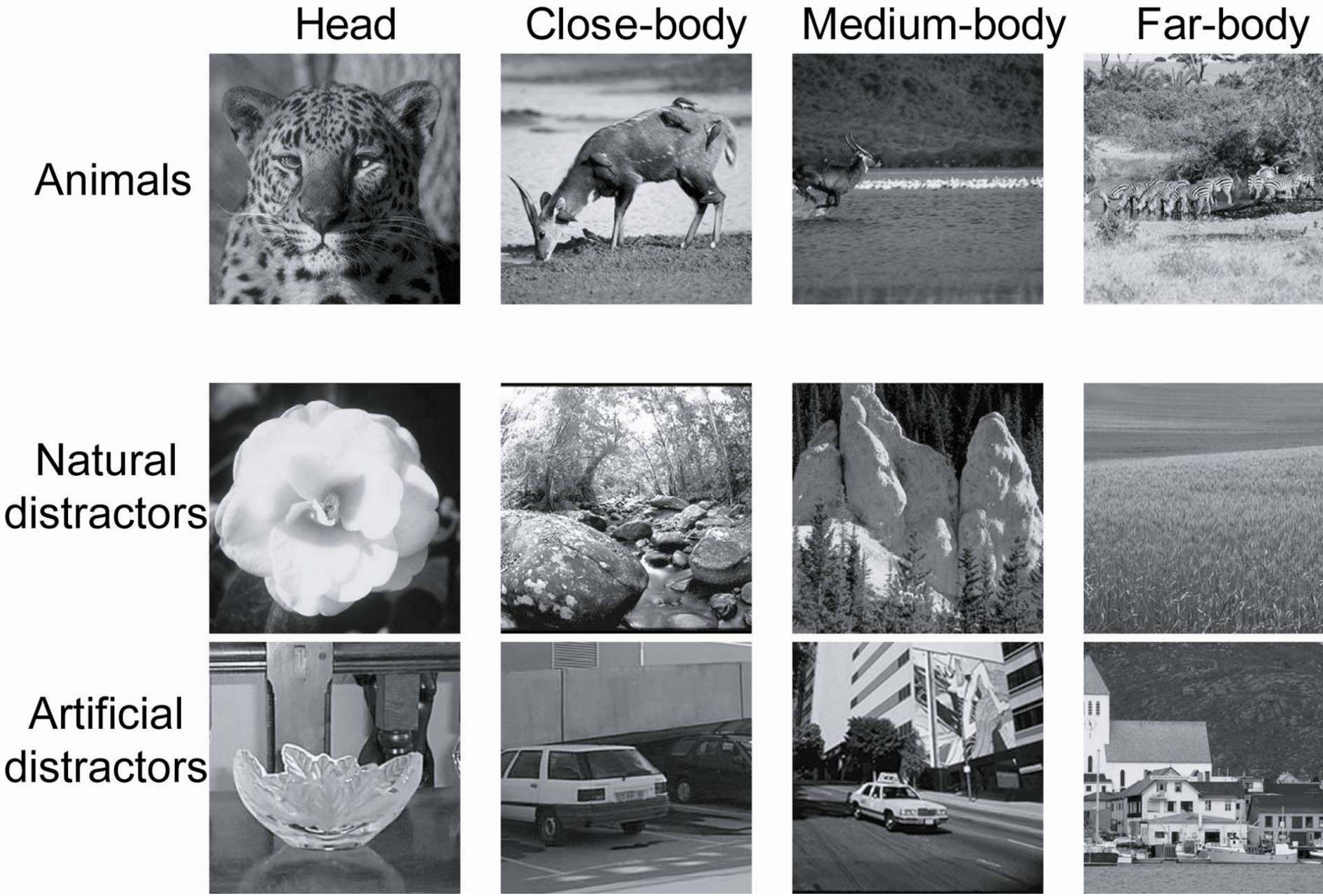
Datasets			AI systems	Model
(CalTech)	Leaves	[Weber et al., 2000b]	84.0	97.0
(CalTech)	Cars	[Fergus et al., 2003]	84.8	99.7
(CalTech)	Faces	[Fergus et al., 2003]	96.4	98.2
(CalTech)	Airplanes	[Fergus et al., 2003]	94.0	96.7
(CalTech)	Motorcycles	[Fergus et al., 2003]	95.0	98.0

How does the model compare to human observers?

Animal vs. non-animal categ.

- 1,200 stimuli (from Corel database)
- 600 animals in 4 categories:
  - Head
  - Close-body
  - Medium-body
  - Far-body and groups
- 600 matched distractors (½ art., ½ nat.) to prevent reliance on low-level cues

(Torralba & Oliva, 2003; Oliva & Torralba, in press)



