Peripheral sensory systems

Fig. 1.1. A drawing of a section through the human eye with a schematic enlargement of the retina.
Pop Quiz #1

How many neurons are there in the human brain? Synapses?
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Human brain contains $\sim10^{11}$ (100 billion) neurons!
(with 100 trillion+ connections inbetween)
Pop Quiz #2

\[
\frac{1}{2\pi a(r_o + r_i)} \frac{\partial^2 V_m}{\partial z^2} = C_m \frac{\partial V_m}{\partial t} + G_K(V_m, t)(V_m - V_K) \\
+ G_Na(V_m, t)(V_m - V_Na) + G_L(V_m - V_L)
\]

\[
G_K(V_m, t) = \overline{G}_Kn^4(V_m, t) \\
G_Na(V_m, t) = \overline{G}_Na m^3(V_m, t)h(V_m, t)
\]

\[
n(V_m, t) + \tau_n(V_m) \frac{dn(V_m, t)}{dt} = n_\infty(V_m)
\]

\[
m(V_m, t) + \tau_m(V_m) \frac{dm(V_m, t)}{dt} = m_\infty(V_m)
\]

\[
h(V_m, t) + \tau_h(V_m) \frac{dh(V_m, t)}{dt} = h_\infty(V_m)
\]

What do these equations represent?
Variable Na+ and K+ conductances

Hodgkin Huxley model

\[
G_K(V_m, t) = \overline{G}_K n^4(V_m, t)
\]
\[
G_{Na}(V_m, t) = \overline{G}_{Na} m^3(V_m, t) h(V_m, t)
\]
\[
n(V_m, t) + \tau_n(V_m) \frac{dn(V_m, t)}{dt} = n_\infty(V_m)
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m(V_m, t) + \tau_m(V_m) \frac{dm(V_m, t)}{dt} = m_\infty(V_m)
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\[
h(V_m, t) + \tau_h(V_m) \frac{dh(V_m, t)}{dt} = h_\infty(V_m)
\]
Neurons ("fibers")
= Information highway

Key Point: Electrical properties of cells are important

Figure 1.22
Neurons

Fig. 1.
Photomicrograph of electrode inside giant axon. 1 scale division = 33 μ.
Action potentials

Fig. 1. Reliability of firing patterns of cortical neurons evoked by constant and fluctuating current. (A) In this example, a superthreshold dc current pulse (150 pA, 900 ms; middle) evoked trains of action potentials (approximately 14 Hz) in a regular-firing layer-5 neuron. Responses are shown superimposed (first 10 trials, top) and as a raster plot of spike times over spike times (25 consecutive trials, bottom). (B) The same cell as in (A) was again stimulated repeatedly, but this time with a fluctuating stimulus [Gaussian white noise, \( \mu_s = 150 \text{ pA}, \sigma_s = 100 \text{ pA}, \tau_s = 3 \text{ ms}; \) see (14)].
 Somehow, the information is “transformed”, encoded into some other “language”....

“Neural code”
Cell membrane

- Membrane primarily consists of a “lipid bilayer” (to separate inside from outside)

- All sorts of “stuff” embedded inside, to allow for “communication” across membrane

Figure 1.22

Figure 2.19
Biophysical model of a neuron

Variable Na+ and K+ conductances

Hodgkin Huxley model

Weiss (1996)
Consider how you “process” this picture....
Light

- Definition?

According to the dictionary (various other uses/adverbs/adjectives aside, and there are a LOT):

Light – Electromagnetic radiation that can produce a visual sensation

- We’ll use the term “light” a bit more broadly → All *electromagnetic radiation*

- The Greeks started to crystallize the study of light (e.g., Euclid’s *Optica*)

  e.g., light travels in straight lines, mathematical-based notions of reflection/refraction

- Etymologically, the word “light” derives from notions of brightness/illumination

- The study and use of light is a foundation of all science, historical & modern.....
The notion of “light” is such an integral part of our daily lives...
The notion of “light” is such an integral part of our daily lives....
Creative use of “light” is now a key approach in neuroscience

http://optogenetics.weebly.com/why--how.html
Light (examples)

- Brain tissue light transmission calculator
- Angeled Stereotax coordinate calculator (MatLab)
- Opsin and fluorophore spectra tool

http://web.stanford.edu/group/dlab/optogenetics/
So what is light?

