Large-scale “realistic” models of V1 cortex

Robert Shapley
Center for Neural Science NYU

Collaborative work with
Michael Shelley, David McLaughlin, Jim Wielaard, Louis Tao, Wei Zhu
Courant Institute of Mathematical Sciences, NYU

Dajun Xing
Center for Neural Science, NYU
Aims

• Realistic network models of V1 cortex
• What is needed to emulate V1 function?
• Orientation selectivity
• Simple and Complex cells
• Spatial Frequency Selectivity
Bill Gates’ greatest contribution (D. Barry)

The idea of “the Version”.

Version 1 is OK. Version 2 improves on Version 1 but it still doesn’t work. And so on, by induction...
Primate visual system, cartoon
Macaque V1
Cortico-cortical connections: columns and layers
Orientation tuning dynamics of firing rate
(Celebrini et al 1993)
Figure 8. Averaged tuning curves of visual response of orientation-selective cells (OSI ≥ 0.50) in each layer.
Increment counter corresponding to this orientation by +1

Input Image Sequence

Nerve Impulse Train

Time
Features of the Version 1 Model

• $O(10^4)$ integrate and fire neurons
• two populations, E and I neurons in cortex
• fast LGN-->cortical excitation
• fast cortico-cortical excitation
• fast cortical inhibition
• very strong cortico-cortical inhibition
• local cortico-cortical connections
• isotropic in cortical space
• no selectivity in the local connections
• Relatively weak cortico-cortical excitation
Model details

- Integrate & fire, point neuron model
- 16,000 neurons/sq mm
- 12,000 excitatory, 4000 inhibitory
- A patch (1 sq mm) of 4 orientation hypercolumns
- Orientation pref from convergent LGN input
- Coupling architecture, set by anatomy
- Local connections isotropic
- Excitation longer range than inhibition
- Cortical inhibition dominant
\[
\frac{dv^j_\sigma}{dt} = -g_R v^j_\sigma - g^j_{\sigma E}(t)[v^j_\sigma - V_E] - g^j_{\sigma I}(t)[v^j_\sigma - V_I]
\]

\(v^j_\sigma\) -- membrane potential

-- \(\sigma = \) Excitation, Inhibition
-- \(j = 2\)-dimensional label of location on cortical layer

\(V_E\) & \(V_I\) -- Excitatory & Inhibitory Reversal Potentials
Synaptic Conductances

Excitatory

\[ g_{oE}(t) = g_{\text{LGN}}(t) + g_{\text{noise}}(t) + g_{\text{cortical}}(t) \]

(driving term) (synaptic noise) (cortico-cortical)

Inhibitory:

\[ g_{oI}(t) = g_{\text{noise}}(t) + g_{\text{cortical}}(t) \]

(synaptic space scale) \((L_{\text{Exc}} > L_{\text{Inh}})\)
Cortico-cortical and LGN input
Disk of Monosynaptic Inhibition

Inhibition - "local" in cortical space
- "global" in orientation (θ)
  (near pinwheels)
V1 responses to drifting gratings, version 1
Conductances in version 1 response to drifting gratings

(a) excitation

(b) inhibition
The model is in a high conductance state.

dv/dt is negligible, and therefore \( v \) can be approximated as a function \( V_s \) of the conductances

\[
v \sim V_s = \frac{[g_E V_E + g_I V_I]}{g_T} \quad \text{where} \quad g_T = g_R + g_E + g_I
\]
High conductance state: membrane potential tracks $V_s$
Local circuit inhibition acts like “gain” in Version 1 high conductance state

\[ v(t) \simeq V_S = \frac{g_E V_E + g_I V_I}{g_L + g_E + g_I} \]

\[ \simeq \frac{g_E V_E + g_I V_I}{g_I} = V_I \left(1 + K \cdot \frac{g_E}{g_I}\right), \quad (16) \]

with \( K = \frac{V_E}{V_I} \). And so, the modulation of \( V_S \) (and hence \( v \)) is approximately the ratio of excitatory to inhibitory conductances.

From Shelley et al 2002 p. 104
Orientation tuning in version 1

(b) Model

90  180  270
Version 1 prediction of orientation dynamics
Version 2, egalitarian model

• integrate and fire neurons
• two populations, E and I neurons in cortex
• fast LGN-->cortical excitation
• both fast and slow cortico-cortical excitation
• fast cortical inhibition
• very strong cortico-cortical inhibition
• local cortico-cortical connections isotropic in cortical space
• no selectivity in the local connections
• Strong and weak cortico-cortical excitation
Egalitarian model (Version 2)
Simple and complex cells in the version 2 model
drifting-grating responses
Orientation tuning of conductances, voltage and firing rate in sparse egalitarian model (Tao et al. 2006)
Version 3

- Integrate and fire neurons
- Two populations, E and I neurons in cortex
- Fast LGN-->cortical excitation
- Both fast and slow cortico-cortical excitation
- Fast cortical inhibition
- Very strong cortico-cortical inhibition
- Local cortico-cortical connections isotropic in cortical space
- No selectivity in the local connections
- Strong and weak cortico-cortical excitation
- Diverse spatial frequency preferences
Strong correlation between ori and sf tuning
(Xing et al 2004)
LGN inputs to different cells in the Version 3 model
Orientation and spatial frequency tuning in Version 3
Spatial-Frequency and orientation selectivity in Version 3
Spatial Frequency Selectivity correlated with inhibitory conductance

Simple cells

Complex cells
Inhibition, and correlation of ori and sf selectivity version 3

N = 337
r = 0.65

Average Inh = 403; Average Exc = 86
Average Inh = 443; Average Exc = 86
Conclusions

- Selectivity and diversity emerge in recurrent cortical network
- Cortical stability, selectivity require strong recurrent inhibition
- Fluctuations cause spikes in the network neurons
- Spatial-frequency-selectivity as well as orientation-selectivity influenced by (nonlinear) cortical inhibition