Visual cortex as a general-purpose information-processing device

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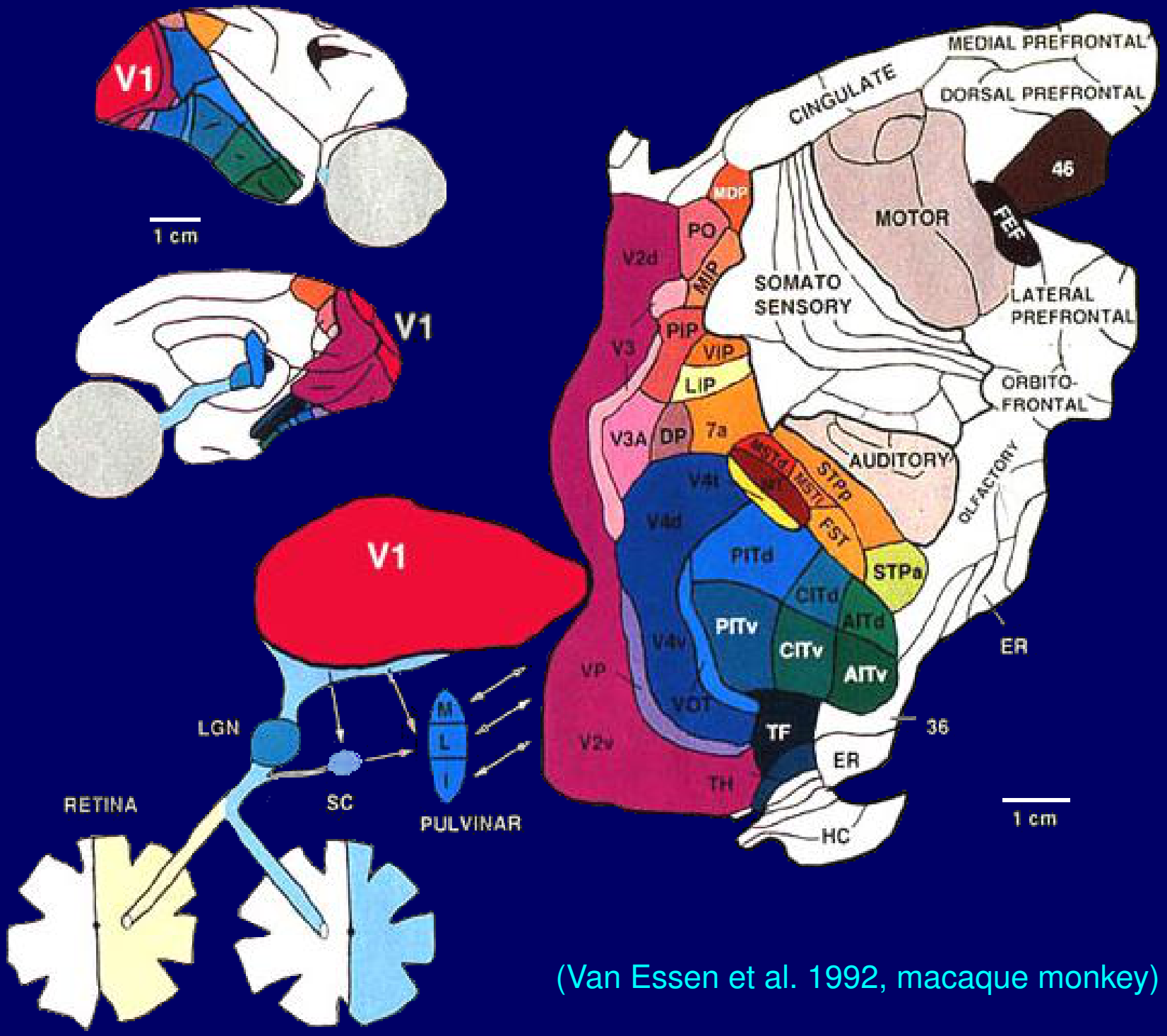
Bio-inspired Vision

How can we learn from biology about building a robust, high-performance, adaptive visual system? One way:

- Gather a lot of data about behavior of neurons in each stage of the adult visual system
- Replicate this behavior in hardware or software
- Fill in missing data with our best guess of how to solve vision problems

Problem: dozens of cortical visual areas in primates, with data sparse except for the lowest levels



(Van Essen et al. 1992, macaque monkey)

Alternative Approach

- Assume equipotentiality of cortical areas
  E.g. auditory cortex responds to rewired visual input
  (Sur et al. 1990; Yuste & Sur 1999)
- Use V1 as a well-studied test case
- Characterize inputs to V1
- Shown how a *generic* cortical region model can develop like V1 automatically, given these inputs
- Use data from V1 to *constrain and validate* the cortical model, not as a blueprint (Bednar 2012)

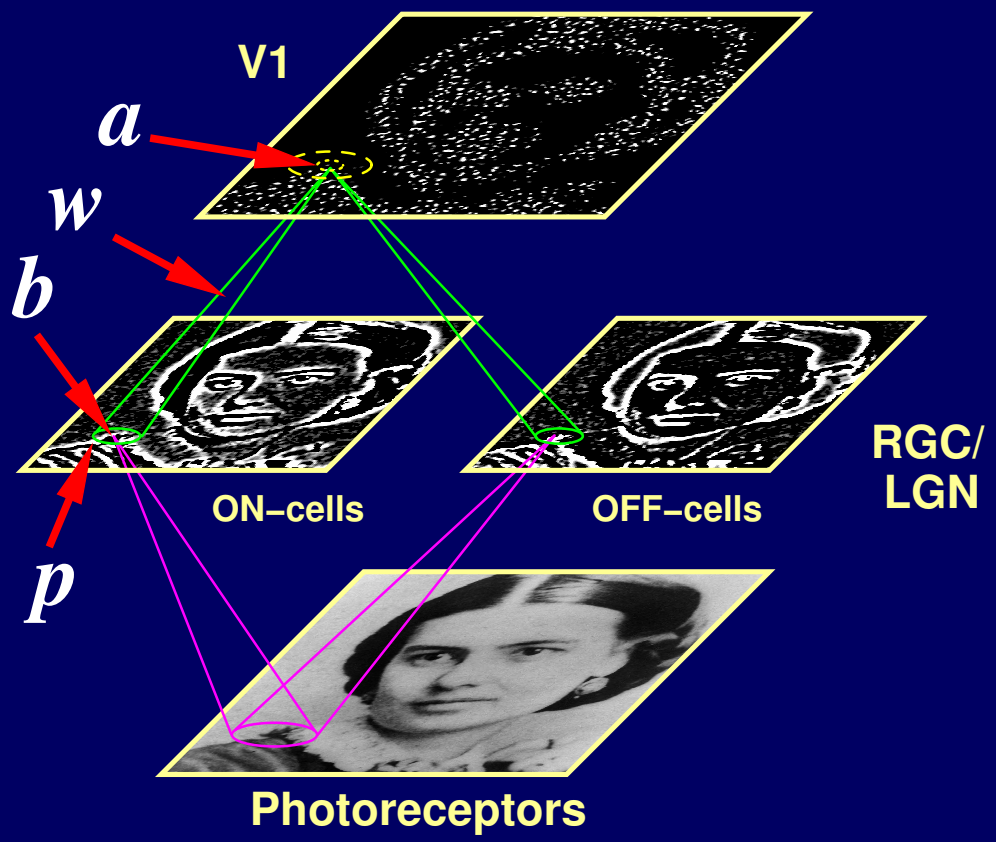
If successful, the resulting cortical model can then be applied to any cortical region, and indeed any information-processing task.

Target properties of V1

1. Neurons selective for retinotopy, orientation, ocular dominance, motion direction, spatial frequency, temporal frequency, disparity, color, in terms of firing rate
2. Preferences for each organized into realistic topographic maps
3. Lateral connections reflecting the structure of these maps
4. Contrast-gain control and contrast-invariant tuning
5. Simple and complex cells
6. Long-term and short-term plasticity (e.g. aftereffects)
7. Realistic surround modulation effects, including their diversity
8. Realistic transient temporal responses

1. Basic GCAL model: X,Y, OR

$$\eta_a = \sigma\left(\sum_p \gamma_p \sum_b X_{pb} w_{a,pb}\right)$$

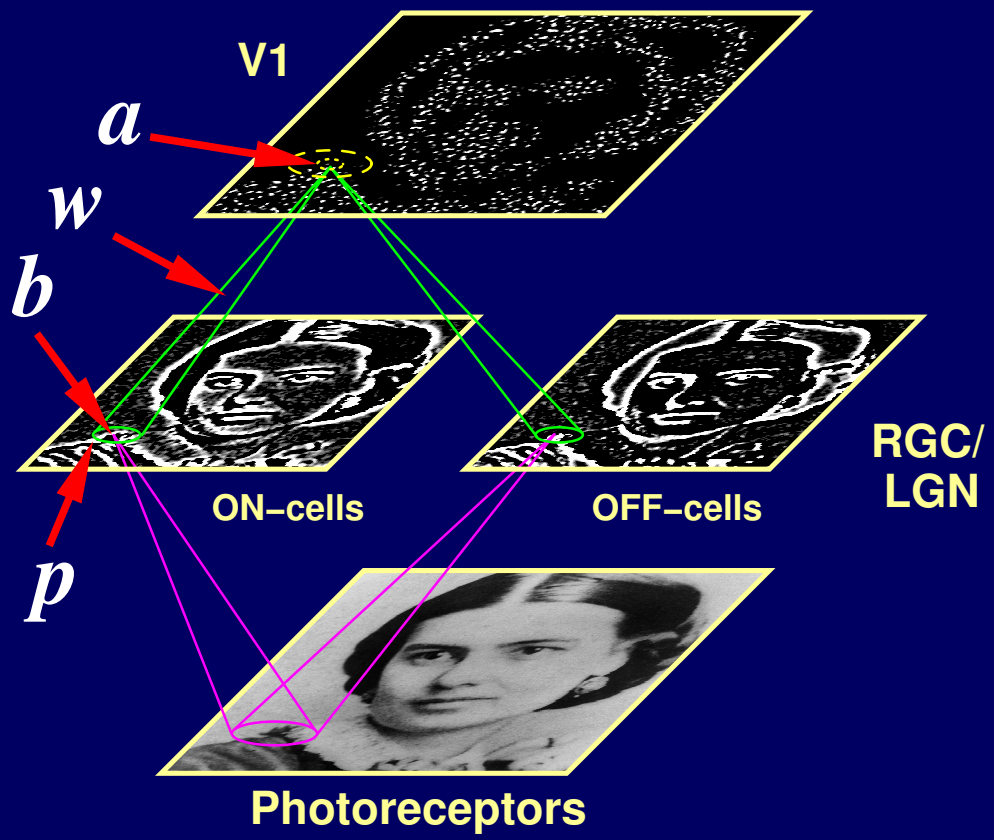


Activity: thresholded weighted sum of all connection fields

Response high when input matches excitatory weights

(Sirosh & Miikkulainen 1994; Law, Antolik, & Bednar 2011)

