Spatiotemporal Dynamics of Spontaneous Activity in V1

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Outline

• Coherent, spontaneous ongoing activity in primary visual cortex

• Large-scale modeling of coupled $10^5$-$6$ integrate-and-fire neuronal networks

• Intermittent De-suppressed (IDS) dynamic regime captures almost all phenomena observed in VSD optical imaging experiment.

• Mechanisms: the network architecture and synaptic dynamics
  – Significance of operating-point of cortical dynamics
    – Fluctuation-dominated Dynamics vs. e.g. Dynamics of Marginal phase.
V1 & the Visual Pathway

Individual neurons are tuned to stimulus orientation
in vivo Optical Imaging based on Voltage Sensitive Dyes

Spatial resolution: 0.5 μm – 50 μm
Temporal resolution: 0.1 msec

from Grinvald, Hildesheim, Nat. Rev. Neurosci 2004
Spontaneous Activity of Single Neurons vs. the Underlying Functional Architecture

- **PCS** (Preferred Cortical State) of a neuron: 
  \[ V_p(x; \theta_{op}) \equiv \sum_i V(x, T_f^i; \theta_{op}) / N_f \] under optimal drive.

- **Spike-triggered Spontaneous Pattern** vs. Evoked: 
  \[ \bar{V}_{st}(x) \equiv \sum_i V(x, T_f^i) / N_f \]

- **SI** (Similarity Index): the correlation coefficient \( \rho(\theta_{op}; t) \) b/w instantaneous \( V(x, t) \) and the PCS

Experiments such as VSD optical imaging in combination of single unit recordings are extremely useful.
Facts
Marginal-Phase  

\[ \tau \frac{d}{dt} m(\theta, t) = -m(\theta, t) + g \left[ h(\theta, t) \right] \]

\[ h(\theta, t) = \int_{-\pi/2}^{\pi/2} \frac{d\theta'}{\pi} J(\theta, \theta') m(\theta', t) + h^\text{ext} (\theta - \theta_0) \]

\[ J(\theta) = -J_0 + J_2 \cos 2\theta \]

\( J_0 > 0 \): a uniform all-to-all inhibition

\( J_2 > 0 \): orientation-specific excitatory coupling

\[ h^\text{ext} (\theta) = c \left[ 1 - \varepsilon + \varepsilon \cos 2\theta \right] \]

\[ m(\theta) = M (\theta - \theta_0) \]

Self-consistency:

\[ M (\theta) = g \left[ H (\theta) \right] \]

\[ M (\theta) = m_0 + m_2 \cos 2\theta \]

\[ H (\theta) = (\varepsilon c + J_2 m_2) \cos 2\theta + c (1 - \varepsilon) - J_0 m_0 \]

\[ M (\theta) = \beta (\varepsilon c + J_2 m_2) [\cos 2\theta - \cos 2\theta_c] \]

where \( H (\pm \theta_c) = 1 \)
**Our Model (~16mm², 64 pinwheels)**

5x10^5 coupled Integrate & Fire (I&F), conductance-based, point neurons

\[
\tau \frac{dV_E(x)}{dt} = -[V_E(x) - E_R] - g_{EE}(x,t)[V_E(x) - E_E] - g_{EI}(x,t)[V(x) - E_I]
\]

\[
g_{EE}(x,t) = F_{LGN}(x) + f_{noise}(x) + S^E_S \sum_{x,x'} K^S_{x,x'} \sum_l G^S_l \left(t - T^l_{f, x'}\right) + S^E_L \sum_{x,x'} K^L_{x,x'} \sum_l G^L_l \left(t - T^l_{f, x'}\right)
\]

**Spontaneous:** \( F_{LGN} = 0 \)

**Local**

**Long Range**

Nonlinearity from spike-threshold:
Whenever \( V(x,t) = V_T \), the neuron "fires", spike-time \( T^l_{f, x'} \) recorded, and \( V(x,t) \) is reset to \( E_R \), held at \( E_R \) for an absolute refractory period \( \tau_{ref} \).

Conductance Time Course:

Local:
\[
G_\text{local}(t) = \frac{f}{\sigma_d - \sigma_r} \left( \exp \left[ -\frac{t}{\sigma_d} \right] - \exp \left[ -\frac{t}{\sigma_r} \right] \right) \theta(t)
\]

Long-range:
\[
G_\text{long}(t) = (1 - \Lambda) G_{\text{AMPA}}(t) + \Lambda G_{\text{NMDA}}(t)
\]

AMPA: ~5ms
NMDA: ~80-100ms
Network Architecture

Tiling of Orientation Hypercolumns

Short Range (Excitatory and inhibitory):

\[ K^S_{xx'} = \frac{1}{2\pi \sigma_{EE}^2} \exp\left(-\frac{|x-x'|^2}{\sigma_{EE}^2}\right) \]

\[ \sigma_{EE}, \sigma_{EI} \sim 100 - 300 \mu m \]

Long Range, Excitatory Connections:

1. Gaussian, \( \sigma_L \sim 1500 \mu m \)
2. NMDA + AMPA
3. Orientation-specific, Anisotropy
Short Range (Excitatory and inhibitory):

\[ K^S_{x,x'} = \frac{1}{2\pi \sigma^2_{EE}} \exp\left( -\frac{|x - x'|^2}{\sigma^2_{EE}} \right) \]

\[ \sigma_{EE}, \sigma_{EI} \sim 100 - 300 \mu m \]

Marino, Schummers, Lyon, Schwabe, Beck, Wiesing, Obermayer, Sur
Nature Neurosci. 2005
Long Range, Excitatory Connections:

1. Gaussian, $\sigma_L \sim 1500\mu m$
2. NMDA + AMPA
3. Orientation-specific, Anisotropy
Two Essential Components in Our Model:

For the long-range coupling,

1) Slow NMDA conductance

2) Orientation-specific

N.B.

