Current Topics in Biophysics (BPHS 2090)

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Website: http://www.yorku.ca/cberge/2090F2015.html
Figure 1.22
Modeling neurons $\rightarrow$ Electrical circuits

**Key Point: Electrical properties of cells are important**

![Diagram of a neuron with key components labeled: Cell body, Dendritic tree, Input cell, Myelinated axon, Axonal tree, Synapse, Normal direction of signal flow, Nerve terminal, Output cell.]

![Diagram of electrical circuits with components labeled: Intracellular, Membrane, Extracellular, Dissolution and diffusion through lipid bilayer channels, Transport through water channels, Transport through gated ion channels, Carrier-mediated transport, Pumps.]

**Model of Steady-State Electrodiffusion through Membranes**

![Diagram of a membrane model with components labeled: Inside, Membrane, Outside, $c_i^i$, $J_n$, $V_m$, $G_n$, $V_n$.]
Deep “biophysical” idea here!
That we can effectively “model” an essential aspect of cell membranes by treating it as an electric circuit (ignoring a lot of messy/excess detail)

→ A cell membrane is complex/messy (and this is a “simple” picture!)
Modeling neurons → Core-conductor & Cable models

- First solved by William Thomson (aka Lord Kelvin) in ~1855
- Motivated by Atlantic submarine cable for intercontinental telegraphy
Modeling neurons \(\rightarrow\) Core-conductor & Cable models

Core Conductor Model

\[ \int - dz \]

\( \Rightarrow \) Biophysical model of a neuron is just like a transmission line!

Current through inner conductor

\[ R_i = r_i \, dz \]

Current through outer conductor

\[ R_o = r_o \, dz \]

Current through membrane

\[ I_m = k_m \, dz \]
Modeling neurons $\rightarrow$ Electrical circuits

- We can model neurons using electrical circuits.
- This forms a core narrative thread of BPHS 3090/4080.

Hodgkin Huxley model

- Several processes are involved, including:
  1. Dissolution and diffusion through lipid bilayer.
  2. Transport through water channels.
  3. Transport through gated ion channels.

- This all forms a core narrative thread of BPHS 3090/4080.
Contrast coding in the electrosensory system: parallels with visual computation

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Abstract | To identify and interact with moving objects, including other members of the same species, an animal’s nervous system must correctly interpret patterns of contrast in the physical signals (such as light or sound) that it receives from the environment. In weakly electric fish, the motion of objects in the environment and social interactions with other fish create complex patterns of contrast in the electric fields that they produce and detect. These contrast patterns can extend widely over space and time and represent a multitude of relevant features, as is also true for other sensory systems. Mounting evidence suggests that the computational principles underlying contrast coding in electrosensory neural networks are conserved elements of spatiotemporal processing that show strong parallels with the vertebrate visual system.

How does the sensory system encode “contrast”?
Box 1 | Characteristics of first- and second-order sensory stimuli

Electrosensory
In the absence of stimuli, the electrosensory system of a weakly electric fish creates a baseline electric field (zeroth-order contrast) generated by a high-frequency electric organ discharge (EOD; see the figure, part a). This signal acts as a stable carrier wave on which environmental signals produce contrast modulations. When two static fish are present, their EODs superimpose and a ‘beat pattern’ in the electric field arises. This pattern is an example of a first-order contrast or amplitude modulation (AM) of the carrier. When the two fish move relative to each other, the amplitude of their combined EOD changes, causing a second-order modulation of beat pattern that is referred to as the stimulus envelope (Env).

Visual
For comparison’s sake, zeroth-order visual contrast can be defined as a spatially homogeneous luminance that saturates the receptive field of ganglion cells (see the figure, part b). First-order visual contrast typically introduces edges and borders within an inhomogeneous pattern of illumination intensity. When extracted, such features can be combined to form representations of contours and outlines. In vision research, this first-order pattern is often referred to as the carrier. Natural images involve further modulations of this pattern, resulting in a second-order contrast (also known as a contrast modulation or a luminance envelope). The bottom panel of part b shows an example of a static, low-frequency spatial contrast modulation (shadows of tall grass and people) of the first-order contrast pattern (fence). A spatiotemporal envelope results if these second-order contrast modulations change over time.

Auditory
In the absence of all stimuli and in a controlled setting, ambient background air forms a noisy, stationary and spatially homogeneous pressure condition (see the figure, part c). When a pure tone is emitted from a source, first-order contrast is generated as a sinusoidal modulation of the spatial distribution of air molecules. Again, this first-order modulation is referred to as a carrier. Superposing constant amplitude pure tones generates a more complex AM. Over time, both the amplitude and frequency that are emitted from the source can change to generate second-order contrast (a stimulus envelope).

Mechanosensory
First- and second-order contrast are also important to haptic senses. Imagine running a finger over a surface, making contact with a surface and breaking contact at regular intervals (see the figure, part d; approximation shown as a square wave). The pressure on the fingertip sensors is a first-order spatiotemporal contrast pattern. Second-order modulations may arise if the surface is uneven, with a lower-frequency envelope that results in variable pressure; alternatively, more or less finger pressure may be applied over time.