1. Basic GCAL model: X,Y, OR



$$w_{a,pb}(t+1) =$$

$$\frac{w_{a,pb}(t)+\alpha_p \eta_a X_{pb}}{\sum_c [w_{a,pc}(t)+\alpha_p \eta_a X_{pc}]}$$

Learning:

normalized Hebbian

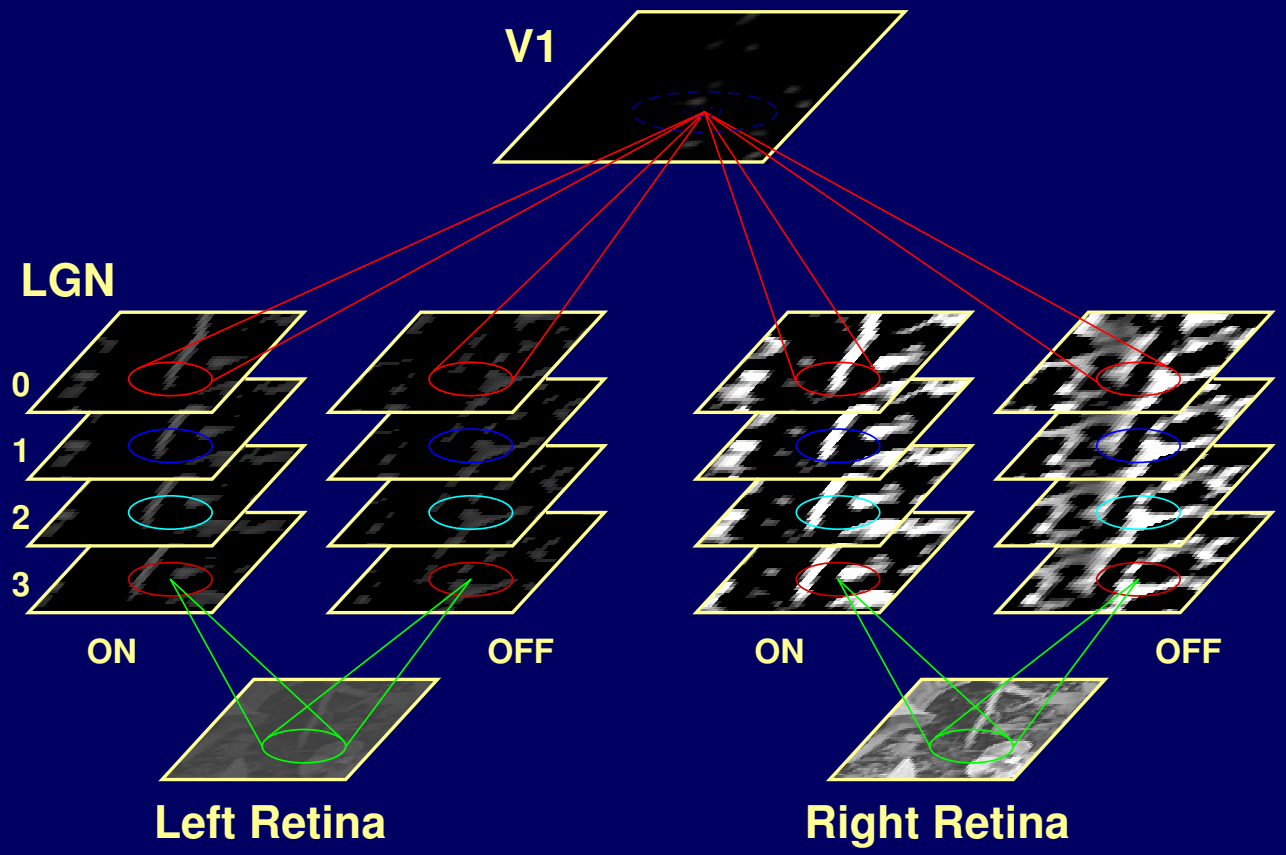
Coactivation $\longrightarrow$

strong connection

Normalization:

distributes strength

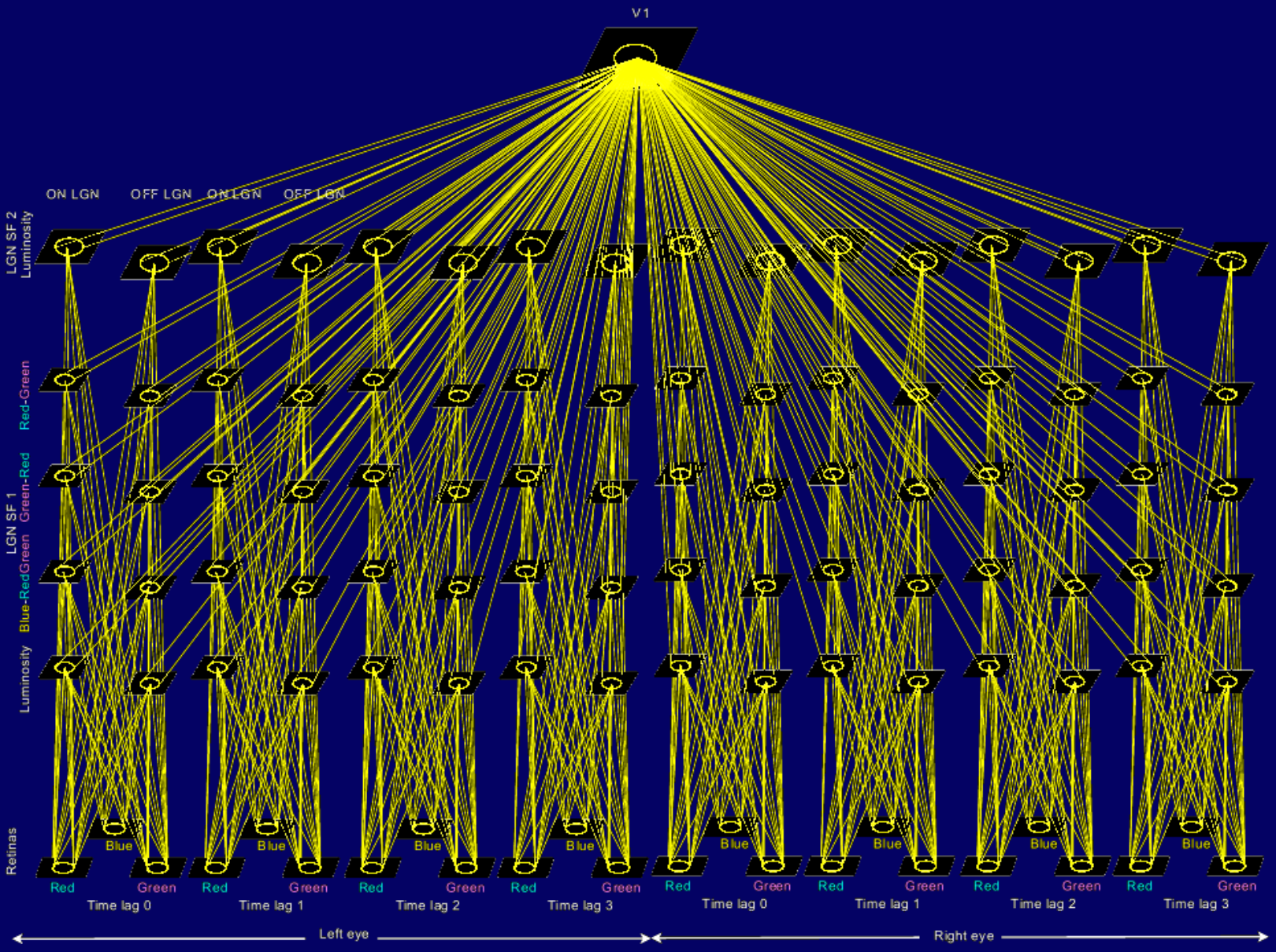
2. X,Y, OR, OD, DY, DR, TF



Add another eye, multiple delays $\longrightarrow$ 19 sheets

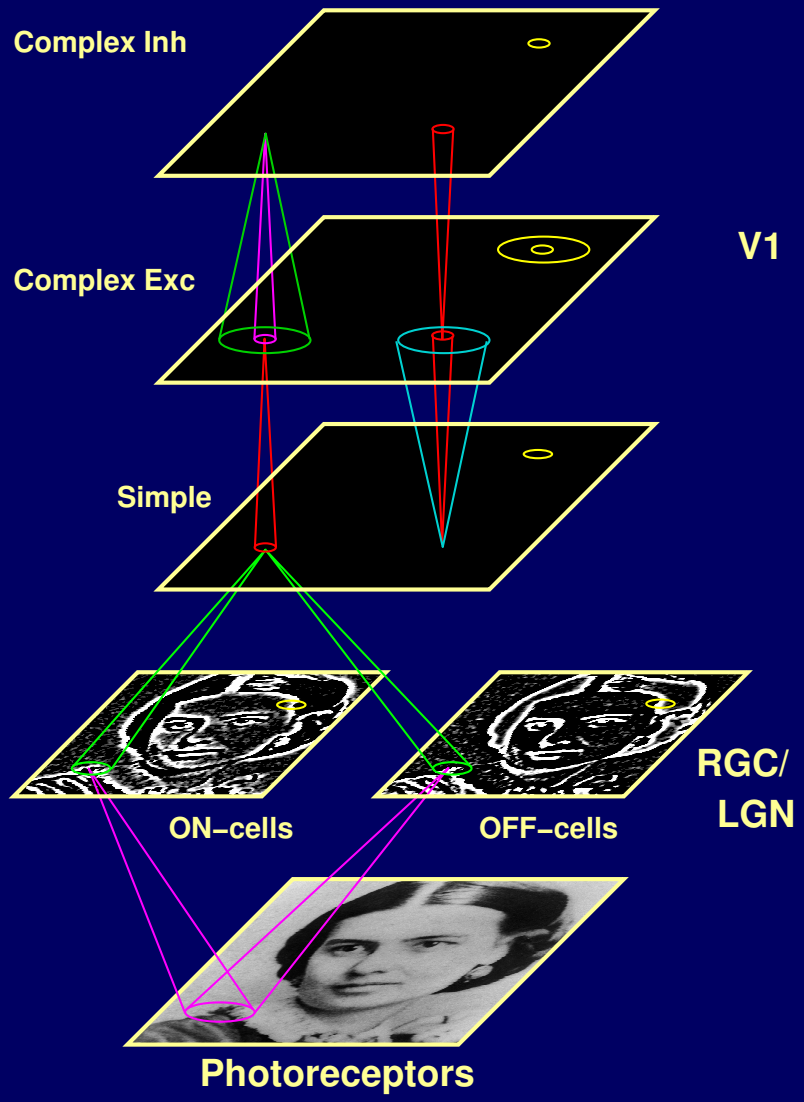
(Bednar & Miikkulainen 2006)