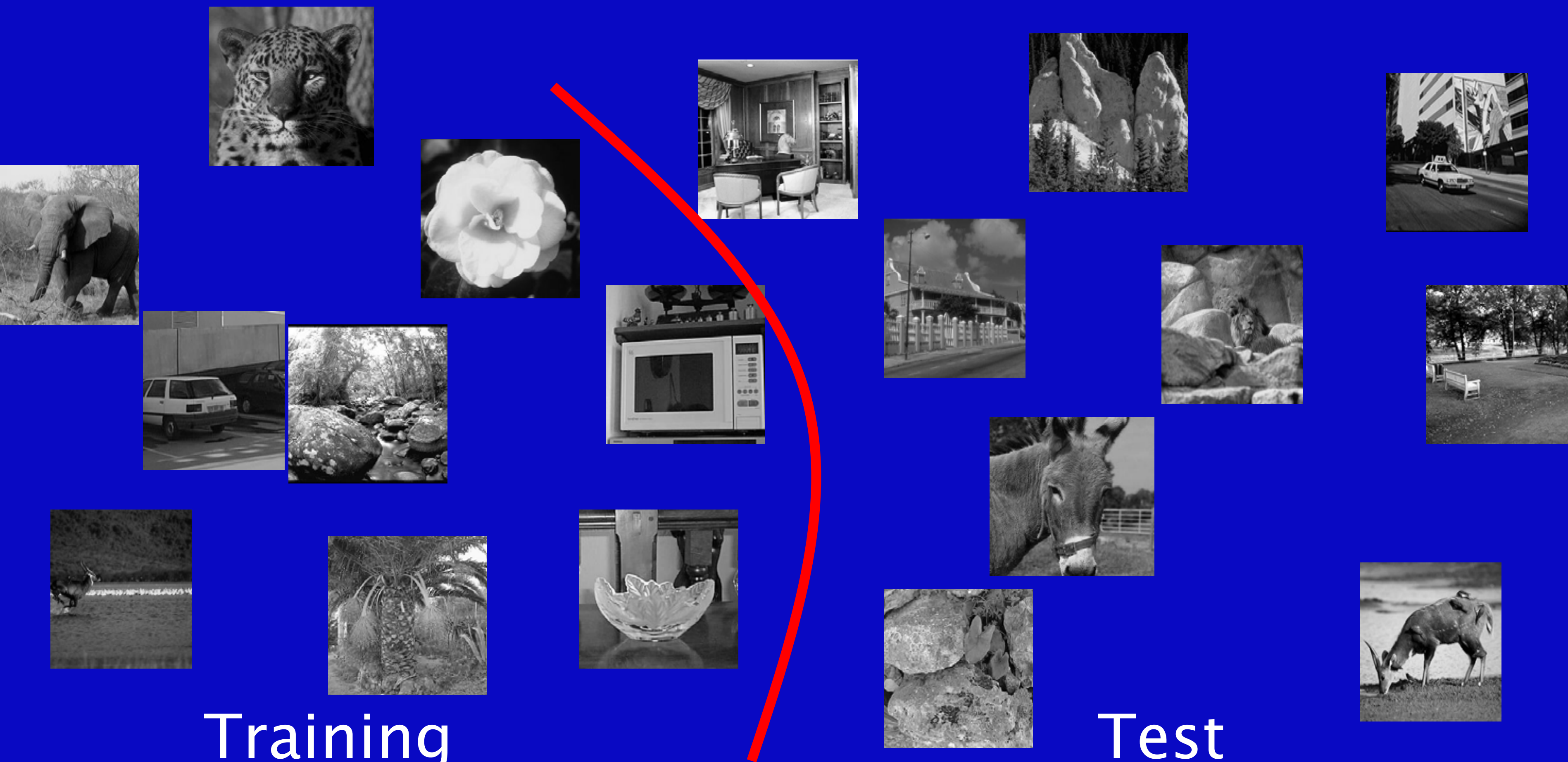
(Torralba & Oliva, 2003; Oliva & Torralba, in press)

Training and testing the model

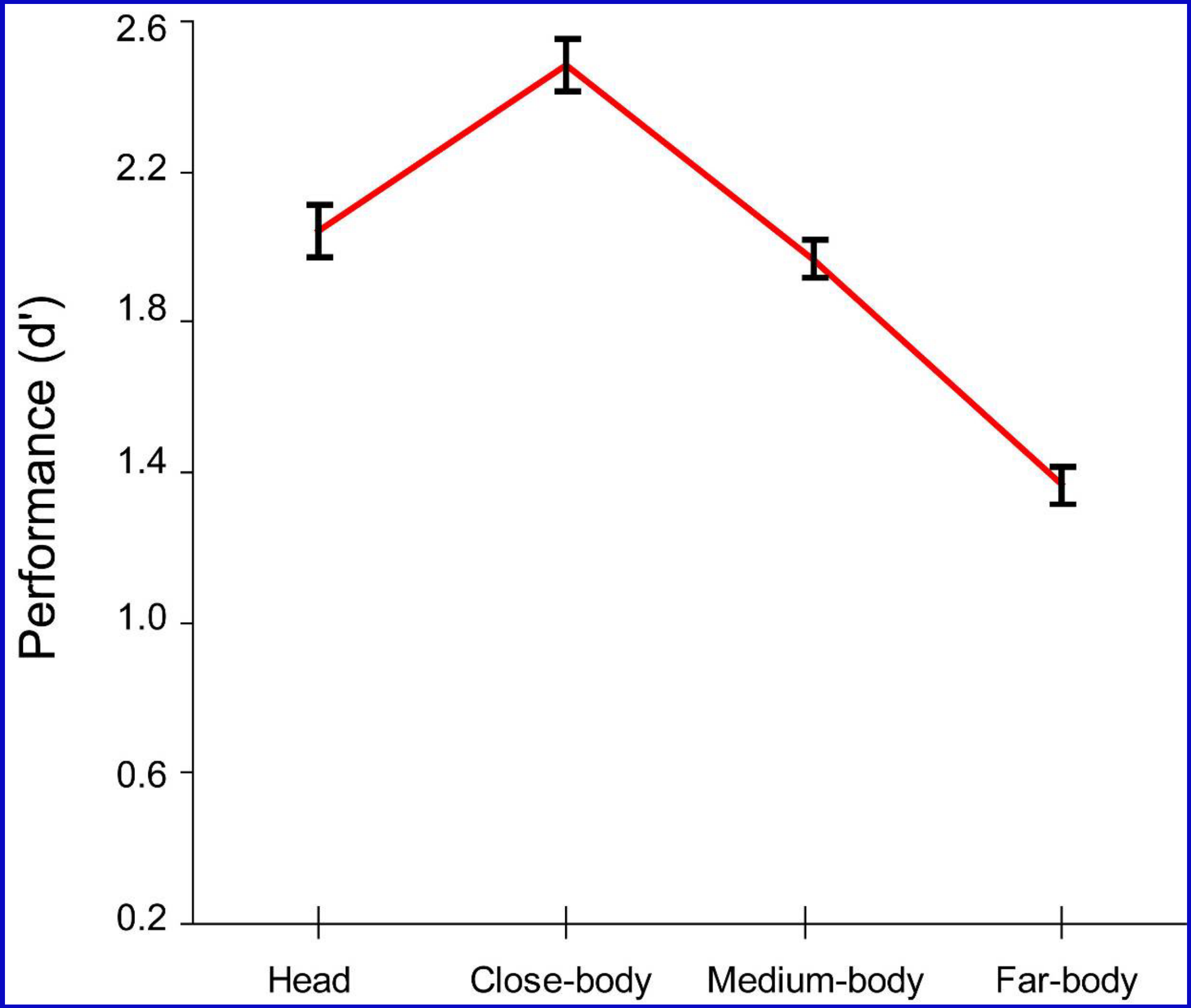
- ➢ Random splits (good estimate of expected error)
- ➢ Split 1,200 stimuli into two sets