For all types of stimuli, alternative assignments of zeroth-, first- and second-order stimuli have been used, depending on the history of a field.
Contrast coding in the electrosensory system: parallels with visual computation

**“Current Topic”**

- **Zeroth order**
  - Electric fish
  - Recording dipole
  - EOD

- **First order**
  - EODs

- **Second order**
  - Theremin (the only musical instrument you play by not actually touching!)
Here we show a little Theremin module which plugs onto a Arduino Board that gives out the tune to a speaker or puts out the tune as control signal like MIDI, Servo etc. We were using this device not only as a musical instrument, various kinds of proximity sensors, pointing devices or as interface in combination with Processing, Max or Pd have been build with this technique.

**How it Works**

The Theremin Module itself is as little LC type Radio frequency oscillator which generates a radio wave and gives out the frequency signal to the Arduino board. An Antenna connected to the LC resonator provides the Theremin effect when a person or some conductive material is placed next to the antenna. This leads to a slightly frequency deviation of the oscillator frequency which is registered by the Arduino software.

The Arduino itself acts in this case as a accurate frequency meter which transforms this frequency deviation into sound or control signals. Since you will find numerous articles in the web describing the principle of a Theremin we leave here only that brief description.
Contrast coding in the electro sensory system: parallels with visual computation

**Figure 1** | **Natural electro sensory signals.**

**a** | The formation of static electric images. Conductive objects, such as those made of brass, cause a localized increase in the amplitude of the electric field relative to its background levels (driven by the electric organ discharge (EOD)). By contrast, non-conductive objects, such as plastic, cause a localized decrease in the amplitude of the electric field. Thus, these two object classes create either positive or negative local-to-background, or spatial, contrast. There is no focusing mechanism and so the electric image spreads across the skin in a roughly Gaussian manner.

**b** | The formation of a dynamic electric image. The green dot indicates the location of a small recording dipole, which measures the amplitude of the electric potential experienced across the skin. As the fish swims by an object (a conductive sphere in this illustration), the EOD is locally increased above its baseline amplitude. The movement of the sphere through the electric field thus causes a low-frequency amplitude modulation (AM) that, in turn, excites the primary electro sensory neurons.

**c** | The effects of EOD summation when two fish are in close proximity. The summation of the EODs of the two fish results in a global sinusoidal AM (beat), the frequency of which equals the difference of the EOD frequencies.

**d** | A high-frequency communication signal that results from a purposeful frequency modulation of the EOD. This creates another type of AM, which occurs on timescales shorter than the typical beat period shown in part c. The top panels of parts b and c are reproduced with permission from REF. 5. Elsevier.
Different neuron “types” can differentially encode contrast via firing rate patterns
Human brain contains $\sim 10^{11}$ (100 billion) neurons!
(with 100 trillion+ connections inbetween)
→ Neurons (e.g., your brain, right now) does a LOT of communicating via diffusion....
The processes behind neuronal communication have not yet been resolved in detail, but dyes, microscopy and protein analysis are beginning to fill in the gaps.

Synapses are crucial to the communication between neurons, but the events that happen there have been difficult to capture.
Figure 23.3  Schematic diagram of an axon terminal in a neuron (Figure 23.2). Action potentials cause the release of neurotransmitters in vesicles that have an excitatory or inhibitory role on the spiking potentials formed by neighbouring dendrites.
Two basic flavors of synapses
- Electrical
- Chemical

**Figure 1.17** Schematic diagram illustrating the flow of signals and electric current at an electrical junction (left panel) and at a chemical junction (right panel).

Remember: Electrical properties of cells are important.
Chemical synapses

- Still much is not well understood about the physical mechanism(s) underlying synaptic dynamics
- Different models proposed for how vesicles interact with (pre-synaptic) membrane

→ How might one explore such experimentally?
Owing to the physical properties of light, events in the synapse are too small-scale to discern with traditional confocal microscopy. By using fluorescent molecules and two lasers in sequence — a technique called stimulated emission depletion (STED) — scientists can capture some of the dynamic events in the synapse more clearly.
This image of a neuron was captured via "two photon" microscopy (covered in BPHS 4090), which also allows for probing synaptic dynamics.
Improved signaling as a result of randomness in synaptic vesicle release

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The probabilistic nature of neurotransmitter release in synapses is believed to be one of the most significant sources of noise in the central nervous system. We show how $p_0$, the probability of release per docked vesicle when an action potential arrives, affects the dynamics of the rate of vesicle release in response to changes in the rate of arrival of action potentials. Furthermore, we examine the theoretical capability of a synapse in the estimation of desired signals using information from the stochastic vesicle release events under the framework of optimal linear filter theory. We find that a small $p_0$, such as 0.1, reduces the error in the reconstruction of the input, or in the reconstruction of the time derivative of the input, from the time series of vesicle release events. Our results imply that the probabilistic nature of synaptic vesicle release plays a direct functional role in synaptic transmission.

Significance

Noise is not only a source of disturbance, but it also can be beneficial for neuronal information processing. The release of neurotransmitter vesicles in synapses is an unreliable process, especially in the central nervous system. Here we show that the probabilistic nature of neurotransmitter release directly influences the functional role of a synapse, and that a small probability of release per docked vesicle helps reduce the error in the reconstruction of desired signals from the time series of vesicle release events.
Noise may actually help in some way to preserve “signals”
Moving on: Sensory systems
What is sound?

Note the periodic nature present....

Pulkki & Karjalainen (2015)
Tonotopy

An Acoustic Prism

Zweig et al. (1976)