3. X,Y, OR, OD, DY, DR, TF, SF, CR



Add RGC sizes, color opponency $\longrightarrow$ 87 sheets

4. X,Y, OR, Complex cells, SM

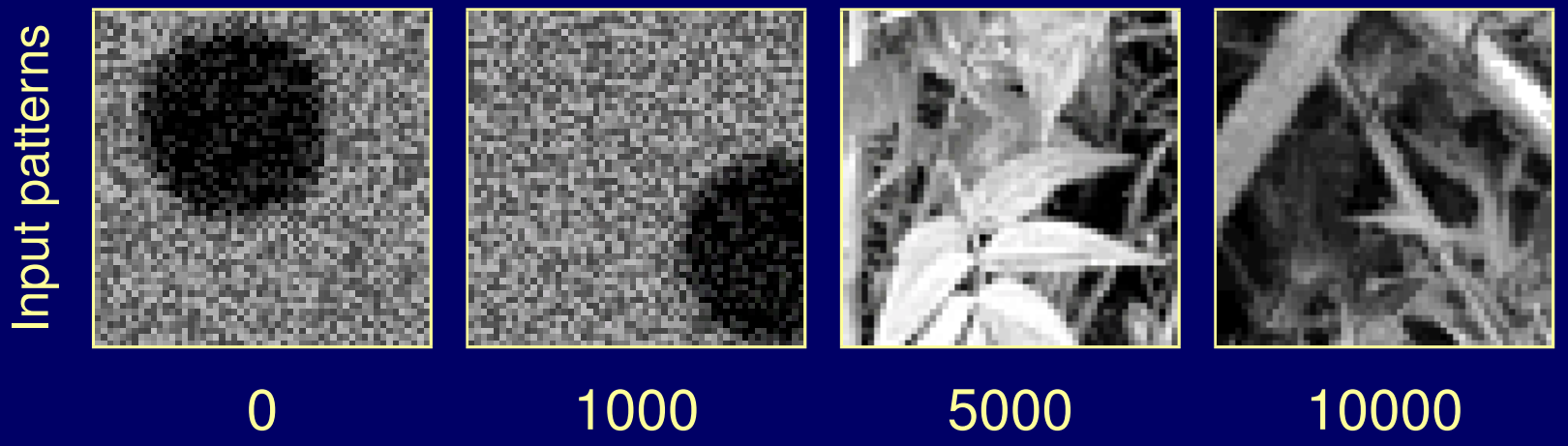


For complex cells and contrast-dependent surround modulation, must:

- Model V1 with multiple layers/populations
- Use realistic connectivity: long-range excitation, local inhibition, feedback

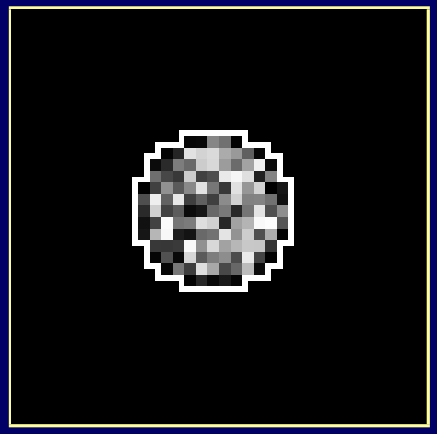
(Antolik & Bednar 2011)

1. Basic training Patterns

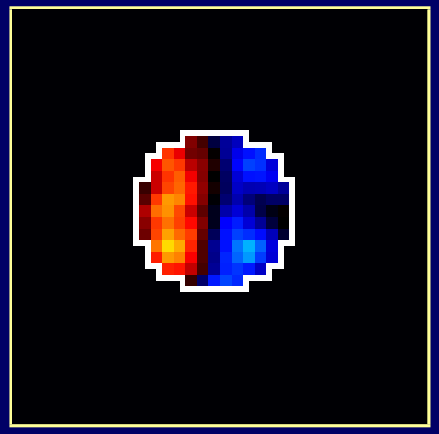


- **Prenatal:** internal activity (retinal waves; Feller et al. 1996)
- **Postnatal:** natural images (Shouval et al. 1996)

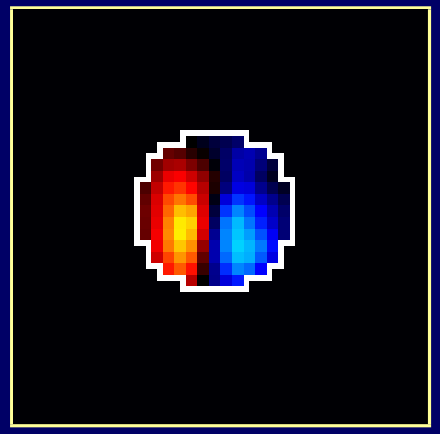
1. Basic RF, map results



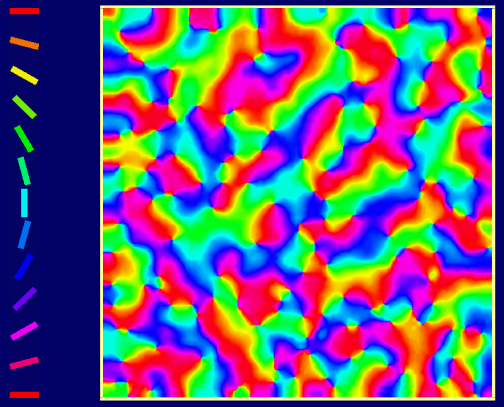
Iteration 0



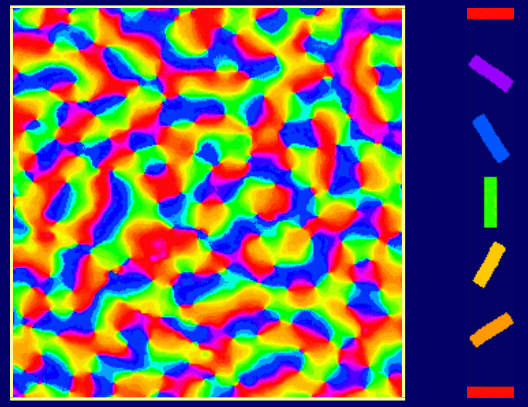
Iteration 1000



Iteration 10000

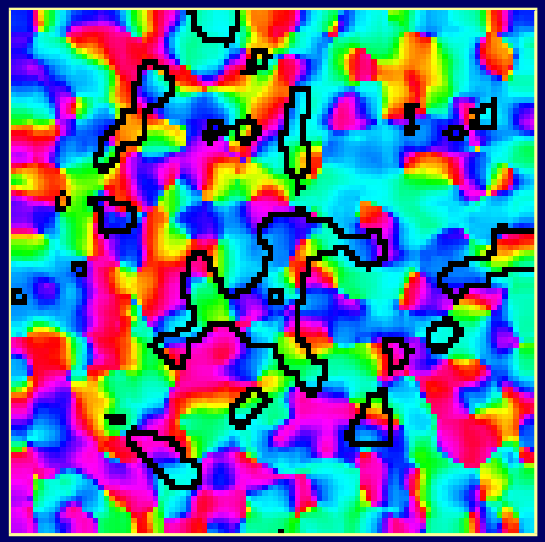


Model

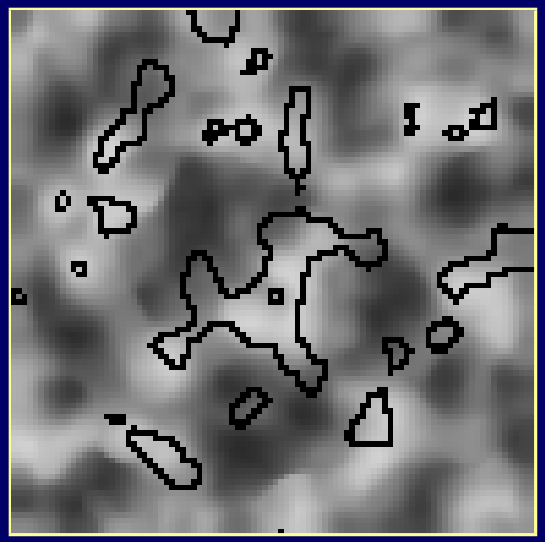


(Macaque, Blasdel 1992; 5×5mm)

