A mechanistic model of the development and function of the primary visual cortex

Dr. James A. Bednar

Institute for Adaptive and Neural Computation
The University of Edinburgh
How can we build a visual system with these properties?

1. RFs selective for retinotopy, orientation, ocular dominance, motion direction, spatial frequency, temporal frequency, disparity, color

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
Make a model with:

1. Natural images and spontaneous activity patterns
2. Firing-rate point neurons
3. Subcortical pathway with various LGN or retinal ganglion cell types
4. Layered cortical architecture
5. Initially isotropic, topographic connectivity
6. Hebbian learning with normalization
7. A bunch of parameters
1. Basic model: X, Y, OR

\[ \eta_a = \sigma \left( \sum_r \gamma_r \sum_b X_{rb} w_{a,rb} \right) \]

**Activity**: thresholded weighted sum of all connection fields

Response high when input matches weights

with J. Sirosh, R. Miikkulainen, J. Law, J. Antolik
1. Basic model: X,Y, OR

\[ w_{a,r}(t+1) = \frac{w_{a,r}(t) + \alpha r \eta a X_{rb}}{\sum_c [w_{a,c}(t) + \alpha r \eta a X_{rc}]} \]

Learning:
- normalized Hebbian
- Coactivation → strong connection

Normalization:
distributes strength
2. X, Y, OR, OD, DY, DR, TF

Add another eye, multiple delays → 19 sheets
3. X, Y, OR, OD, DY, DR, TF, SF, CR

Add RGC sizes, color opponency → 87 sheets
4. X, Y, OR, Complex cells, SM

Add gain control in LGN

Model V1 with multiple layers/populations with different connectivity

Connectivity matches known constraints:
long-range excitation, local inhibition, feedback

(with J. Antolik and J. Law)
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; $5 \times 5\text{mm}$
2. OR, OD, DR lateral connections

- 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. Individual model maps

Subsets of features developed in different models

(with C. Ball, T. Ramtohul, C. Palmer, J. De Paula, K. Gerasymova)
3. Combined map model

Work in progress! (smoothed)
(with K. Gerasymova, C. Ball)
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

(with C. Ball, J. Ciroux, 1998-)
4. Complex cells

Simple OR
Simple phase
Complex OR
Complex phase

Modulation ratios

Macaque; Ringach 02
4. Contrast-invariant tuning

Orientation tuning curves

Sheet V1Complex, coordinate(x,y)=(0.100,0.000) at time 010000.00

Sheet V1Complex, coordinate(x,y)=(-0.100,0.000) at time 010000.00

Layer 4C

Layer 2/3
4. Surround: Size tuning

- Retinal pattern
  - Radius = 0.2
  - Radius = 0.8
  - Radius = 1.8

- Layer 2/3 activity
4. Surround: Size tuning curves
4. OR-contrast tuning
4. 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
Related and Ongoing Work

- Decoding 2-photon imaging (with J. Antolik, T. Mrsic-Flogel, 2008-)
- Face aftereffects (with C. Zhao, P. Hancock 2006-)
- Whisker barrel cortex maps (with S. Wilson, T. Prescott 2007-)
- Random retinal wiring (with C. Ball, A. Hurlbert 2009-)
- Real-time pan/tilt camera input (with C. Fillion, 2009-)
- Virtual reality input (with J. Adwick, 2008-)
- Auditory maps (with B. Khan 2009-)
- Topographica simulator (with C. Ball, J. Provost, et al. 2004-)
Conclusions

• Should be feasible to build one model visual system incorporating all these features

• Seems to explain a large percentage of structure, 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


Erwin, E., & Miller, K. D. (1998). Correlation-based development of ocularly matched orientation and ocular dominance maps:


Miller, K. D. (1992). Development of orientation columns via com-
petition between ON- and OFF-center inputs. *NeuroReport*, 3, 73–76.