- A difficult question. Two (seemingly disparate) answers:

  1. Light is a wave. Specifically, an electromagnetic wave.

  2. Light is a “particle”. We call such a photon.

- We do not really have all the tools (yet) to fully understand these notions (let alone their distinction). But we can flesh each out a bit....

→ This dichotomy above ties directly to what is termed wave-particle duality, a fundamental concept of modern physics.

"But what is light really? Is it a wave or a shower of photons? There seems no likelihood for forming a consistent description of the phenomena of light by a choice of only one of the two languages. It seems as though we must use sometimes the one theory and sometimes the other, while at times we may use either. We are faced with a new kind of difficulty. We have two contradictory pictures of reality; separately neither of them fully explains the phenomena of light, but together they do."

- Albert Einstein & Leopold Infeld (1938)

http://www.upscale.utoronto.ca/GeneralInterest/Harrison/Complementarity/CompCopen.html
Consider how you “process” this picture....
Fig. 1.1. A drawing of a section through the human eye with a schematic enlargement of the retina.

Question: How is information being “transduced” here?
Receptive field

Fig. 2. Simple diagram of the organization of the retina.
WebVision (Utah)

→ Incident pattern on an area causes unique optical nerve fiber firing rate from a given point

Weiss (1996)
“Neural code”
Is this “image” a bitmap or vector-based?
Many ways to “encode” something....

Bitmap version

Vector version

zoom-in about corner of eye
Many ways to “encode” something....

→ “Same” image, two very different representations
Does your eye/nervous system process and store this image like a computer does? Probably not.....

Aside: Images as numbers (i.e., a “bitmap”)
Human brain contains $\sim 10^{11}$ (100 billion) neurons!
(with 100 trillion+ connections inbetween)

→ Understanding this thing is a really (really!) hard problem
Inverse problems are Ill-posed:
You know the “answer”, but not the “question”….

What is the question?

- It is gold
- It has gold balls
- It has gold balls & is glittery
- It has gold balls, is glittery, & has lights
- It has gold balls, is glittery, has lights, & a star on top
- It has gold balls, is glittery, has lights, a star on top, and is shaped like a green cone

**Question:** What does your neighbor’s x-mas tree look like?
Another fine mess...

review article

Simple mathematical models with very complicated dynamics
Robert M. May*

Logistic map

$$X_{t+1} = aX_t (1 - X_t)$$

→ Even the simplest nonlinearities can greatly complicate matters!

→ period doubling cascade (i.e., chaos)
(Pedantic) Aside: What is biophysics?

“It is a remarkable thing that, pulling on the threads of one biological phenomenon, we can unravel so many general physics questions.”

(William Bialek, 2012)

Applying principles of physics to study biological systems

OR

Examining (complex/messy) biological systems to motivate new physics

Franklin & Gosling (1953)

Watson & Crick (1953)
Cool factoids about the ear....

- At threshold, eardrum move ~1 pm

- At threshold, sensory cells move on the order of 100 pm (despite thermal noise agitating them roughly an order of magnitude more)

- Dynamic range spans 12+ orders of magnitude (in terms of incident energy)

- Spectral range spans 6-12 octaves (1 oct = x2 in Hz)

- Highest resting trans-membrane potential in whole body (~130–170 mV)

- Middle ear contains three smallest bones in the body (ossicles)

- Cochlea encased in the hardest bone in the body (petrous part of temporal bone)
Slides available at:
http://www.yorku.ca/cberge/

Fini