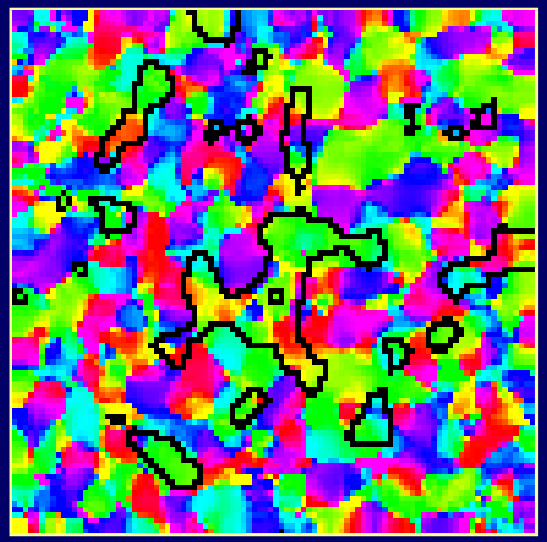
2. OR, OD, DR lateral connections



OR+lateral

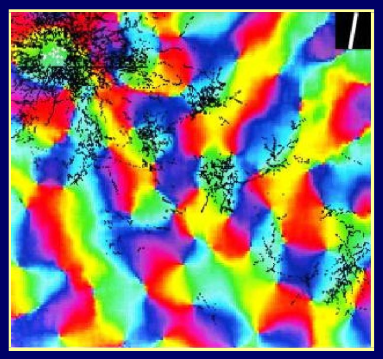


OD+lateral



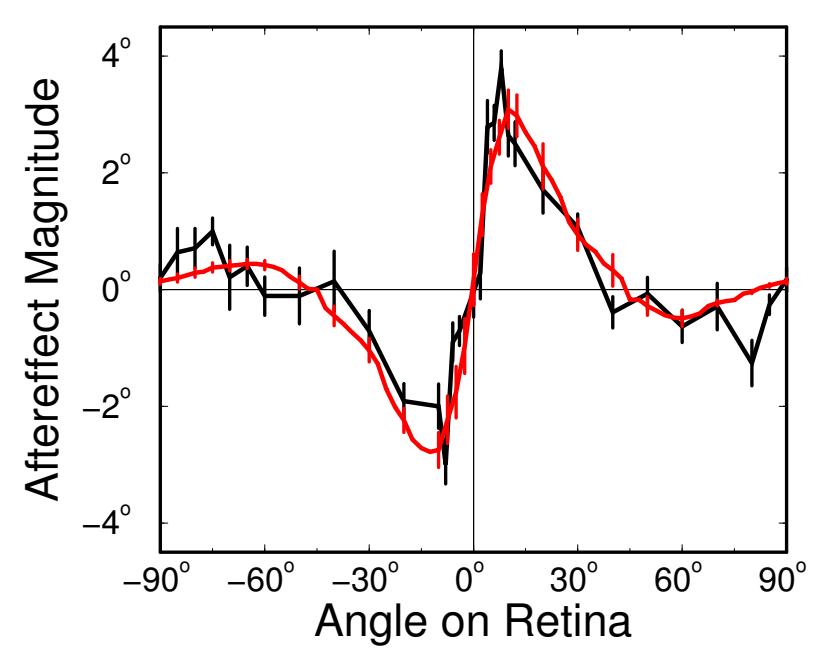
DR+lateral

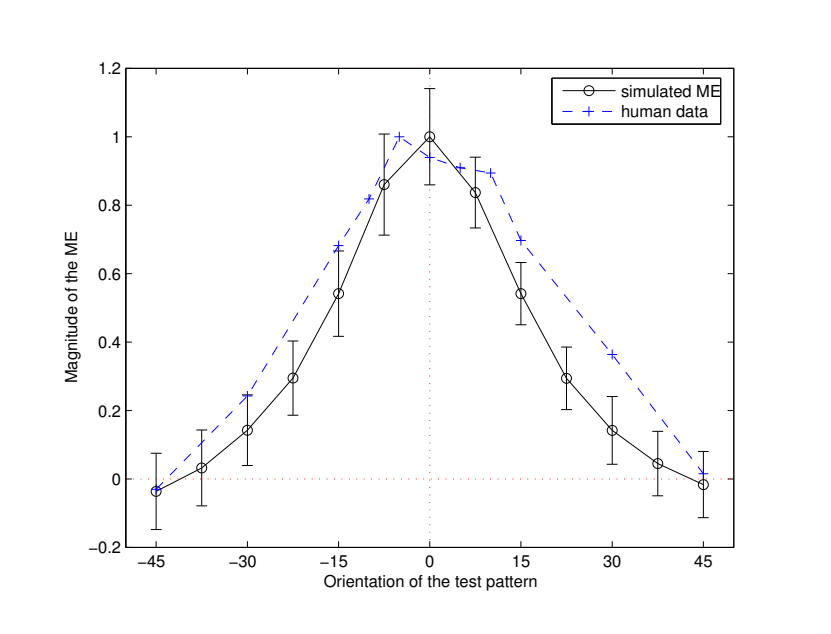
- The lateral connections respect all maps simultaneously, to some degree
- Elongation along orientation axis depends on training set, e.g. with Fitzpatrick lab cages



(Tree shrew; Bosking et al. 1997)

3. Aftereffects

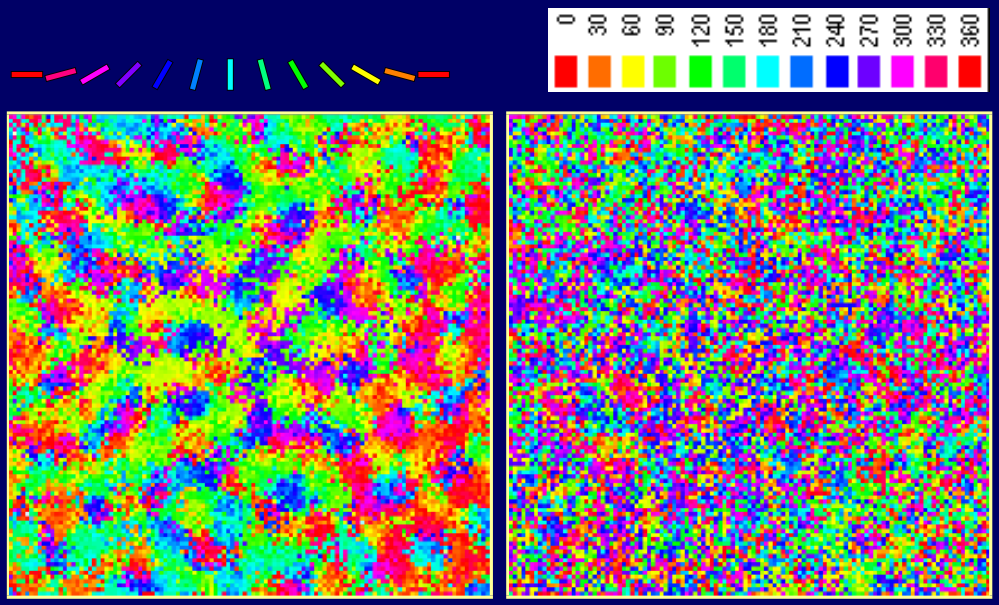




- Complete networks can be tested for psychophysical behavior
- Population response can be decoded as e.g. vector average
- OR maps: tilt aftereffects
- Color maps: McCoullogh effect
- Direction maps: motion aftereffects

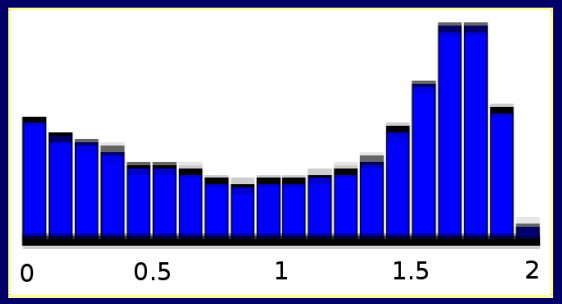
(Bednar & Miikkulainen 2000; Ciroux 2005)

