IV.B. Biological Neural Networks

1. Overview

A Very Brief Tour of Real Neurons

(and Real Brains)

The Lobes of the Cerebral Hemispheres
The brain is organized over sizes that span 6 orders of magnitude.

J W Lichtman, W Denk Science 2011;334:618-623

Published by AAAS
Overview of Brain to Neurons

<http://www.youtube.com/watch?v=DF04XPBj5uc>

(Play Flash Video)

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

(fig. from Carter 1998)
Neural Density in Cortex

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

Cortical Areas

- (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
2. Neurons

Typical Neuron

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 lentiform nucleus
J. double pyramidal cell, Ammon’s horn of hippocampal cortex
K. thalamic nucleus
L. globus pallidus of lentiform nucleus

(Fig. from Trues & Carpenter, 1964)
Axonal Terminations (Tectum of Turtle)

Axonal Net

Neural Connections
(array tomography by O’Shea at SmithLab, Stanford)
Part 4B: Real Neurons

Minicolumn

- Up to ~100 neurons
  - 75–80% pyramidal
  - 20–25% interneurons
- 20–50 μ diameter
- Length: 0.8 (mouse) to 3mm (human)
- ~ 6 × 10^5 synapses
- 75–90% synapses outside minicolumn
- Interacts with 1.2 × 10^5 other minicolumns
- Mutually excitable
- Also called microcolumn

Layers and Minicolumns

- ~ 70 inhibitory-coupled minicolumns in humans
- 70% of minicol. connections are within macrocol.
- Basket neurons provide shunting inhibition between minicolumns
- Winner-takes-all networks
- Represent microfeatures
Intracortical Connections

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

Neural Networks in Visual System of Frog
Part 4B: Real Neurons

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**Synapses**

- video by Hybrid Medical Animation

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**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

(fig. from Anderson, Intr. Neur. Nets)

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**Typical Receptor**

(fig. from Anderson, Intr. Neur. Nets)
Fig. 3 Activity-dependent modulation of pre-, post-, and trans-synaptic components.

V. M. Ho et al. Science 2011;334:623-628
Published by AAAS

Fig. 4 Local regulation of the synaptic proteome.

V. M. Ho et al. Science 2011;334:623-628
Published by AAAS

Fig. 2: A 3D model of synaptic architecture.
A. A section through the synaptic bouton, indicating 60 proteins.
B. High-zoom view of the active zone area.
C. High-zoom view of one vesicle within the vesicle cluster.
D. High-zoom view of a section of the plasma membrane in the vicinity of the active zone. Clusters of syntaxin (yellow) and SNAP-25 (red) are visible, as well as a recently fused synaptic vesicle (top). The graphical legend indicates the different proteins (right). Displayed synaptic vesicles have a diameter of 42 nm.

B. G. Wilhelm et al. Science 2014;344:1023-1028
Published by AAAS
Fig. 3. A 3D model of synaptic architecture.

(A) Action through the synapse, indicating 60 proteins. The proteins are shown in the numbers indicated in tables S1 and S2 and in positions determined according to the imaging data (Fig. 2 and fig. S6) and to the literature (see fig. S6 for details).

(B) High-zoom view of the active zone area.

(C) High-zoom view on vesicles with vesicle clusters.

(D) High-zoom view on the plasma membrane in the vicinity of the active zone. Clusters of syntaxin (yellow) and SNAP 25 (red) are visible, as well as a recently fused synaptic vesicle (top). The graphical legend indicates the different proteins (right). Displayed synaptic vesicles have a diameter of 42 nm.
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: \( V_m = C^{-1} I_{net} \) (\( C^{-1} \) is rate constant)

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

Equilibrium \( V_m = \frac{g_E E_E + g_f E_i}{g_e + g_i + g_l} \)

Slow Potential Neuron

Action Potential Generation

(Fig. Anderson, Intr. Neur. Nets, 2nd Ed)
Frequency Coding

Variations in Spiking Behavior

Dendritic computation in pyramidal cells.

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(T Branco Science 2011;334:615-616) Published by AAAS
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 $g_e$ relative to a threshold value $g_e^θ$

$$\theta = \frac{g_e^θ E_r + g_e E_i + g_i E_i}{g_e^θ + g_i + g_i}$$

$$g_e^θ = \frac{g_e (E_r - \theta) + g_i (E_i - \theta)}{\theta - E_r}$$

$$y = f(g_e - g_e^θ)$$

Activation Function

- Desired properties:
  - threshold (~0 below threshold)
  - saturation
  - smooth
- Smooth by convolution with Gaussian to account for noise
- Activity update:
  $$y_{out} = y_t + C(y_t - y_t)$$