Scale-up using fast algorithms

1) Integrating Factor;
2) Spike-Spike Corrections
3) Spatially Local Structures

Realizability
Coherent, Spontaneous Ongoing Activity:

Intermittent De-Suppressed (IDS) State:

- Patterns corresponding to particular orientations persist, drifting for ~80msec.
- Simultaneous emergence of activity over > 0.5mm

Patterns do not have to span the entire network.
— not transient, also persist, drifting
— not marginal phase

Coherent, Spontaneous Ongoing Activity:

Simulation:
Coherent, Spontaneous Ongoing Activity — *Simulation*

Intermittent De-suppressed Regime
Intermittent De-Suppressed Dynamics — Patterns
— Controlling parameter: Long-range coupling strength

 PCS:
Simulation:

Experiment:

Spike-triggered (Spontaneous)
Intermittent De-Suppressed Dynamics — Timescales

— Controlling parameter: Long-range coupling strength

Time Correlations —
Voltage: Similarity Index:

\[ C_V \]
\[ C_{SI} \]

N.B.
If AMPA only, timescale \( \sim O(10\text{msec}) \) instead of \( \sim O(100\text{msec}) \)

\[ \rho(\theta_{op},t) \text{ vs Time} \]

\[ \theta_{op} \]

\[ \rho(\theta_{op},t) \text{ vs Time} \]

\[ \theta_{op} \]

\[ \rho(\theta_{op},t) \text{ vs Time} \]

\[ \theta_{op} \]

\[ \rho(\theta_{op},t) \text{ vs Time} \]

\[ \theta_{op} \]
Intermittent De-Suppressed Dynamics — SI Distributions

— Controlling parameter: Long-range coupling strength

\[ P(\text{spike} \mid SI) = \frac{P(SI \cap \text{spike})}{P(SI)} \]
The Underlying Mechanisms: **Intermittent De-suppressed State**

\[
\frac{d}{dt} V = -g_T (V - V_S),
\]

\[g_T = g_L + g_{AMPA} + g_{NMDA} + g_{Inhi}\]

\[V_S \approx \mathcal{E}_E \frac{g_{NMDA}}{g_{Inhi}} + \mathcal{E}_I\]

1) **High Conductance State:**

\[g_T \gg 1 \quad V \sim V_S\]

2) **Strongly Inhibited Intermittent De-suppressed:**

\[V_S \sim V_R, \quad \frac{g_{inhi}}{g_{exc}} \sim 6\]

Not a ‘balanced’ network!
Causality: Patterns vs. Firings

\[ \rho(\theta, t), \quad m(\theta, t) \]
Additional Features of Intermittent De-suppressed Dynamics

Synchronized spontaneous fluctuations:

Lampl, Reichova, and Ferster, Neuron 1999

Cell 1

Cell 2

Simulation:
Additional Features of Intermittent De-suppressed Dynamics

Disinhibition from Cross-orientation Sites:

Synchrony of Neuronal ensembles:

cf. A.B. Bonds et al.
Homogeneous Dynamic Regime

— Weak long-range connection strength

- Single-State Hypothesis?  
  Goldberg, Rokni, Sompolinsky, Neuron 2004

\[ \rho(\theta_{op}, t) \text{ vs Time} \]

\[ \theta_{op} \]

\[ \theta_{op} \]

SI vs. Time

SI vs. Time

1000 2000 3000 4000 msec

Correlation coefficient

Correlation coefficient

Correlation coefficient

Probability of firing

Spike-triggered (Spontaneous)

Distribution of SI

PCS: Spike-triggered (Spontaneous)

Goldberg, Rokni, Sompolinsky, Neuron 2004
Locked Dynamic Regime

— Strong long-range connection strength

➢ Multi-state Hypothesis (Marginal Phase)?

Goldberg, Rokni, Sompolinsky, Neuron 2004

\[ \rho(\theta_{op}, t) \text{ vs Time} \]

\[ \theta_{op} \]

\[ 0, 20, 40 \]

\[ 0, 90, 180 \]

SI vs. Time

\[ 0, 0.5, 1 \]

\[ -0.5, 0, 0.5 \]

\[ 1000, 2000, 3000, 4000 \text{ msec} \]

\[ 0, 0.5, 1, 1.5, 2 \]

Correlation coefficient

Spike-triggered (Spontaneous)

Distribution of SI

All frames

Spike-triggered

Goldberg, Rokni, Sompolinsky, Neuron 2004
Conclusions

• Experiments such as VSD optical imaging with high spatial and temporal resolutions in combination with single neuron recordings are powerful
  – Provide spatiotemporal information in concert with individual neuron activity to strongly constrain network dynamics modeling.
  – Can sharply discriminate competing network mechanisms.

• Our large-scale I&F modeling shows that fluctuation-dominated dynamics reproduces almost all features of the experimental observations
  – Intermittent De-suppressed regime is a possible cortical operating-point
  – Long-range: NMDA and orientation-specific