4. Complex cells

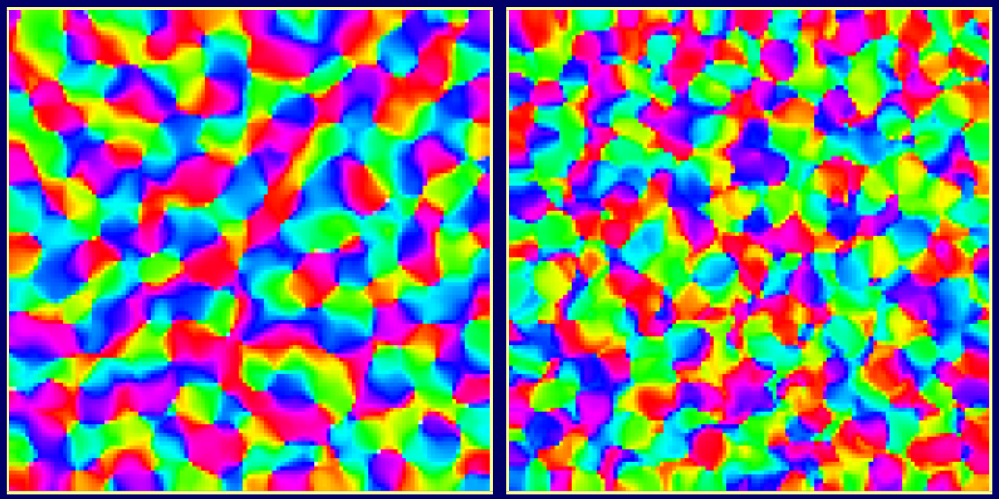


Simple OR

Simple phase

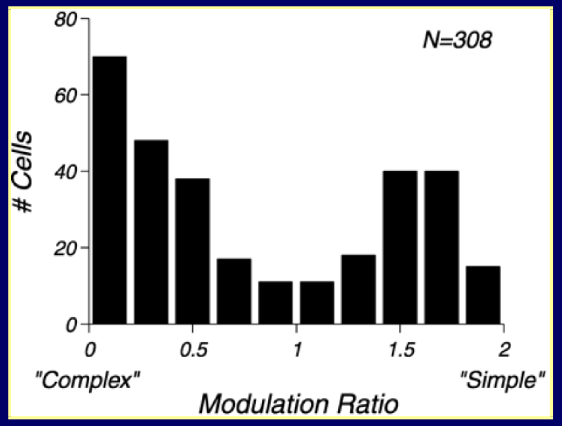


Modulation ratios



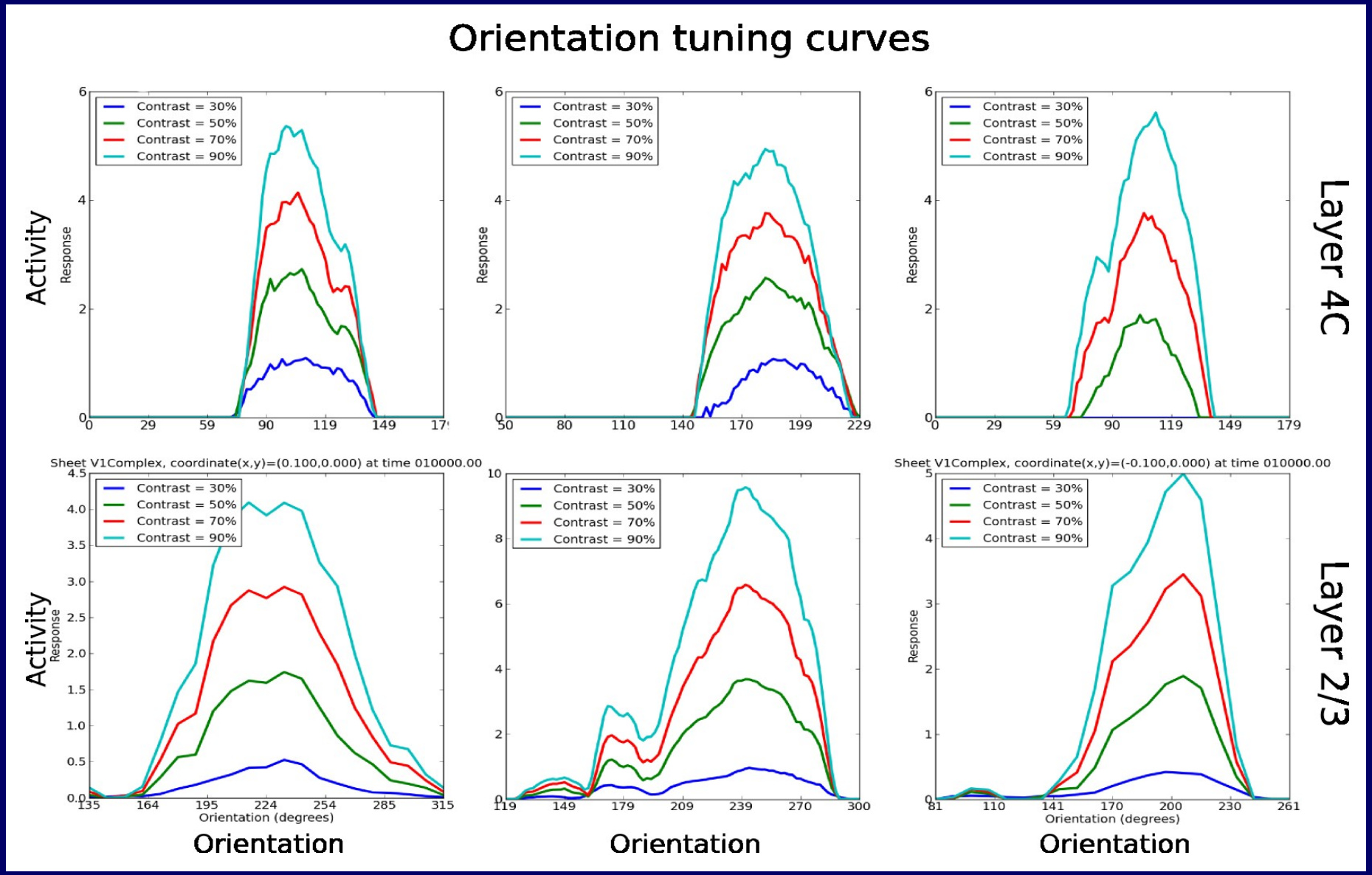
Complex OR

Complex phase



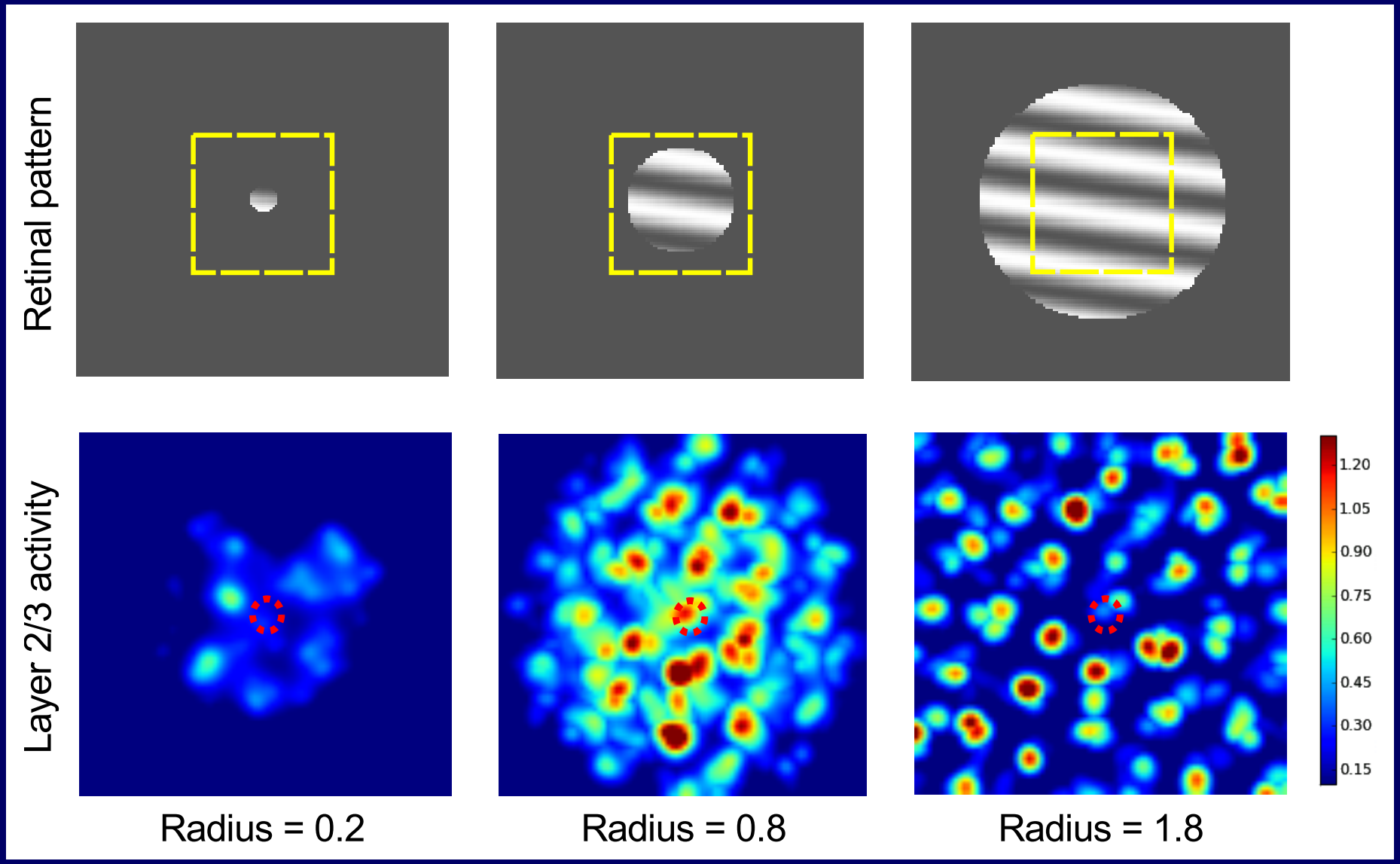
(Macaque; Ringach et al. 2002)

5. Contrast-invariant tuning



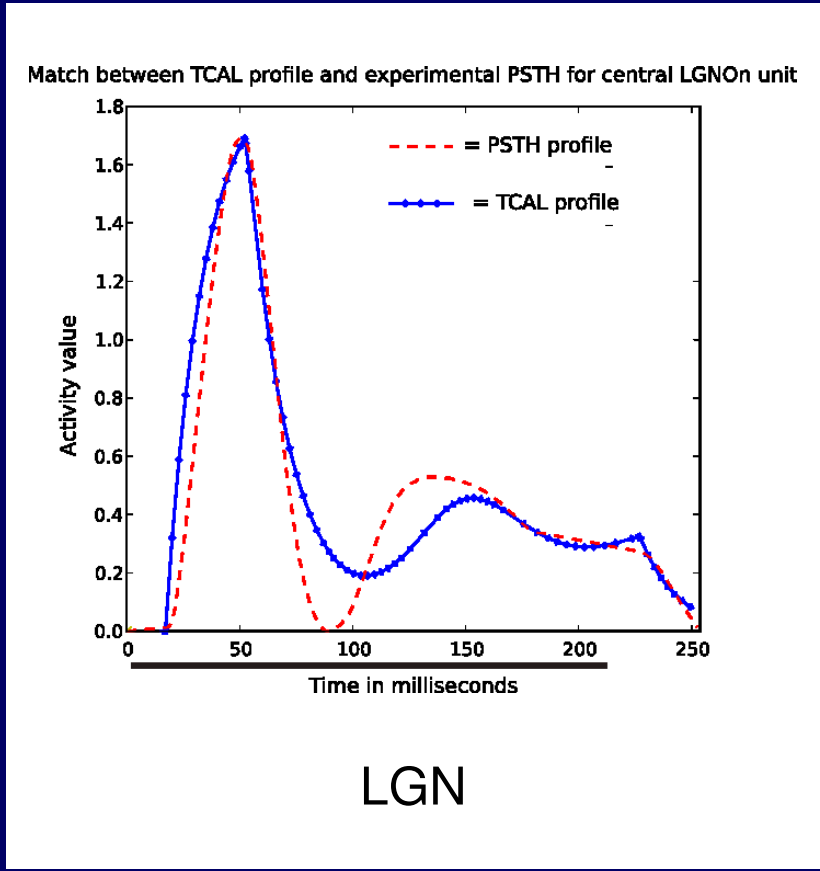
(Antolik 2010)

6. Surround: Size tuning

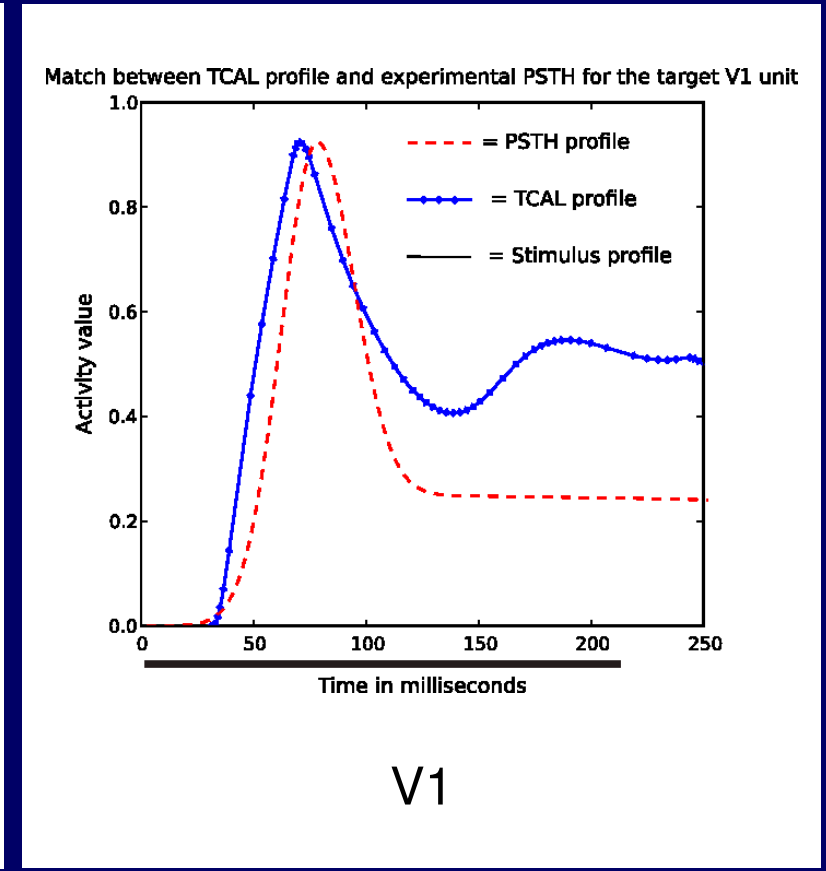


(Antolik 2010)

7. Temporal responses



LGN

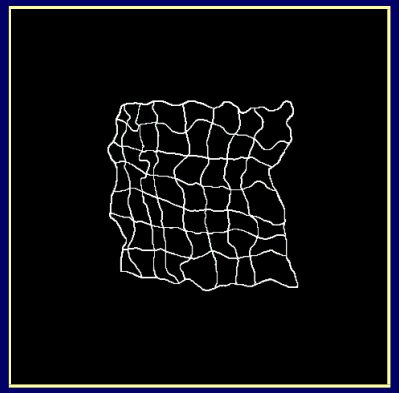


V1

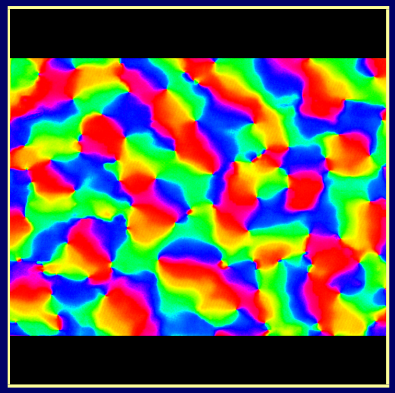
- Smaller timestep and hysteresis (one new parameter) allow match of PSTHs of cat and macaque neurons
- Transient response due to lateral interactions in LGN, V1

(Rüdiger, Stevens, & Bednar 2012; Stevens 2011)

