Coding with Dynamic Synapses and Receptive Fields

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Two Parts

- Both motivated by our work on weakly electric fish
- Two general coding principles
Part 1: Synchrony and Receptive Fields

• Motivation: Electrosensory communication
• Synchrony data
• Neural modeling of decoding
• Synchrony decoded with large receptive fields

Electrosensory system

Weakly electric fish (brown ghost)
From Brian Rasnow, Caltech
Electrolocation

Beat patterns due to neighbors
Parallel Fish

Kelly, Babineau, Longtin, Lewis,  Biol. Cybern. 2008
ELECTRORECEPTORS

- ALL SPATIO-TEMPORAL SCALES

- The EOD field excites 16,000 cutaneous electroreceptors.
Electrocommunication

Female: EOD < 800 Hz
Male: EOD > 800 Hz
Same gender interactions: Calls synchronize receptors

Benda, Longtin, Maler, J. Neurosci. 2005
Female-Male Interactions: Calls desynchronize receptors

Benda, Longtin, Maler, Neuron 2006
Leaky Integrate-and-Fire Model with Dynamic Threshold


\[
\dot{v} = -\frac{v}{\tau_v} + a(t)\sin(2\pi ft) + \xi(t)
\]

\[
\dot{w} = \frac{w_0 - w}{\tau_w}
\]

\[
v(t_{fire}^+) = 0 \quad \text{if} \quad v(t_{fire}) = w(t_{fire})
\]

\[
w(t_{fire}^+) = w(t_{fire}) + \Delta w \quad \text{if} \quad v(t_{fire}) = w(t_{fire})
\]
How are changes in synchrony decoded?

Model of receptors
Models of ELL pyramidal cells driven by receptor data
Eventually include short-term plasticity between them
Spectral measures

Fourier transform

$$\tilde{x} = \frac{1}{\sqrt{T}} \int_{0}^{T} dt \ e^{2\pi if t} x(t)$$

Cross spectra of synaptic input/voltage and input signal

$$S_{Xs} = \langle \tilde{X} \tilde{s}^* \rangle \quad \quad S_{Vs} = \langle \tilde{V} \tilde{s}^* \rangle$$

Coherence functions

$$C_{Xs} = \frac{|S_{Xs}|^2}{S_{ss} S_{XX}} \quad \quad C_{Vs} = \frac{|S_{Vs}|^2}{S_{ss} S_{VV}}$$
Data: synchronous spike coherence

- **Paired single units**
  - all spikes
  - synchronous spikes

- **Dual unit recordings**
  - all spikes
  - synchronous spikes

- **Shuffled dual units**
Postsynaptic Decoders

• 3 Somatotopic maps:

• Centro-medial (CMS)

• Centro-lateral (CLS)

• Lateral (LS)
Cerebellar granule cells

Pyramidal cells

GABA interneurons

Electroreceptors

columns

LS

CLS

CMS

ELL

Maps
Receptive Fields

CMS map: small receptive fields = high spatial frequency

CLS map: intermediate

LS map: large receptive fields = low spatial frequency
Temporal Filtering Properties

coherence

CMS

CLS

LS

Frequency

0.8
0.6
0.4
0.2
0

0
20
40
60

low-pass

high-pass

Mehaffey, et al. (2008)
Neural models: experimental constraints

- Different receptive field (RF) sizes:
  LS - large RFs (high convergence)
  CMS - small RFs (low convergence)

- Different spike thresholds:
  LS - high threshold (-67mV)
  CMS - low threshold (-61 mV)

- Output firing rates are roughly conserved across maps:
  LS - 18 Hz
  CMS - 14 Hz
Neural models: current threshold model

Low convergence
low threshold

High convergence
high threshold

Input

Threshold

Current threshold model

Coherence

Frequency (Hz)

Time (ms)

Stimulus

Superthreshold current
Synchronous spikes
Conductance-based model

\[ C \frac{dv(t)}{dt} = I_{DC} - g_{shunt} (v(t) - E_{shunt}) - g_{syn} x(t) (v(t) - E_{AMPA}) \]
Temporal Filtering Properties

- **coherence**
  - CMS
  - CLS
  - LS

- low-pass
- high-pass

Mehaffey, et al. (2008)
Summary

- Synchronous (electro)sensory afferent activity encodes high frequency information
- Summed activity encodes all frequencies
- Postsynaptic cells with high convergence and high spike threshold preferentially decode synchronous activity
- ELL: high convergence map (LS) decodes fast chirps
- Other sensory systems (visual: X and Y cells) could consist of parallel streams of different temporal information which are determined by transmission of synchronous activity
Part 2: Coding with Plastic Synapses

- General properties of short term plasticity
- Amplitude-rate picture
- Frequency response picture
- Spontaneous Poisson activity
- Modulated Poisson activity
- Controlling Broadband Coding

- Lindner, Gangloff, Longtin, Lewis,
Short-term plasticity

Change in the synaptic efficacy by incoming spikes

- Increase in efficacy = synaptic facilitation
- Decrease in efficacy = synaptic depression
Possible roles of short-term plasticity

• input compression (Tsodyks & Markram 1997, Abbott et al. 1997)

• signaling of transients (Lisman 1997, Senn et al. 2000, Richardson et al. 2005)

• switching between neural codes (Tsodyks & Markram 1997)


• synaptic amplitude can keep info about the presynaptic spike train seen so far (e.g. Fuhrmann et al. 2001)

• redundancy reduction (Goldman et al. 2002)

• sensory adaptation and decorrelation (Chung et al. 2002)
Information transfer

• Need more than synaptic amplitudes
• One also needs accompanying noise
• Noise comes mainly from (asynchronous) inputs
• Need to figure out how synaptic amplitudes and noise depend on time (due to signal)
Facilitation-depression model from experiments