Training the model

- Repeat 20 times
- Average model performance over all

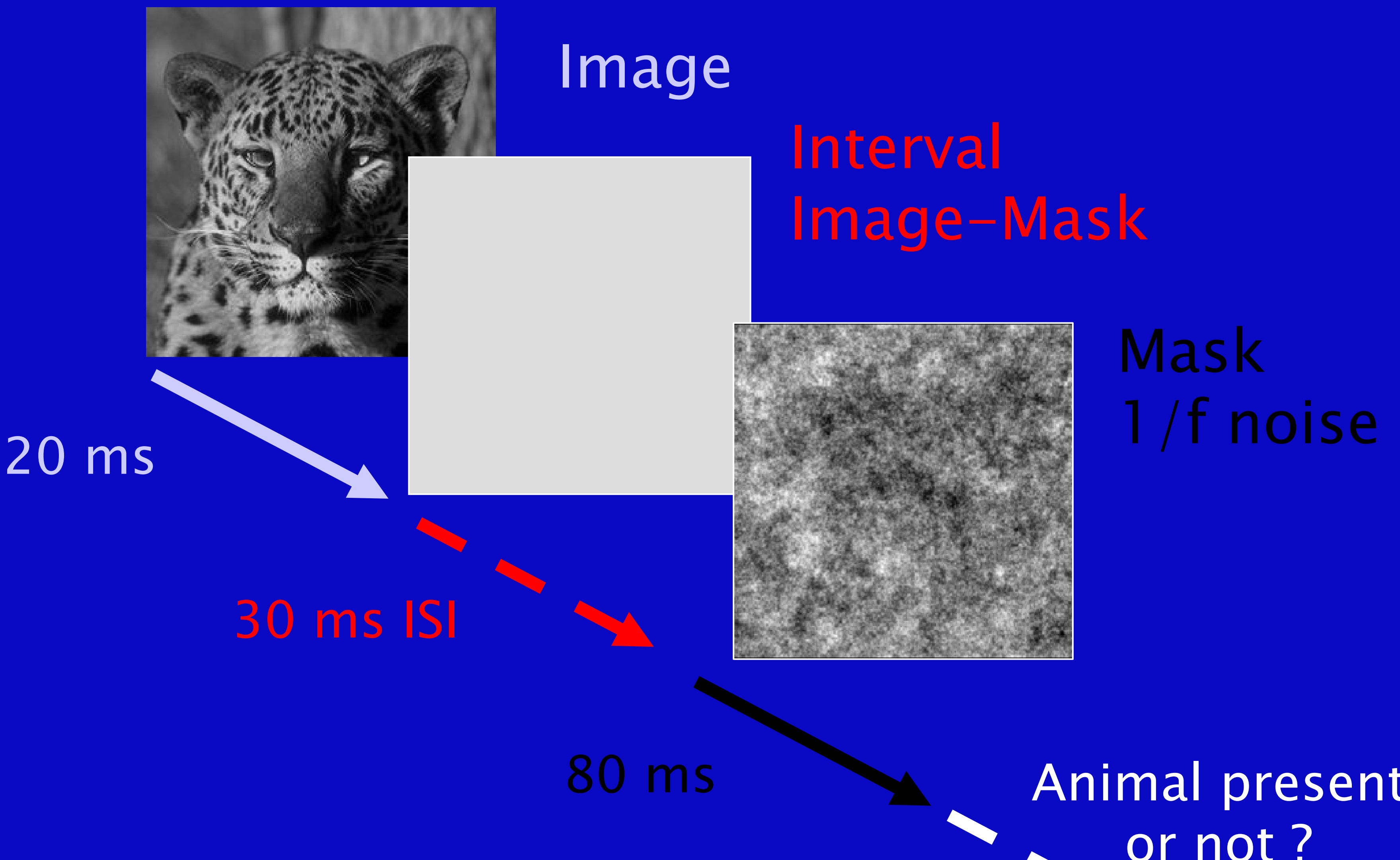


Results: Model



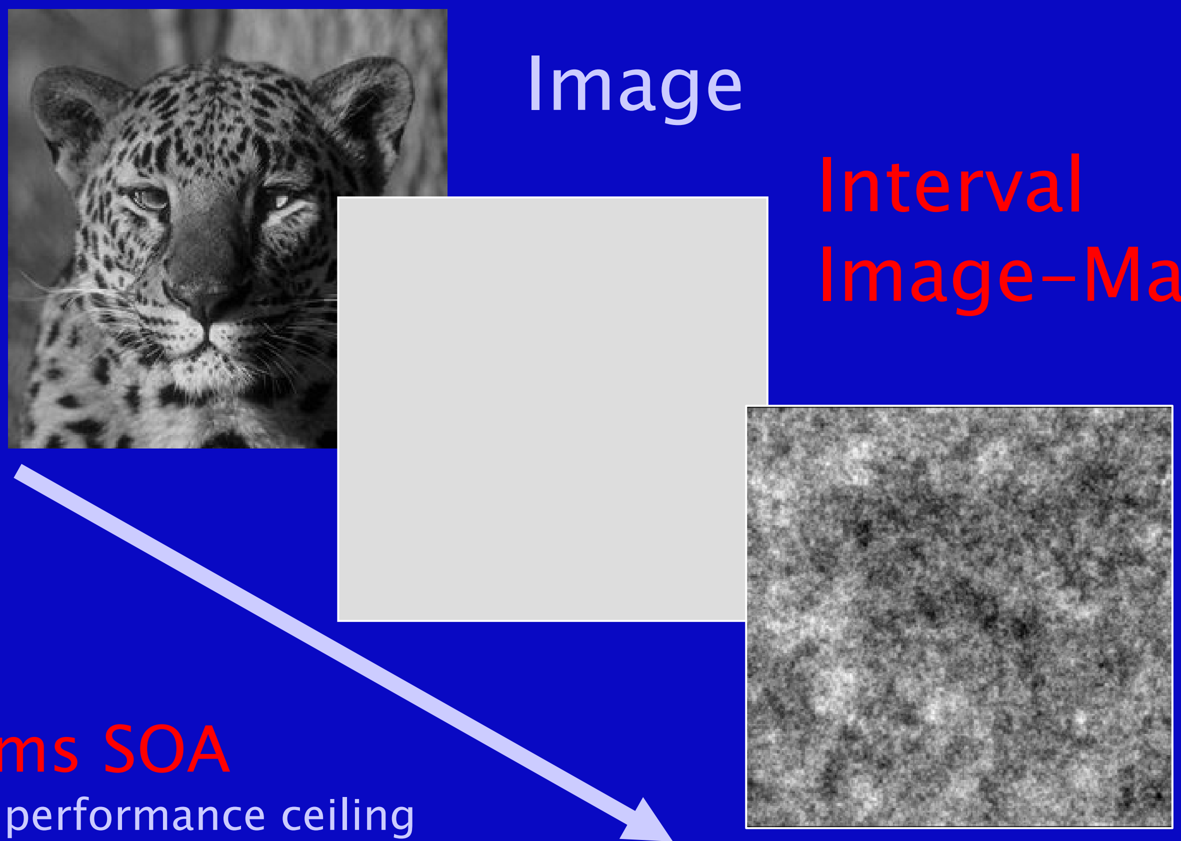
model

Rapid categorization task