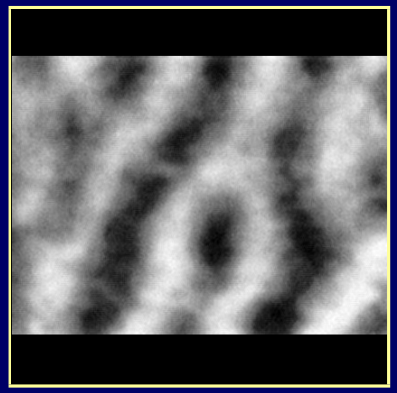
8. Other V1 maps



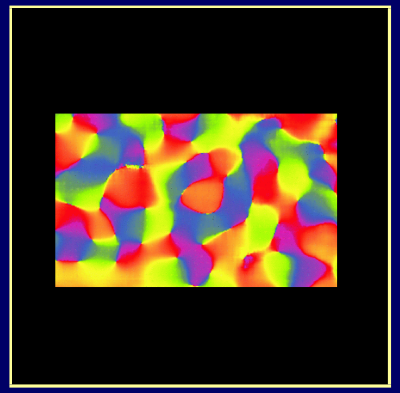
X/Y, tree shrew



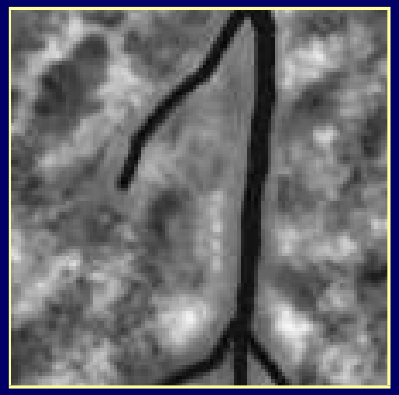
OR, macaque



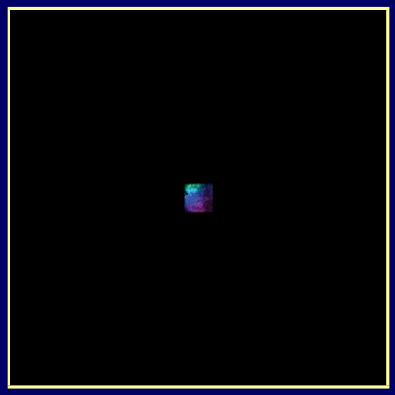
OD, macaque



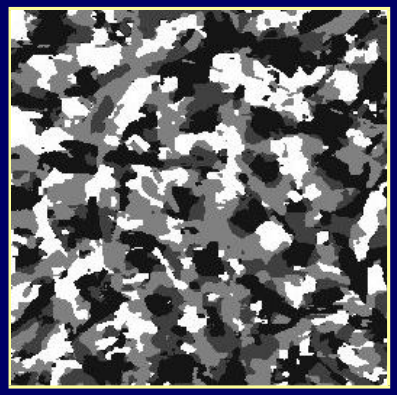
DR, ferret



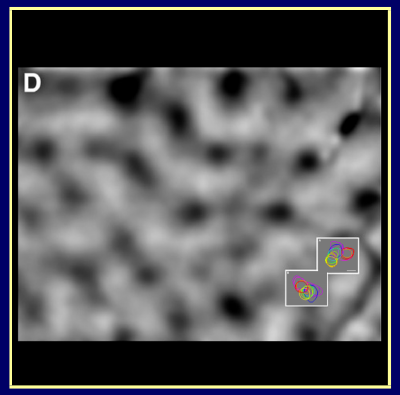
TF, bush baby



DY, cat



SF, owl monkey

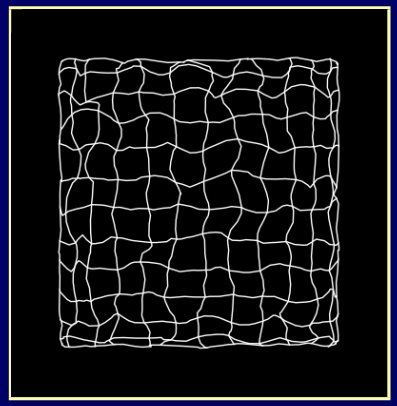


CR, macaque

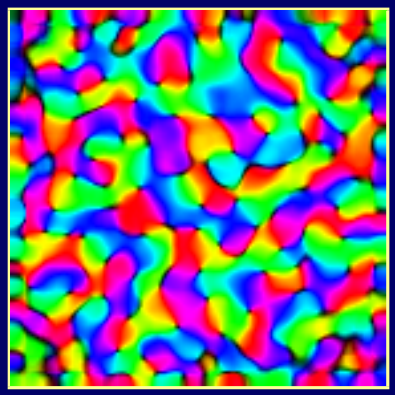
(Each panel shows 4mm × 4mm)

(Blasdel 1992; Bosking et al. 2002; Kara & Boyd 2009; Purushothaman et al. 2009, Weliky et al. 1996; Xiao et al. 2007; Xu et al. 2007)

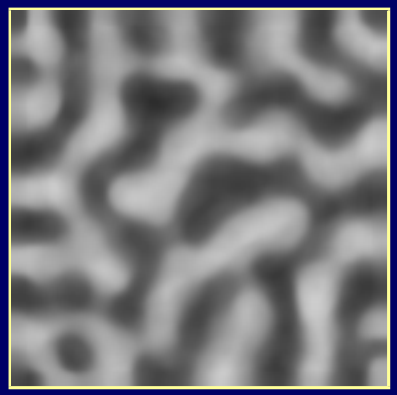
8. Individual model maps



X,Y



OR



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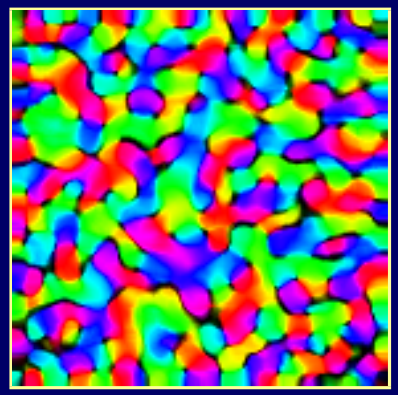

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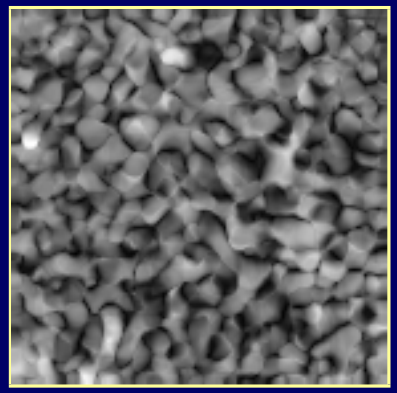
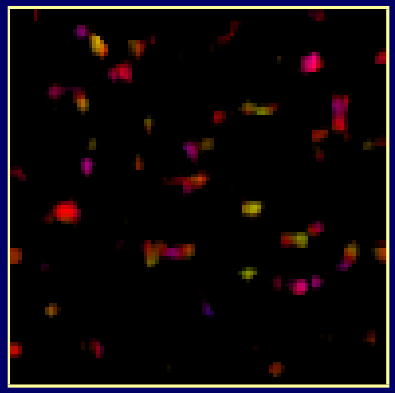
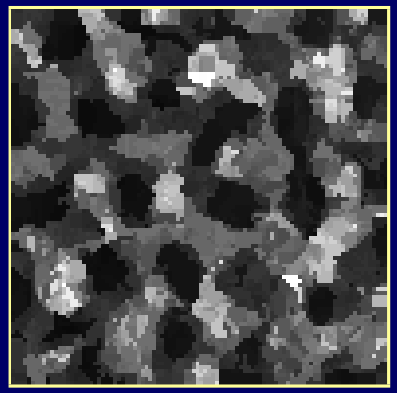


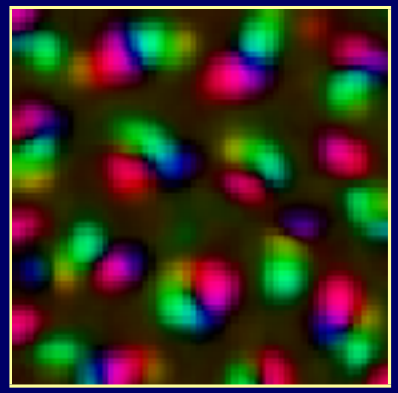
TF



DY



SF



CR

Subsets of features developed in different models

(with C. Ball, T. Ramtohul, C. Palmer, J. De Paula, K. Gerasymova)

Related and Ongoing Work

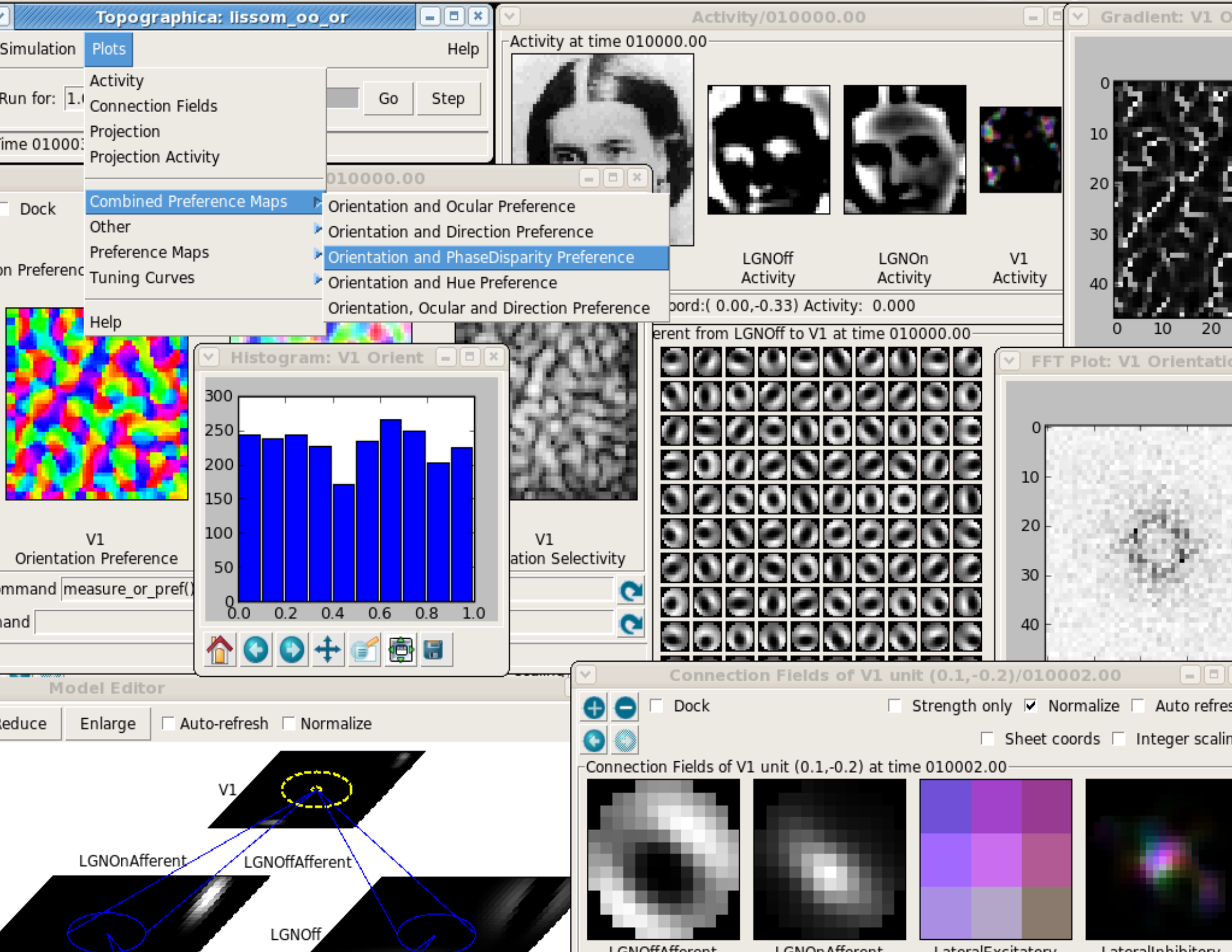
- Whisker barrel cortex maps (S. Wilson et al. 2010)
- Auditory maps (with B. Khan 2009-2011)
- Feedback from V2 (with P. Rudiger, 2011-)
- Mouse/cat models (with J. Law, T. Mrsic-Flogel, 2007-2010)
- Face aftereffects (C. Zhao, Seriès, Hancock, & Bednar 2011)
- Evolving complex systems: (V. Valsalam et al. 2007)
- Real-time pan/tilt camera input (with C. Fillion, 2009-)
- Virtual reality input (with J. Adwick, 2008-)

