IV.B. Biological Neural Networks

1. Overview

A Very Brief Tour of Real Neurons (and Real Brains)

The brain is organized over sizes that span 6 orders of magnitude

Typical Neuron

The brain is organized over sizes that span 6 orders of magnitude

Published by AAAS
Overview of Brain to Neurons

Animation of Neuron

- An animated film about nicotine addiction
- A good visualization of a single neuron
- ©2006, Hurd Studios
- Winner of NSF/AAAS Visualization Challenge

View Flash Video

Grey Matter vs. White Matter

Neural Density in Cortex

- 148,000 neurons / sq. mm
- Hence, about 15 million / sq. cm

Cortical Areas

Intercortical Connections

- (1) Short arcuate bundles, (2) Superior longitudinal fasciculus, (3) External capsule, (4) Inferior occipitofrontal fasciculus, (5) Uncinate fasciculus, (6) Sagittal stratum, (7) Inferior longitudinal fasciculus
Part 4B: Real Neurons

Intercortical Connections
(diffusion spectrum imaging)

Brodman’s Areas

Somatosensory & Motor Homunculi

Reorganization of Cortex
• Median nerve sectioned to show fluidity of cortical organization
• (C) before
• (D) immediately after
• (E) several months later

Macaque Visual System

Hierarchy of Macaque Visual Areas

(figs from Clark, Being There, 1997)
(fig. Bert Van Essen & al. 1992)
2. Neurons

Dendritic Trees of Some Neurons
A. inferior olivary nucleus
B. granule cell of cerebellar cortex
C. small cell of reticular formation
D. small gelatinosa cell of spinal trigeminal nucleus
E. ovoid cell, nucleus of tractus solitarius
F. large cell of reticular formation
G. spindle-shaped cell, substantia gelatinosa of spinal cord
H. large cell of spinal trigeminal nucleus
I. putamen of lenticular nucleus
J. double pyramidal cell, Ammon’s horn of hippocampal cortex
K. thalamic nucleus
L. globus pallidus of lenticular nucleus

Axonal Terminations
(Tectum of Turtle)

Axonal Net

Neural Connections
(array tomography by O’Shea at SmithLab, Stanford)
Minicolumn

- Up to ~100 neurons
  - 75–80% pyramidal
  - 20–25% interneurons
- 20–30µm diameter
- Length: 0.8 (mouse) to 3mm (human)
- ~6 × 10^3 synapses
- 75–90% synapses outside minicolumn
- Interacts with 1.2 × 10^5 other minicolumns
- Mutually excitable
- Also called *microcolumn*

Macrocolumns

- ~70 inhibitory-coupled minicolumns in humans
- 70% of minicolumn connections are within macrocolumn
- Basket neurons provide shunting inhibition between minicolumns
- Winner-takes-all networks
- Represent microfeatures

Intracortical Connections

- Dendrites extend 2–4 minicolumn diameters
- Axons extend 5 × (or even 30–40 × minicolumn diameter)
- Periodic spacing of axon terminal clusters causes entrainment
- ~2 × 10^7 connections to macrocolumn

Layers and Minicolumns

- Intracortical circuitry
- Dendritic bundle minicolumns in VP

Neural Networks in Visual System of Frog

- Projection macrocolumn: 0.5–1.0mm wide
- Intersecting columns in anterior cingulate gyrus
- Intersecting input columns in superior temporal sulcus

(figs. from Arbib 1995, p. 270)
Synapses

video by Hybrid Medical Animation

Chemical Synapse

1. Action potential arrives at synapse
2. Ca ions enter cell
3. Vesicles move to membrane, release neurotransmitter
4. Transmitter crosses cleft, causes postsynaptic voltage change

Typical Receptor

Fig. 3 Activity-dependent modulation of pre-, post-, and trans-synaptic components.

Fig. 3: Activity-dependent modulation of pre-, post-, and trans-synaptic components.

Fig. 4 Local regulation of the synaptic proteome.

Fig. 4: Local regulation of the synaptic proteome.
Input Signals

- **Excitatory**
  - about 85% of inputs
  - AMPA channels, opened by glutamate
- **Inhibitory**
  - about 15% of inputs
  - GABA channels, opened by GABA
  - produced by inhibitory interneurons

- **Leakage**
  - potassium channels
- **Synaptic efficacy**: net effect of:
  - presynaptic neuron to produce neurotransmitter
  - postsynaptic channels to bind it

Membrane Potential (Variables)

- $g_e =$ excitatory conductance
- $E_e =$ excitatory potential (~0 mV)
- $g_i =$ inhibitory conductance
- $E_i =$ inhibitory potential (~−70 mV)
- $g_l =$ leakage conductance
- $E_l =$ leakage potential
- $V_m =$ membrane potential
- $\theta =$ threshold
Membrane Potential

Currents: \( I_x = g_x (E_x - V_m) \), \( x = e, i, l \)

Net current: \( I_{net} = I_e + I_i + I_l \)

Change in membrane potential: \( \dot{V}_m = C^{-1} I_{net} \) (\( C^{-1} \) is rate constant)

\[
\dot{V}_m = C^{-1} [g_e (E_e - V_m) + g_i (E_i - V_m) + g_l (E_l - V_m)]
\]

Equilibrium \( V_m = \frac{g_e E_e + g_i E_i + g_l E_l}{g_e + g_i + g_l} \)

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Slow Potential Neuron

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Action Potential Generation

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Frequency Coding

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Variations in Spiking Behavior
Rate Code Approximation

- Rate-coded (simulated) neurons:
  - short-time avg spike frequency
  - avg behavior of microcolumn (~100 neurons) with similar inputs and output behavior
- Rate not predicted well by $V_m$
- Predicted better by $g_r$ relative to a threshold value $g_r^\theta$

\[ \theta = \frac{g_r^\theta E_x + g_x E_i + g_i E_i}{g_r + g_x + g_i} \]

Rate is a nonlinear function of relative conductance

\[ y = f(g_x - g_r^\theta) \]

Activation Function

- Desired properties:
  - threshold (~0 below threshold)
  - saturation
  - smooth
- Smooth by convolution with Gaussian to account for noise
- Activity update:
  \[ y_{t+1} = y_t + C(y - y_t) \]

\[ y = \frac{x}{x + 1} \quad \text{where} \quad x = \eta [g_x - g_x^\theta] \]

\[ y = \frac{1}{1 + \frac{1}{\eta [g_x - g_x^\theta]}} \]