(Thorpe et al, 1996; Van Rullen & Koch, 2003; Bacon-Mace et al, 2005; Oliva & Torralba, in press)

Rapid categorization task



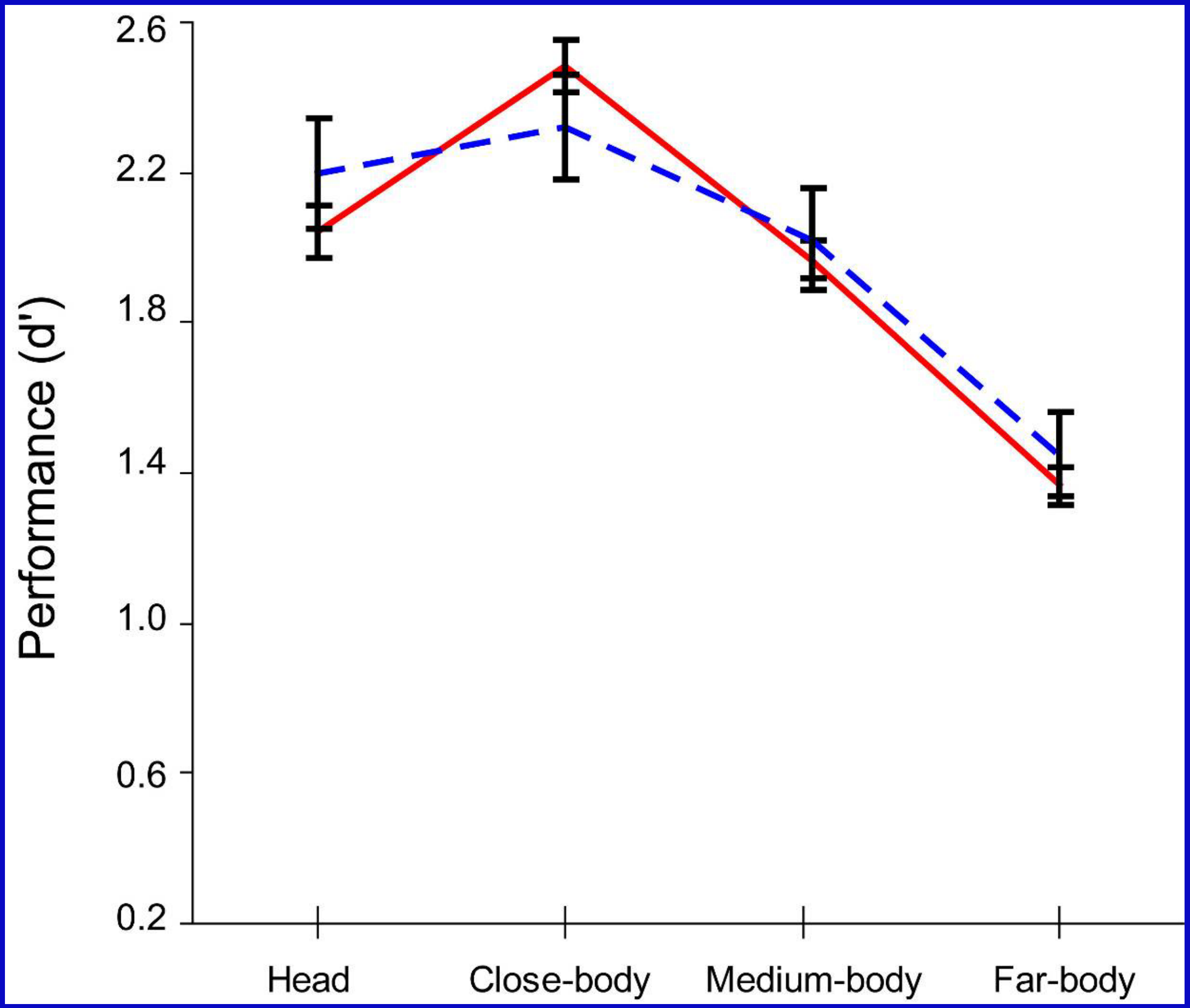
~ 50 ms SOA
close to performance ceiling
in (Bacon-Mace et al, 2005)

80 msec

Animal present
or not ?