Postsynaptic amplitude

\[ A_j = F_j D_j \]

Facilitation and Depression Dynamics

\[ \dot{D}_j = \frac{1 - D_j}{\tau_D}, \quad t = t_{i,j} \Rightarrow D_j \rightarrow D_j(1 - F_j) \]

\[ \dot{F}_j = \frac{F_0 - F_j}{\tau_F}, \quad t = t_{i,j} \Rightarrow F_j \rightarrow F_j + \Delta \]

\[ F_j(t) > 1 \Rightarrow F_j(t) \rightarrow 1; \quad F_0 < F < 1 \]
Trajectories for Poisson stimulus
Model

Poisson input spike trains

Synaptic facilitation and depression

Synaptic input

F-D

F-D

F-D

F-D
Conductance and voltage dynamics

Synaptic inputs

\[ x_j(t) = \sum_i A_{i,j} \delta(t - t_{i,j}), \quad X(t) = \frac{1}{N} \sum_j x_j(t) \]

Conductance dynamics

\[ \dot{g} = -\frac{g}{\tau} + g_0 X(t) \]

Membrane voltage dynamics

\[ C_m \dot{V} = -g_L (V - V_L) - g(t) (V - V_E) \]
Spontaneous activity
Model for spontaneous activity
Map description

**Facilitiation** (for small input rates)

\[ F_{i+1,j} = F_0 + (F_{i,j} - F_0 + \Delta)e^{-T_{i,j}/\tau_F} \]

**Depression**

\[ D_{i+1,j} = 1 + (D_{i,j} - 1 - F_{i,j}D_{i,j})e^{-T_{i,j}/\tau_D} \]

\[ T_{i,j} \quad \text{input ISI} \]
Mean value for low input rates
Distinction between different regimes

At low firing input rate

- **Facilitation dominated regime** (FDR)  \[ \left. \frac{d\langle A_j \rangle}{dr} \right|_{r=0} > 0 \]

- **Depression dominated regime** (DDR)  \[ \left. \frac{d\langle A_j \rangle}{dr} \right|_{r=0} < 0 \]
Distinction between different regimes

When does facilitation dominate? And when depression?

\[ \Delta > \frac{F_0^2 \tau_D}{\tau_F - F_0 [\tau_F^{-1} + \tau_D^{-1}]}^{-1} \]

\[ \Delta < \frac{F_0^2 \tau_D}{\tau_F - F_0 [\tau_F^{-1} + \tau_D^{-1}]}^{-1} \]
**Power spectra**

Summed spike trains with dynamic amplitudes $A_{i,j}$: general expression for the power spectrum

$$S_{xx} = \langle A_{i,j} \rangle^2 S_0 + r \left\langle \sum_{l=-\infty}^{\infty} (A_{k,j}A_{k+l,j} - \langle A_{k,j} \rangle \langle A_{k+l,j} \rangle) e^{2\pi i f(t_{k+l,j} - t_{k,j})} \right\rangle$$

For Poisson input with a weak rate

$$S_{XX} \approx rN \langle A_{i,j}^2 \rangle + 2r^2 N \langle A_{i,j} \rangle \left[ \frac{\Delta \tau_F}{1 + (2\pi f \tau_F)^2} - \frac{F_0^2 \tau_D}{1 + (2\pi f \tau_D)^2} - \frac{\Delta F_0 \bar{\tau}}{1 + (2\pi f \bar{\tau})^2} \right]$$

Neglecting the multiplicative nature of the conductance noise:

$$S_{VV} = \frac{[g_0 \tau \tau_{eff}(\langle V \rangle - V_e)]^2}{(1 + (2\pi f \tau)^2)(1 + (2\pi f \tau_{eff})^2)} \frac{S_{XX}(f)}{N^2},$$
Power spectra

![Graph showing power spectra and frequency]
Signal transmission
Model with rate modulation

Modulation of the input firing rate by a band-limited Gaussian white noise (0-100Hz)

\[ R(t) = r \cdot [1 + \varepsilon s(t)] \]
$0 < \text{COHERENCE} < 1$

\[ C_{ZR} = \frac{|S_{ZR}(f)|^2}{S_{ZZ}(f)S_{RR}(f)} \]
Input = electrical stimulus    Output = ELL spikes

How can one infer receptor-to-ELL plasticity?

\[ C_1 = C_2 = C_3 \]

Chacron et al., Nat. Neurosci. 2005
Depression alone

Szaliszyno, Longtin, Maler, Biosystems 2008
Facilitation alone

![Graph showing gain (cycle histogram fitting) versus modulation frequency (Hz) with varying $\tau_f$ (msec). $\tau_g = 10$ msec.](image)
Prediction that D dominates, mixed AMPA+NMDA
Band-limited noise stimulus (0-100Hz)

\[ \sigma = 0.42 \]
Cross-spectra
Coherence function DDR

\[ C_{ZR} = \frac{|S_{ZR}(f)|^2}{S_{ZZ}(f)S_{RR}(f)} \]
Coherence function

FDR

\[ C_{ZR} = \frac{|S_{ZR}(f)|^2}{S_{ZZ}(f)S_{RR}(f)} \]
Input: Poisson rate modulation
Output: LIF spikes
Summary

- Analytical results for the spontaneous case permit distinction between different regimes (FDR & DDR)

- Synaptic input and subthreshold membrane voltage show a flat coherence with rate modulation for both FDR and DDR
  -> broadband coding

- Information transmission about a stationary rate modulation is always reduced by dynamic synapses

- Coherence can be controlled by LIF mean rate
Stochastic Dynamics of Neural and Genetic Networks

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