Basic neurophysics

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Sources (except where cited otherwise)

- Kandel, Schwartz, Jessell, Siegelbaum, Hudspeth (eds): Principles of Neuroscience, 5th Edition. McGrawHill, 2013
- James Tresilian: Sensorimotor control & learning. Palgrave McMillan 2012.

Sources (except where cited otherwise)

Peter Dayan, Larry F Abbot: Theoretical Neuroscience, MIT Press, Cambridge MA, 2001

sections 1.1, 1.2, 1.4, 2.3

Wulfram Gerstner, W M. Kistler, R Naud, L Paninski: Neuronal Dynamics: From single neurons to networks and models of cognition. Cambridge Univ Press, 2014

section 2

http://neuronaldynamics.epfl.ch/index.html

the brain motor cortex

visual cortex



to motor output

neurons



~10^11 with 10000 synapses each

neurons



neurons

four components of neurons



neurons as input-output units



spike recorded intra-cellularly



spike recorded extra-cellularly



threshold behavior



temporal summation



two functional components

Α

membrane potential (mV)

membranes: dendrites, soma, axons







source

- membrane=double lipid layer that is an electrical insulator
- neuron is electrically charged: more negative potential inside than outside cell
- based on ions K+, Na+, and Cl-



source

higher concentration of K+ inside cell

Iower concentration of Na+ inside cell

membrane less permeable to Na+ than to K+

>Na+ gradient is steeper than the K+ gradient

=> more positive outside cell

=> negative potential



source

gradient comes from ion pumps: protein channels in membrane that transport Na+ out of cell, K+ into cell, establishing gradient

this is where energy is consumed (a lot):ATP used to pump ions



source

synapses

- at a synapse, the membranes of two neurons comes very close
- this is where transmission across neurons takes place



two types of synapses

- electrical: currents across the membrane directly from one cell to another through "gap junctions"
 - very fast, but not flexible.
 - exists in the peripheral nervous system... but not very common

[Source: Neuroscience. 2nd edition. Purves D, Augustine GJ, Fitzpatrick D, et al., editors. Sunderland (MA): Sinauer Associates; 2001.]



two types of synapses

chemical:

- pre-synaptic cell releases neurotransmitter in response to an action potential that arrives through the axon
- post-synaptic potential induced by action of neurostransmitters on receptors

[Source: Neuroscience. 2nd edition. Purves D, Augustine GJ, Fitzpatrick D, et al., editors. Sunderland (MA): Sinauer Associates; 2001.]



two types of synapses

chemical synapse: the more common one.. an much more flexible

slower transmission... I to 2 ms

[Source: Neuroscience. 2nd edition. Purves D, Augustine GJ, Fitzpatrick D, et al., editors. Sunderland (MA): Sinauer Associates; 2001.]



post-synaptic post protection of the post of the post

depending on the receptor type, synaptic
transmission
induces post-synaptic potentials
of different forms
and sign

that travel to the soma, where a spiking decision is made

[Source: Neuroscience. 2nd edition.



spiking mechanism



spiking mechanism

- all or none nature of spikes
- spike generation is coincidence detection
 - overlap of incoming post-synaptic potentials that have propagated to soma within about 10 ms required to sum...
 - typical in cortex: 10 inputs needed, 10000 potential inputs...
- neuron as a "switch"



Hodgkin-Huxley





 $x_{0}(u) = \alpha_{x} \begin{pmatrix} x \\ u \end{pmatrix} / [\alpha_{x} (u)^{x} + \beta_{x} (u)^{x}] \quad [ms^{-1}]_{\tau_{x}(u)} = [\alpha_{x} (u) + \beta_{x} (u)^{x} [ms^{-1}]_{\tau_{x}(u)}$

Hodgkin-Huxley

based on data from squid-axon...



Hodgkin Huxley

the spiking mechanism is an instability => threshold effect



Hodgkin Huxley

 au_h

spike rate reflects input current

U



 au_m

+

h

h

т



Hodgkin Huxley

time varying inputs make time varying rate



Conduction along axons

- spikes travel down the axon... major source of time delays
- saltatory conduction based on myelination



Conduction along axons

Propagation speed (m/s)

- spikes travel down the axon... major source of time delays
- saltatory conduction based on myelination



Synaptic dynamics

represent the current induced by a presynaptic spike as a time dependent conductivity of the dendritic membrane, g_syn(t) and induces a current l_syn=g_syn(t) (u - E_syn)

syn(t)=exponential time course with time
scale in ms range



Dale's law

all synaptic connections coming from a given neuron are of the same type



Patterns of connectivity

forward connectivity



Patterns of connectivity

recurrent connectivity



Learning by plasticity

- learning is mediated by synaptic plasticity
- synaptic strengths change as a function of pre/post synaptic neural state



Learning by plasticity

spike-time dependent plasticity

- strengthening of synapses in which pre-synaptic spike precedes post-synaptic spike
- weakening synapses when the temporal order is the reverse...

Spike-time dependent plasticity





...back to the brain

organization of the brain in terms of cytoarchitectonics



Cytoarchitectonics

Iayered structure of cortex and many subcortical structures

homogeneous along surface

boundaries of areas well-defined



[Binzegger, Douglas, Martin 2004]

Canonical cortical circuits



[Douglas, Martin, 2004]

Canonical cortical circuit

three-layer response

Functional mapping

- link anatomical structures to function
- based on input-output relations
- and on neuropsychology/ cognitive neuroscience

Sensor cells

Sensor characteristic

Sensor characteristic

Sensor characteristic

photoreceptors

A Phototransduction and neural signaling

C Voltage response to light

retinal network

receptive fields

space-time structure of receptive fields

retinal ganglion cells

tuning curves in primary visual cortex

A Visuotopic map

Sensory networks

Pattern of excitation in response to striped stimulus

V2

V1

cortical feature maps

topography

D Blobs, interblobs (V1), and stripes (V2)

Thin stripe Thick stripe

Motor neurons

Motor neurons

Peripheral neural circuits

B Monosynaptic pathways (stretch reflex)

stretch reflex

Motor networks

Functional organization of the brain

[Lisman, Neuron 2015]

Challenge

- understanding how the functional organization structures behavior
- in closed loop with the environment
- and with internal closed loops (mostly within areas/populations)
- => need dynamics to understand that....