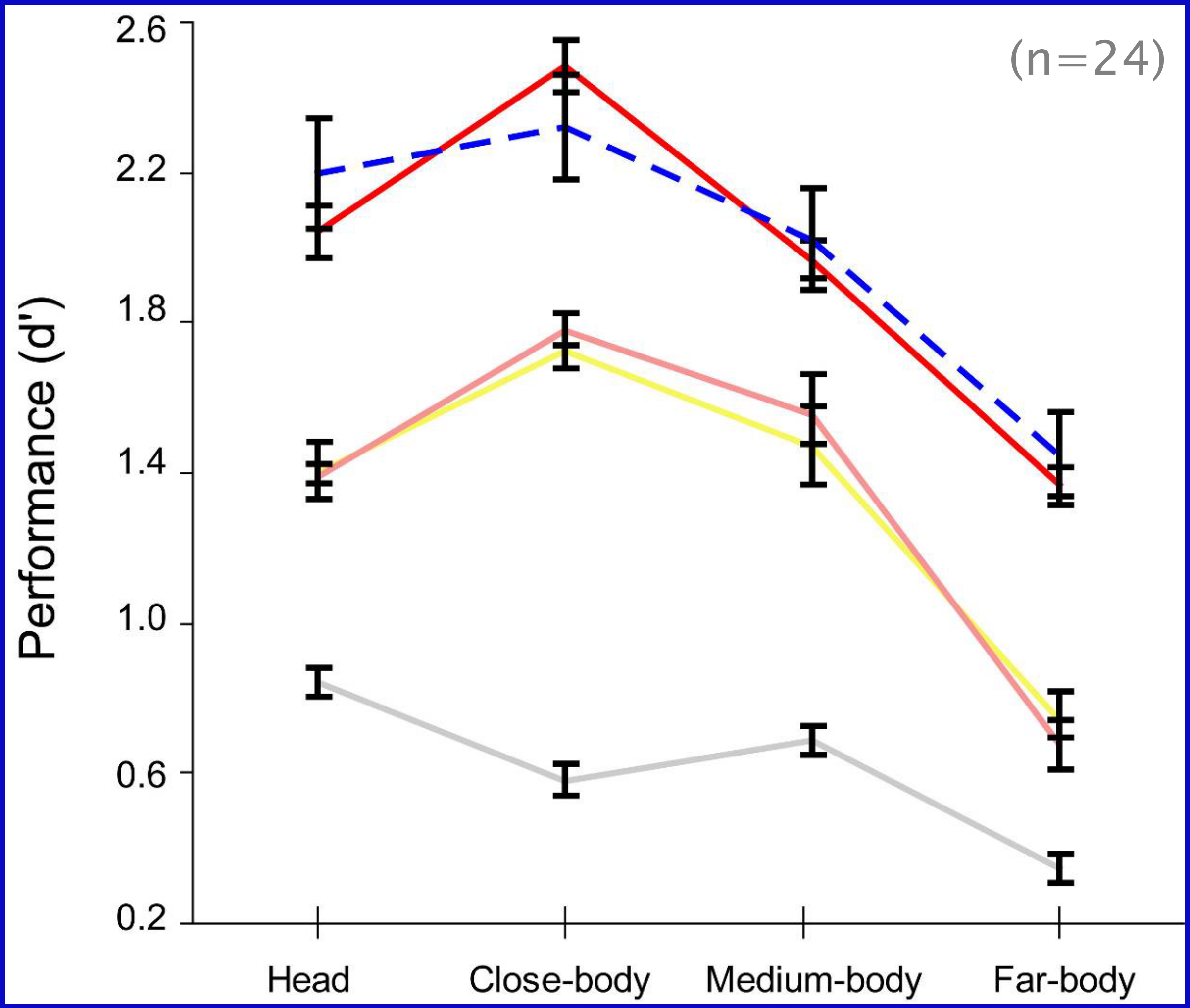
(Thorpe et al, 1996; VanRullen & Koch, 2003;
Bacon-Mace et al, 2005; Oliva & Torralba, in press)

Results: Human-observers



50 ms SOA (ISI=30 ms)
model

“Simpler” models cannot do the job



50 ms SOA (ISI=30 ms)

model

Model C1

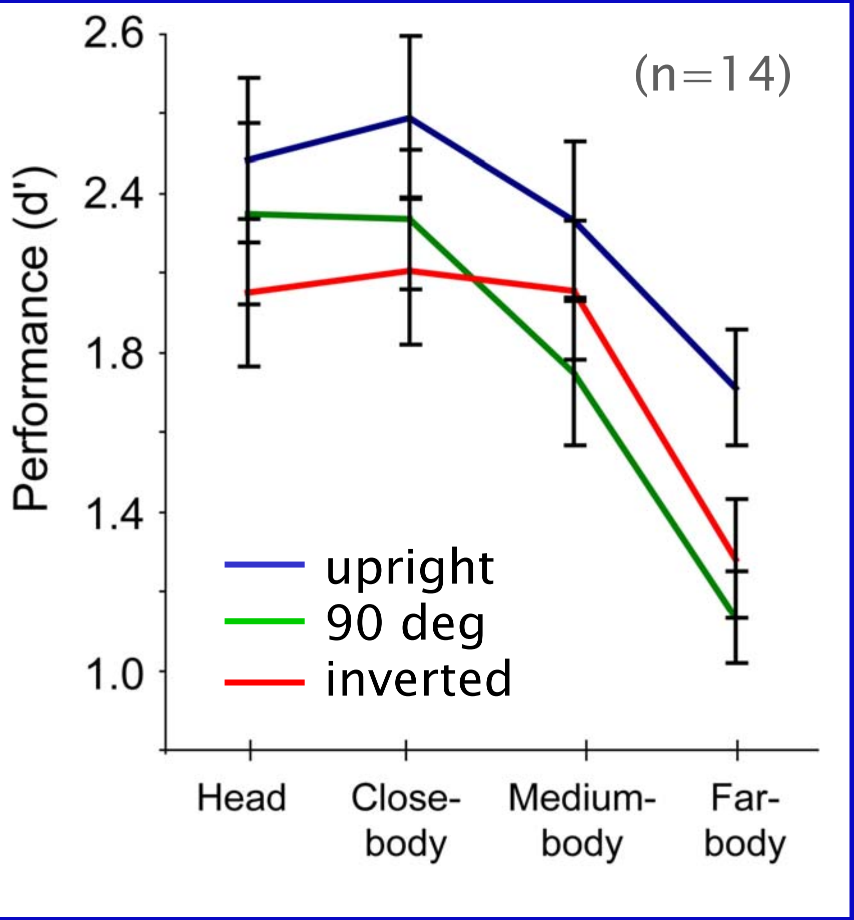
(Torralba & Oliva, 2001)

