Burst Ensemble Multiplexing
Linking dendritic activity to inhibitory microcircuits

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Neocortical Neural Code is Hierarchical

Felleman and van Essen, *Cereb Cortex* (1991)
Gilbert and Li, *Nat Rev Neurosci* (2013)
Synaptic inputs 1 or sensory stimulation

Firing Rate 1
Rate Rate 2
Outline

Introducing Bursting and the Neural Code
Part I: Burst Ensemble Multiplexing
Part II: Information-Limiting Factors in Multiplexing
Part III: Role of Inhibitory Microcircuitry
Hierarchical Codes: A Role for Multiplexing?
PART I

Burst Ensemble Multiplexing
Ensemble Firing Rate

Ensemble

Input (sensory)

Neural Decoding

Membrane Potential

Firing Rate

Knight J Gen Physiol (1972)
Wilson and Cowan Biophys J (1972)
Gerstner Neural Comp (2000)
Tchumatchenko et al., J Neurosci (2011)
Input-derivative encoding

Conjunction of inputs
Burst Ensemble Multiplexing

Firing times

1 Burst

1 Singlet

Events

Firing Rate

Event Rate

Burst Rate

Singlet Rate
Distinct Nature of Inputs to Apical VS Perisomatic

Dendritic
Top-down
(Attention, expectation, top-down partial credit)

Somatic
Sensory - Bottom-up

Deep-layer (L5B) pyramidal cells

Gilbert and Sigman *Neuron* (2007)
Larkum *Trends Neurosci* (2013)
Cortical Microcircuits

Tsodyks and Markram *PNAS* (1998)
Lovett-Baron *Nat Neurosci* (2012)


Gilbert and Li, *Nat Rev Neurosci* (2013)
Bursts of Action Potentials in vivo

In vivo ISI distributions are **bimodal**: Bursts and single spikes

Bursts are **sparse**
Bursts are **short**
Bursts are **stereotypical**

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Bursting in L5B cells: BAC-Firing

Deep-layer (L5B) pyramidal cell population

Characterization of Active Dendrites

Two-compartment model fitted on electrophysiological data
- Predicts 85% of spike times
- Morris-Lecar dendritic compartment and LIF soma (+ adaptation)
- Back-propagating action potential and Forward propagating calcium spike

Naud, Bathellier and Gerstner, *Front Comp Neuro* (2014)
Each compartment receives **background noise**

Amplitude of noise **tuned to yield 5 mV** standard deviation

(Polack et al. *Nat Neurosci* 2013)

Background noise **replaces E-I balance** and synaptic bombardment
Simulations of Deep Cortical Cells show Burst Ensemble Multiplexing

Naud & Sprekeler, Submitted
Simulations of Deep Cortical Cells show Burst Ensemble Multiplexing

Deep-layer pyramidal cell population

Naud & Sprekeler, Submitted
A single ensemble of pyramidal neurons can encode two streams of information simultaneously with different spike timing patterns.
PART II

Information Limiting Factors in Multiplexing
Encoding Time-dependent Stimuli

Multiplexing holds for quickly changing inputs up to approximately 40 Hz.
Mutual Information of Firing Rate vs Multiplexing

\[ I(A; B) = - \int_0^W \log_2(1 - C(\omega)) d\omega \]

Multiplexing info. \( \sim 420 + 210 = 630 \text{ bits/s} \)
Firing Rate info. \( \sim 300 + 40 = 340 \text{ bits/s} \)

**Burst Ensemble Multiplexing**

*can almost double information rate*

**Burst Ensemble Multiplexing**

*is works with larger ensembles*

Shannon (1948)
Bialek *et al.* (1991)
Lindner *IEEE* (2016)
Information-Limiting Factors

Bandwidth $W$

- $E_0$: Stationary event rate
- $F_0$: Stationary Burst Probability
- $N$: Number of neurons in the ensemble
- $P_s$, $P_d$: Effective membrane potential input-driven variance
- $W$: Bandwidth