Conclusions

- Should be feasible to build one model visual system incorporating all these features
- Already explains much of V1 structure and function
- Eventually hope to have a solid, working real-time visual system up to V1, V2, etc.
- If you want to try this out or build on it, the Topographica simulator and example simulations are freely downloadable from **topographica.org**
- Other general-purpose packages at **ioam.github.com**:

  Param (Configurable Python parameters)
  ImaGen (2D pattern generation)
  Lancet (batch job launcher and results organizer)

Extra Slides


Topographica: lissom_oo_or
Simulation
Plots
Help
Activity
Connection Fields
Projection
Projection Activity
Combined Preference Maps
Other
Preference Maps
Tuning Curves
Help
Orientation and Ocular Preference
Orientation and Direction Preference
Orientation and PhaseDisparity Preference
Orientation and Hue Preference
Orientation, Ocular and Direction Preference
Run for:
Go
Step
Dock
Activity/010000.00
Activity at time 010000.00
LGNOff Activity
LGNOn Activity
V1 Activity
Gradient: V1 O
Histogram: V1 Orient
300
250
200
150
100
50
0
0.0
0.2
0.4
0.6
0.8
1.0
V1 Orientation Preference
V1 ation Selectivity
command
measure_or_pref()
erent from LGNOff to V1 at time 010000.00
FFT Plot: V1 Orientatic
Model Editor
Reduce
Enlarge
Auto-refresh
Normalize
V1
LGNOnAfferent
LGNOffAfferent
LGNOff
Connection Fields of V1 unit (0.1,-0.2)/010002.00
Dock
Strength only
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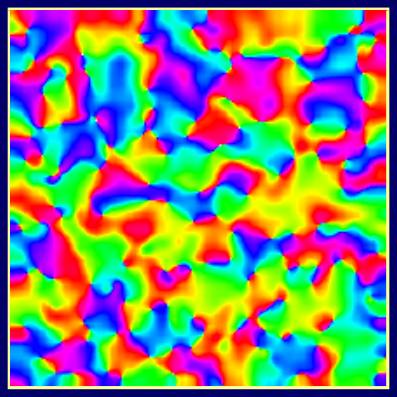
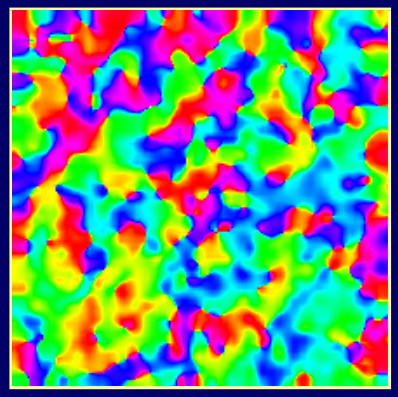
3. Combined map model


X,Y


OR


OD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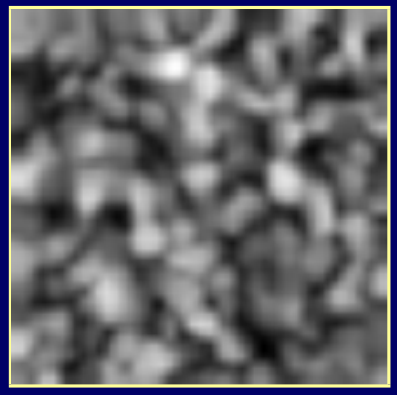
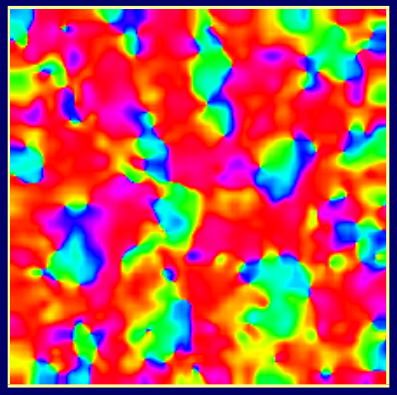
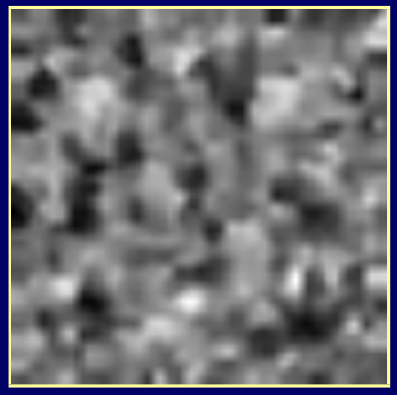
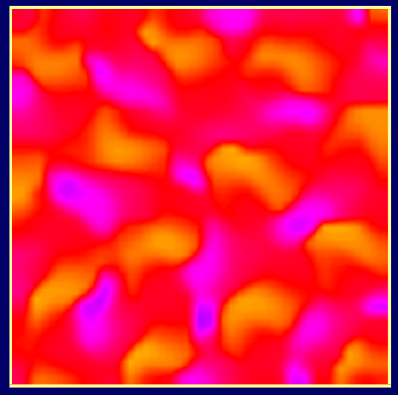

TF


DY

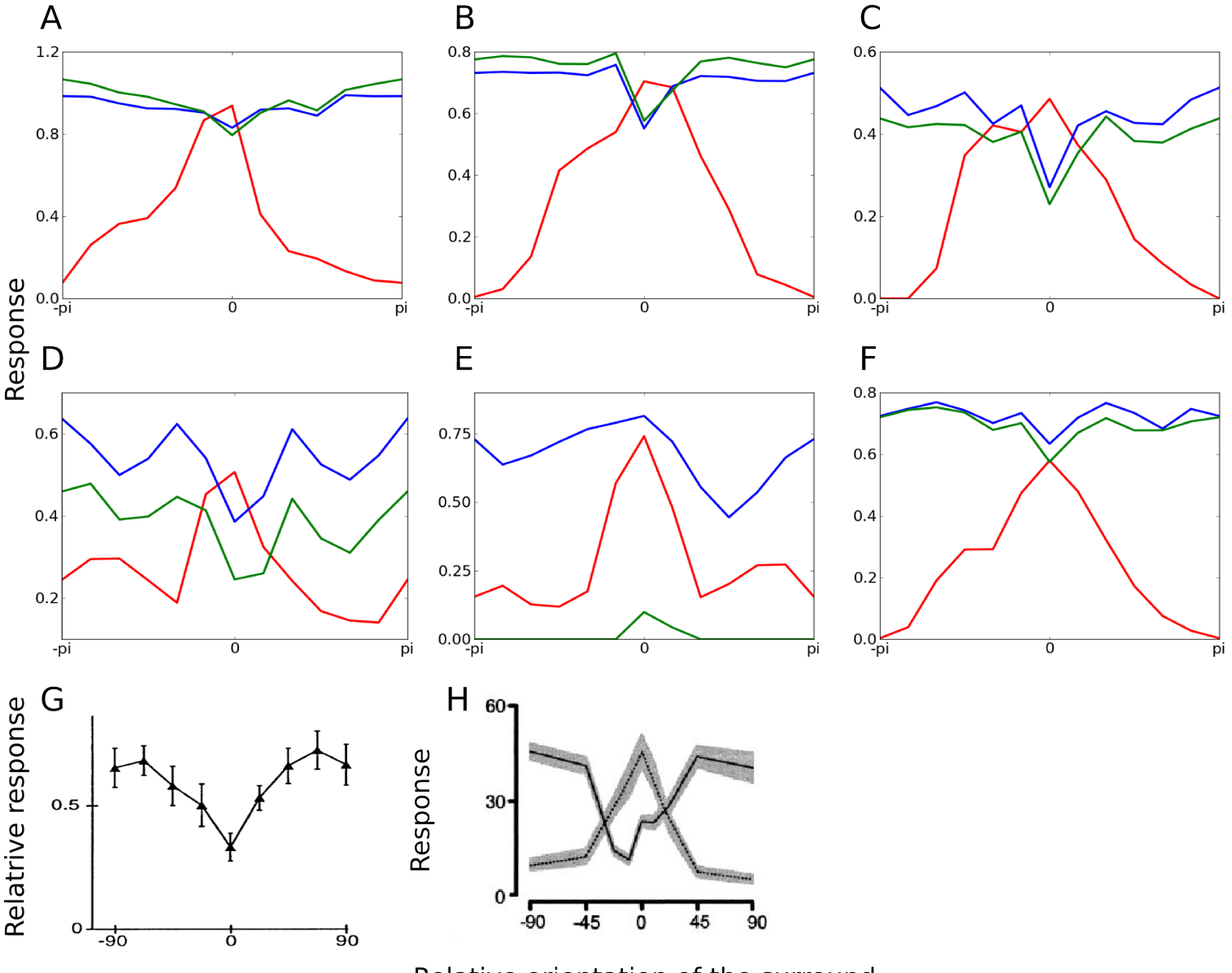

SF


CR

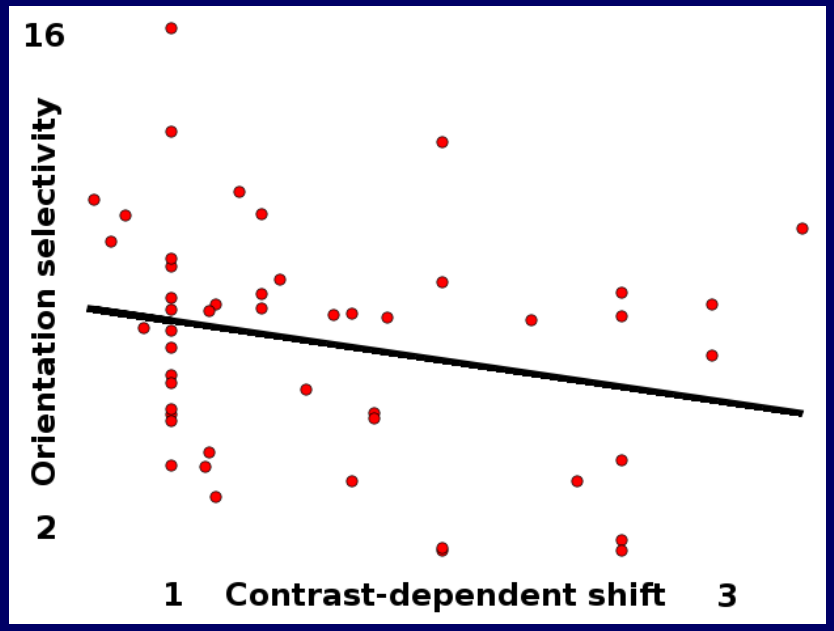
Work in progress! (smoothed)