(Renninger & Malik, 2004)

(Serre, Oliva and Poggio, in prep)

Results: Image orientation

Human observers

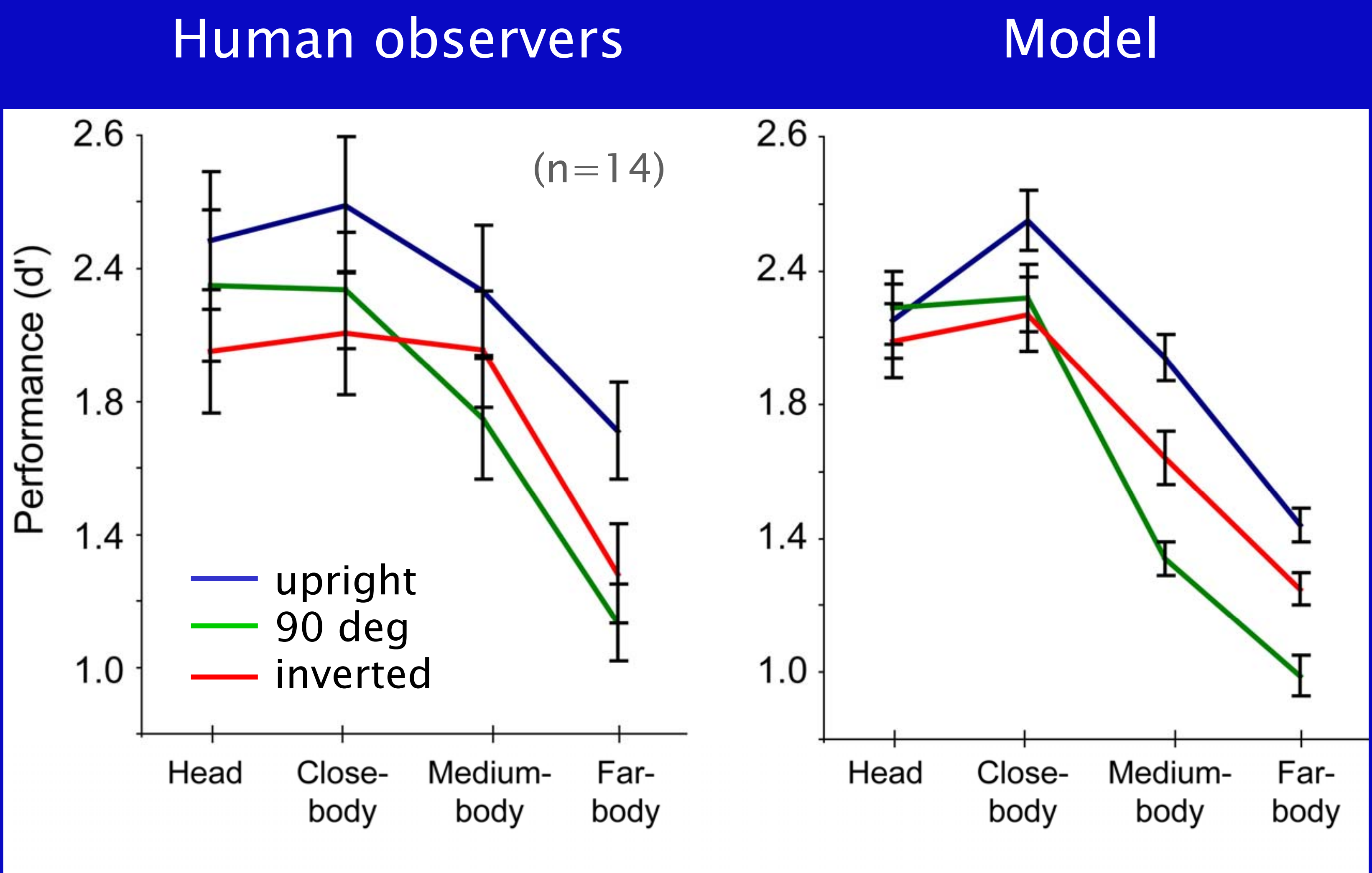


50 ms SOA (ISI=30 ms)

Robustness to image orientation is in agreement with previous results
(Rousselet et al, 2003; Guyonneau et al, ECVP 2005)

(Serre, Oliva and Poggio, in prep)

Results: Image orientation



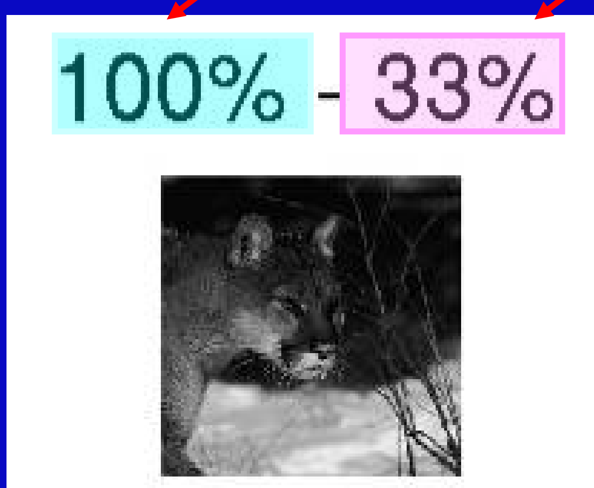
50 ms SOA (ISI=30 ms)

(Serre, Oliva and Poggio, in prep)

Detailed comparison

- For each individual image
- How many times image classified as animal:
  - For humans: across subjects
  - For model: across 20 runs

model humans



- Heads: $\rho=0.71$
- Close-body: $\rho=0.84$
- Medium-body: $\rho=0.71$
- Far-body: $\rho=0.60$