Number of cells
Renewal Theory and Information Theory

Theoretical Estimates of Information Rate

\[ \mathcal{M}_F = W \log_2 \left( 1 + NE_0 F_0 (1 - F_0) \frac{P_d}{W} \right) \]

\[ \mathcal{M}_E = W \log_2 \left( 1 + NE_0 \frac{P_s}{W} \right) \]

- \( E_0 \) Stationary event rate
- \( F_0 \) Stationary Burst Probability
- \( N \) Number of neurons in the ensemble
- \( P_s \) Effective membrane potential
- \( P_d \) input-driven variance
- \( W \) Bandwidth
Theoretical limits to multiplexing

Compare Total Multiplexing Information with Classical firing rate info, \textit{constrained for matched total number of spikes}

\[ M_M = M_E + M_F \]

\[ M_A = W \log_2 \left( 1 + NA_0 \frac{P}{W} \right) \]

\[ A_0 = E_0 (1 + nF_0) \]

Sparse and short bursts are optimal

Naud & Sprekeler, Submitted
PART III

Can Neurons Read a Multiplexed Code?
Neural Demixing: Short-Term Plasticity and Cortical Microcircuits

Events

1 Burst

1 Singlet

Pre-syn. Spike pattern

Post-syn. Membrane potential

Short-term Depression STD

Short-term Facilitation STF

VIP +STD

SOM+ -

PV+ -

STF +

STD +
Simulations of Neocortical Networks show Demultiplexing
Simulations of Neocortical Networks show Demultiplexing

Naud & Sprekeler, Submitted
Theoretical limits to multiplexing

Compare Total Multiplexing Information with Classical firing rate info, **constrained for matched total number of spikes**

\[ M_M = M_E + M_F \]

\[ M_A = W \log_2 \left( 1 + N A_0 \frac{P}{W} \right) \]

\[ A_0 = E_0 \left( 1 + n F_0 \right) \]

**Sparse and short bursts are optimal**

Naud & Sprekeler, *Submitted*
Martinotti Inhibition can Optimize Multiplexing

1) Feedback dendritic inhibition imposes short and sparse bursts,
2) Multiplexing is preserved when inhibition follows the STF + divisive inhibition motif

som. input at 0, 200, 400 pA

som. input at 0 pA

som. input at 400 pA
Summary

- Properties of active dendrites is consistent with a mechanism for encoding two streams of information simultaneously

- Burst Ensemble Multiplexing is a distinct for time-division multiplexing and frequency division multiplexing

- Short and sparse bursts are optimal for multiplexing

- Decoding of two streams of information is consistent with physiology of inhibitory microcircuits in the cortex
Two-way Vertical Communication

Top-Down Dendritic Input

Event Rate in Higher-Level Ensemble

STF and Divisive Inhibition in Descending Connections

STD in Ascending Connections

Burst Probability in Low-Level Ensemble

Bottom-up Somatic Input

Layer-wise Top-down Multiplication

Top-Down Dendritic Input

Event Rate of Higher-level Ensemble

STF in Descending Connections

STD in Ascending Connections

Burst Probability of Low-Level Ensemble

Bottom-up Somatic Input

STD in Ascending Connections

Burst Probability in Low-Level Ensemble

Bottom-up Somatic Input
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Hypothesis: Burst for Multiplexing
Brain Rhythms and Bursting

Bursting imposes a strong correlation structure, even in the asynchronous state.

Louis Vallée
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Burst Ensemble Multiplexing
Cortical Microcircuits

Tsodyks and Markram *PNAS* (1998)
Lovett-Baron *Nat Neurosci* (2012)

Two-compartment model reproduces BAC-firing

Model reproduces
- Spike Timing
- BAC-Firing
- Critical Frequency

Naud, Bathellier and Gerstner, *Front Comp Neuro* (2014)
Rate Coding

Muscle Stretch Neurons in Frog Neck Muscles

1926 Lord Edgar Adrian

Source: backyardbrains.com
Conditions for Information Enhancement