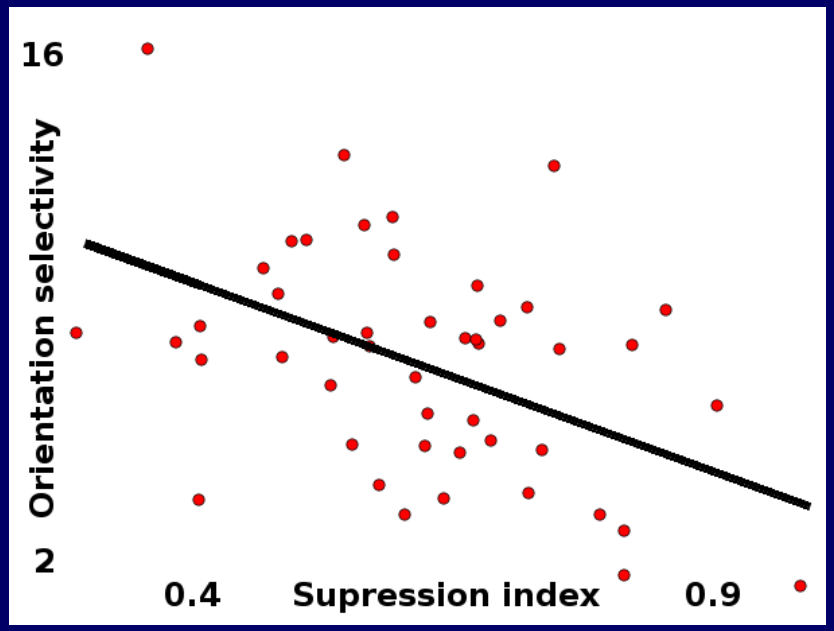
(with K. Gerasymova, C. Ball)

7. OR-contrast tuning



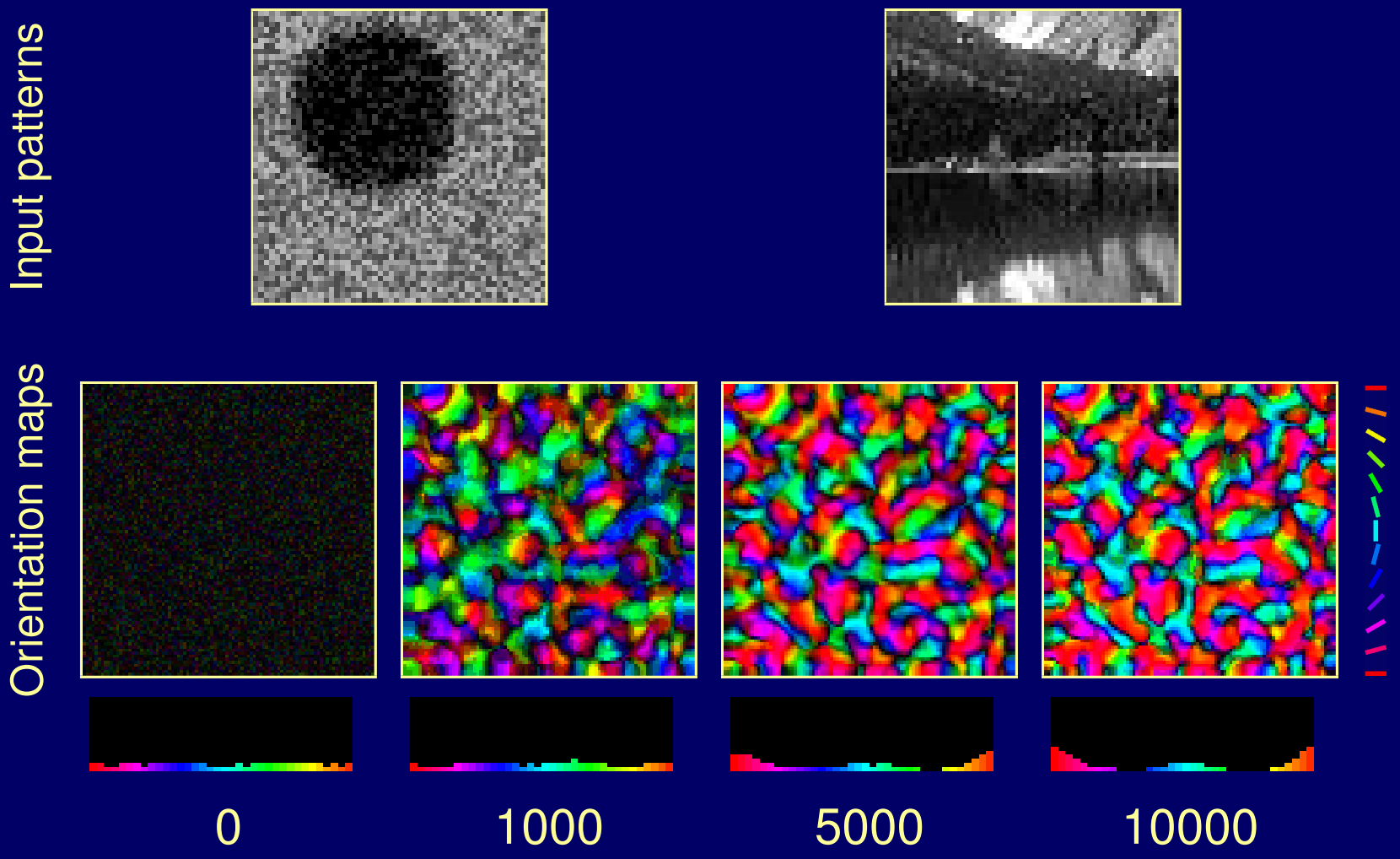
7. Surround: Maps





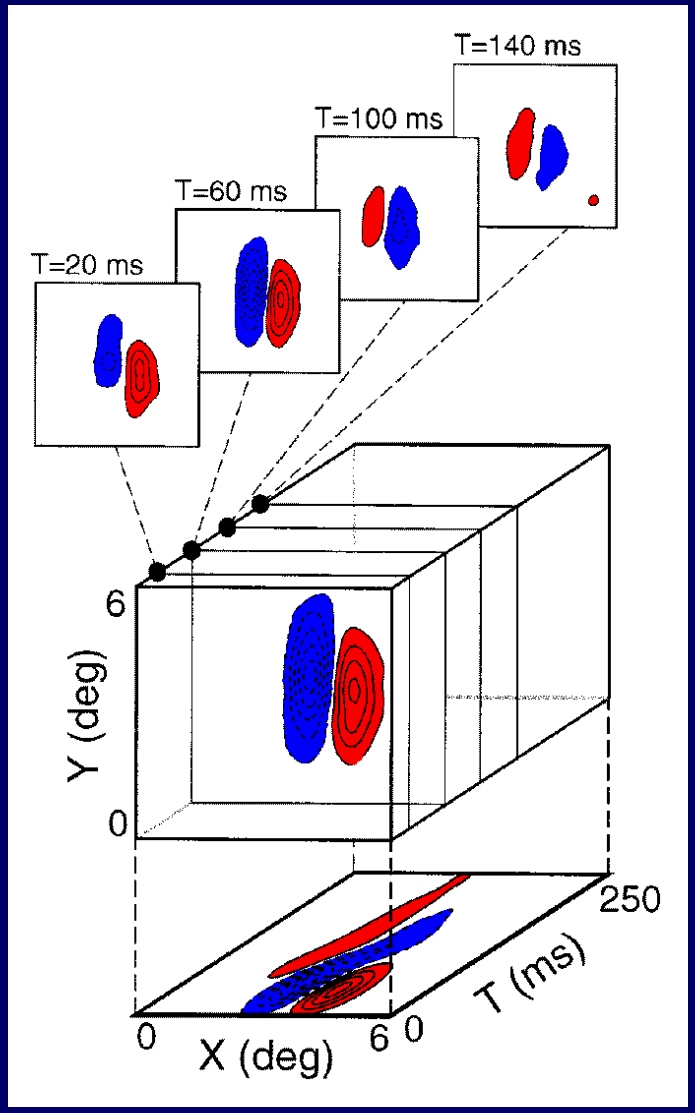
- Prediction: some of the variance is explained by OR selectivity
- Rest likely related to position in maps, connections
- Many effects depend on orientation, position, etc.
- Multidimensional map gives many potential sources of variability

Statistics Drive Development



- Biased image dataset: mostly landscapes
- Smoothly changes into horizontal-dominated map

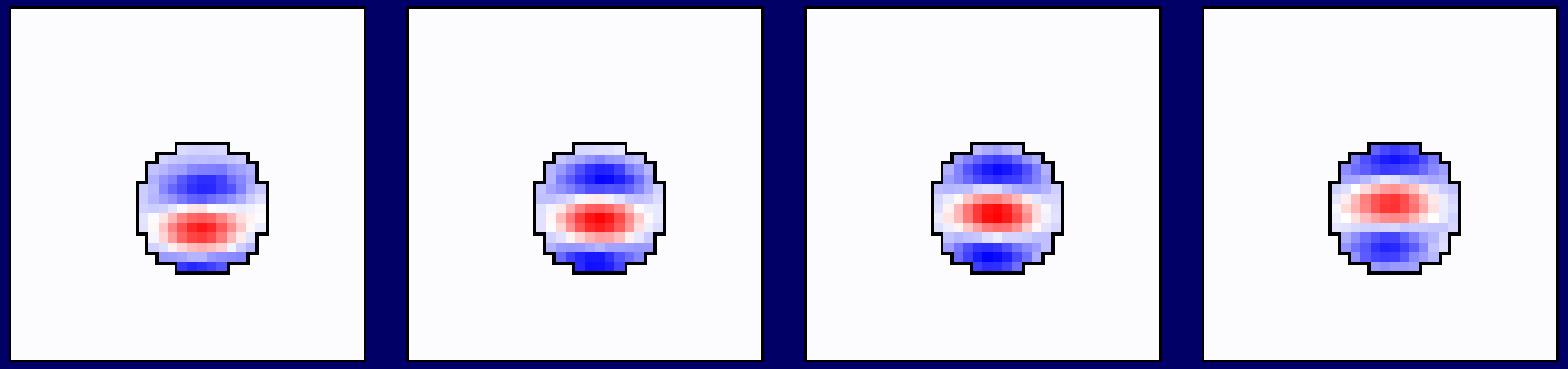
Spatiotemporal Receptive Fields



Cat V1 (DeAngelis et al. 1999)

- Neurons are selective for multiple stimulus dimensions at once
- Typically prefer lines moving in direction perpendicular to orientation preference

Spatiotemporal RFs



Lag 3 Lag 2 Lag 1 Lag 0

- The model develops realistic spatiotemporal RFs
- Strongest response: specific OR, moving in perpendicular DIR

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