Good agreement: Correctly rejections

Good agreement: Correct detections

100% 96%

100% 96%

100% 96%

100% 96%

100% 96%

100% 96%

100% 96%

100% 96%

100% 96%

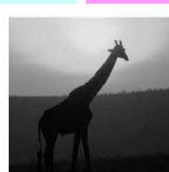
100% 96%

100% 96%

100% 96%

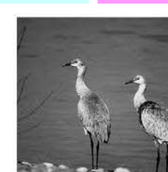
100% 96%

100% 96%

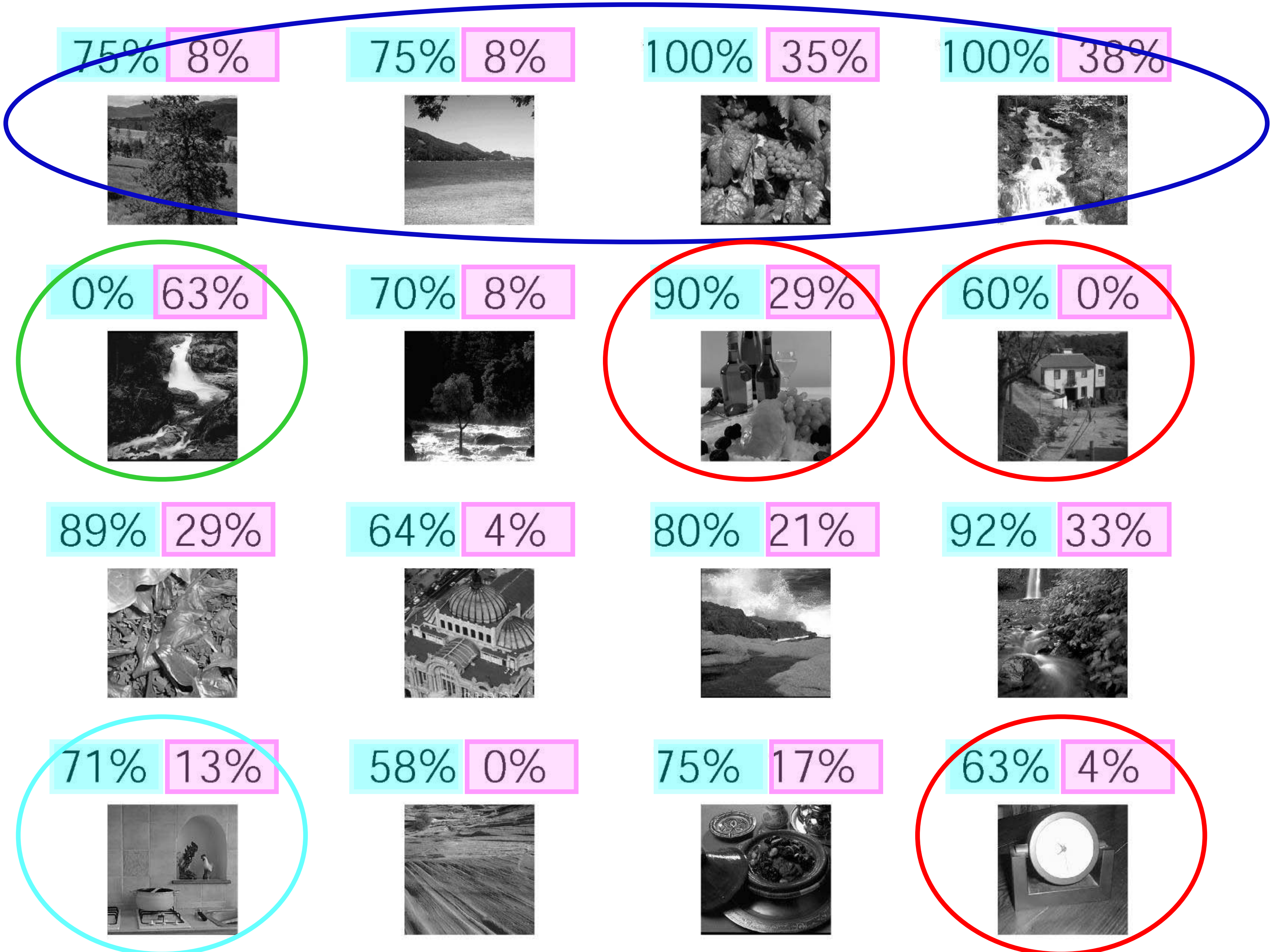


50% 54%

100% 96%



Disagreement



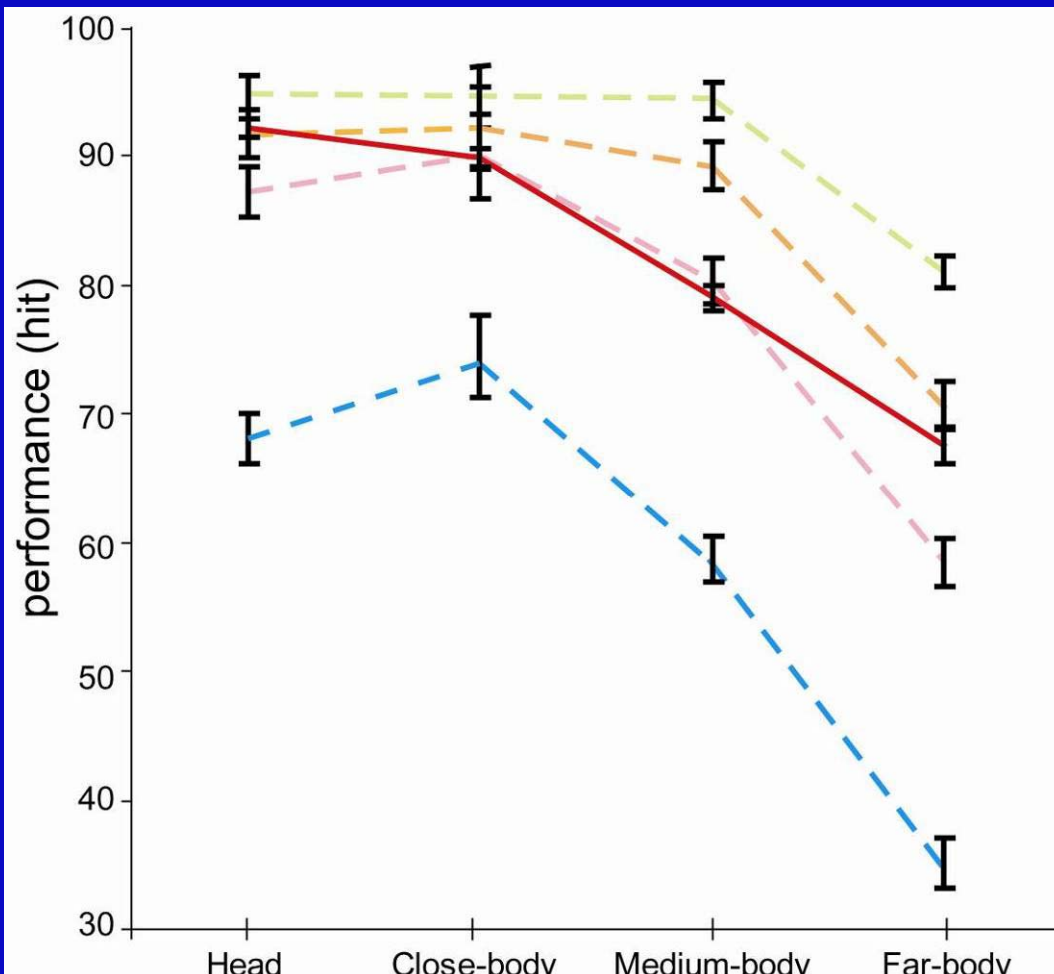
Disagreement

Discussion

- The model predicts human performance extremely well when the delay between the stimulus and the mask, i.e. the SOA is ~50 ms
- What happens for different SOAs?

Discussion

- Why should we except the model to account for human performance around 50 ms SOA?



no mask condition

80 ms SOA (ISI=60 ms)

model

50 ms SOA (ISI=30 ms)

20 ms SOA (ISI=0 ms)

(Serre, Oliva and Poggio, in prep)

Discussion

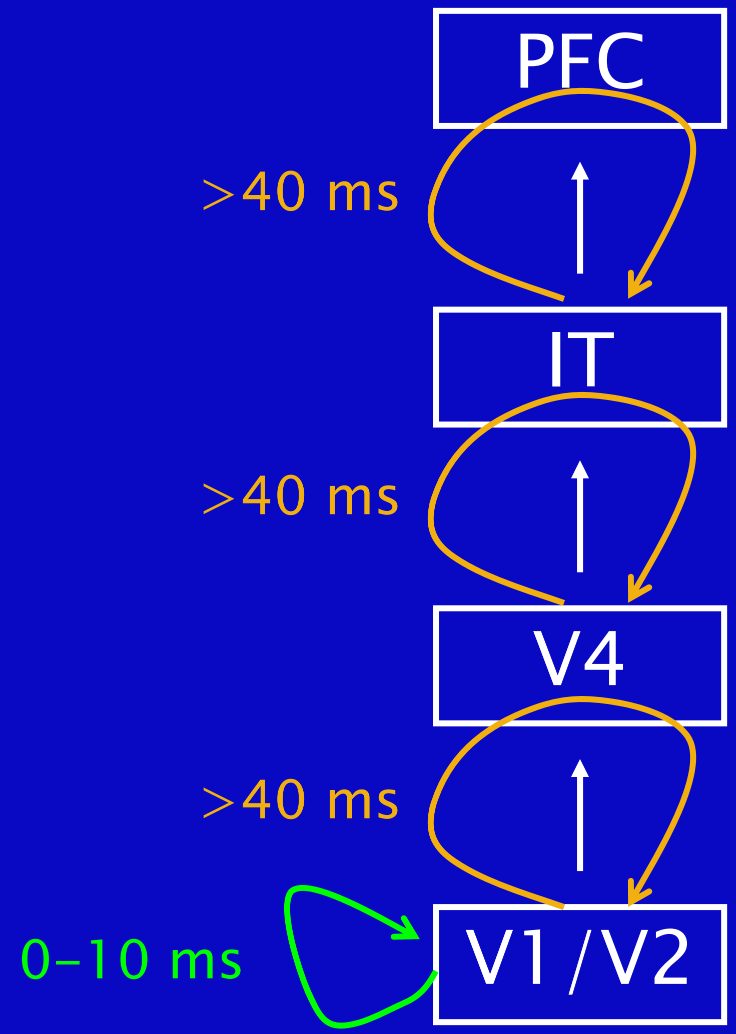
- What is so special with 50 ms SOA?
  - Possible answer:
    - ✓Nothing!!
    - ✓Mask disrupts signal integration at the neural level
    - ✓Model does not yet account for human level of performance

Discussion

- Alternative answer:
  - 50 ms is a very long time!
    - ✓Within 50 ms most of the information has already been transmitted from one stage to the next (Rolls et al, 1999; Vogels et al, 1995, Keysers et al, 2001)
    - ✓Reading out from IT (~10-20ms):
      - both object category and identity
      - largely translation and scale invariant (Hung, Kreiman, Poggio, DiCarlo, 2005)
- So what happened after the first 50 ms?

Speculation!!

- Our model is purely feedforward
  - Only local feedback loops
  - No feedback loops
- Feedback loops may already play a role for SOAs longer than 50 ms
- Discrepancy for longer SOAs may be due to the cortical back-projections



Timing estimates are for monkeys, based on (Thorpe & Fabre-Thorpe, 2001) and (Thorpe, Personal communication)

Summary

- I have described a model that is faithful to the anatomy and physiology of the ventral stream of visual cortex
- The model builds a dictionary of image features from V2 to IT which is compatible with the tuning of cortical neurons in several brain areas
- The model seems to be able to predict very well the level of performance of human observers in a rapid categorization task

Collaborators

- Aude Oliva
- Tomaso Poggio
- Other contributors
  - S. Bileschi
  - C. Cadieu
  - U. Knoblich
  - M. Kouh
  - G. Kreiman
  - M. Riesenhuber
  - L. Wolf