From Single Neurons to Brain-Computer Interfaces

Dorottya Cserpán
Complex Systems and Computational Neuroscience Group
Wigner Research Centre for Physics,
Hungarian Academy of Sciences

August 7, 2015

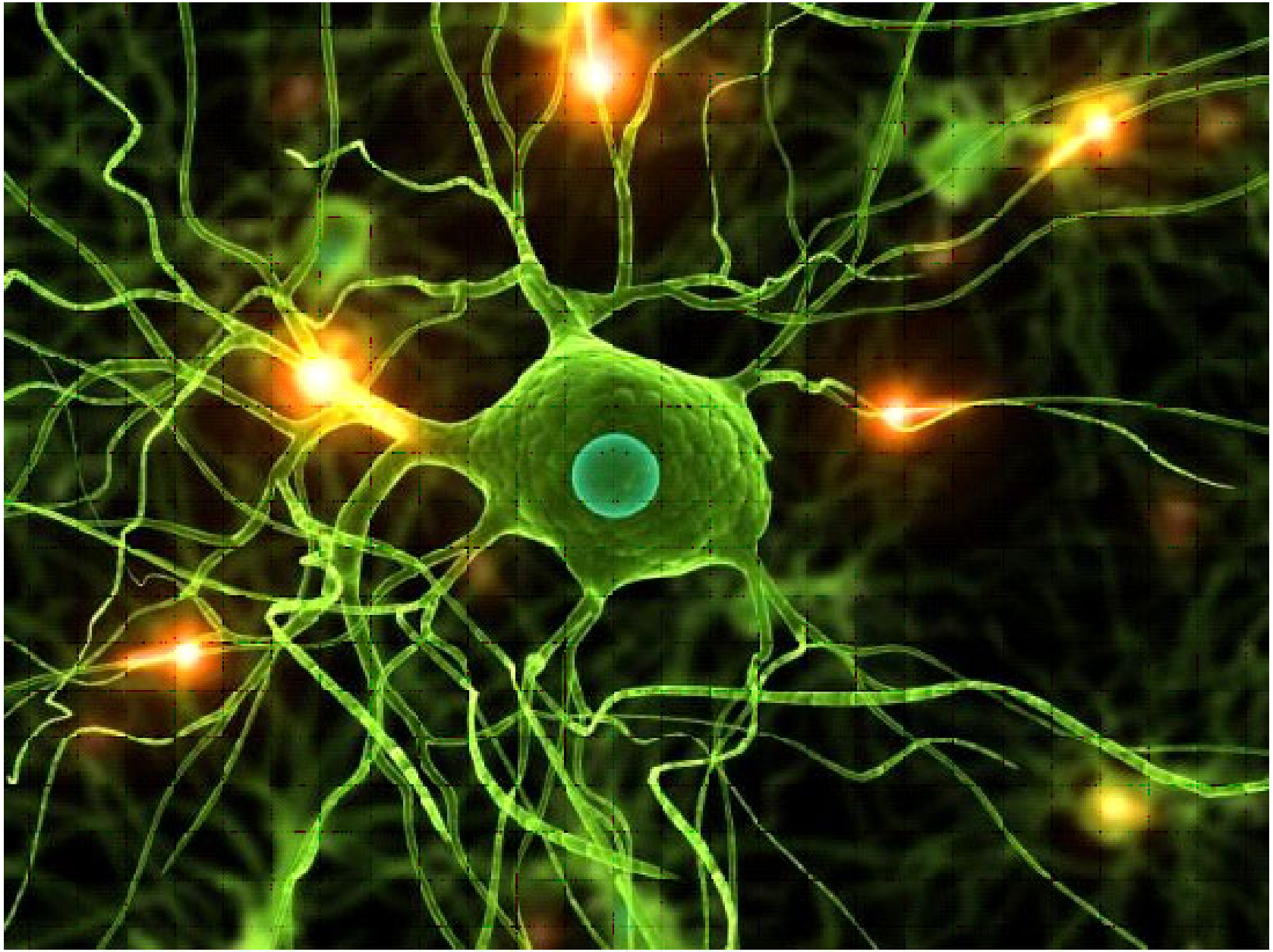
[1] http://ergonomicsindesign.hfes.org:8084/wordpress/ergonomics-illustrated-creativity/

List of unsolved problems in neuroscience

- **Consciousness:** What is the neuronal basis of subjective experience, cognition, wakefulness, alertness, arousal, and attention? Is there a "hard problem of consciousness"? If so, how is it solved? What, if any, is the function of consciousness?
- **Perception:** How are the senses integrated? What is the relationship between subjective experience and the physical world?
- **Learning and memory:** Where do our memories get stored and how are they retrieved again? How can learning be improved? What is the difference between explicit and implicit memories? What molecule is responsible for synaptic tagging?
- **Neuroplasticity:** How plastic is the mature brain?
- **Free will**

- **Sleep:** What is the biological function of sleep? Why do we dream? What are the underlying brain mechanisms? What is its relation to anesthesia?
- **Cognition and decisions:** How and where does the brain evaluate reward value and effort (cost) to modulate behavior?
- **Language:** How is it implemented neurally? What is the basis of semantic meaning?
- **Diseases:** What are the neural bases (causes) of mental diseases?
- **Movement:** How can we move so controllably, even though the motor nerve impulses seem haphazard and unpredictable?
- **Computational theory of mind:** What are the limits of understanding thinking as a form of computing?

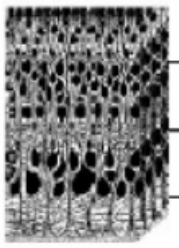
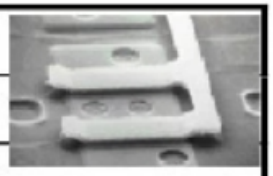
[2] $https://en.wikipedia.org/wiki/List_of_unsolved_problems_in_neuroscience$



3

[3] http://blog.targethealth.com/?m=201001

Brain vs Computer

	1 mm^3 of cortex		1 mm^2 of a CPU	
Number of units	50,000 neurons		1 million transistors	
Connections/unit	10,000		2	
Total connections	500 million		2 million	
Wiring	4 km of axons		0.002 km of wire	

	Whole brain		Whole CPU	
Weight	1.3 kg		~0.4kg	
Power	20 W		27 W	
Units	10^{11} neurons		10^{8} transistors	
connections	1×10^{15}		2×10^{9}	
wiring	8 million km of axons		2 km of wire	

Why are neurons special?

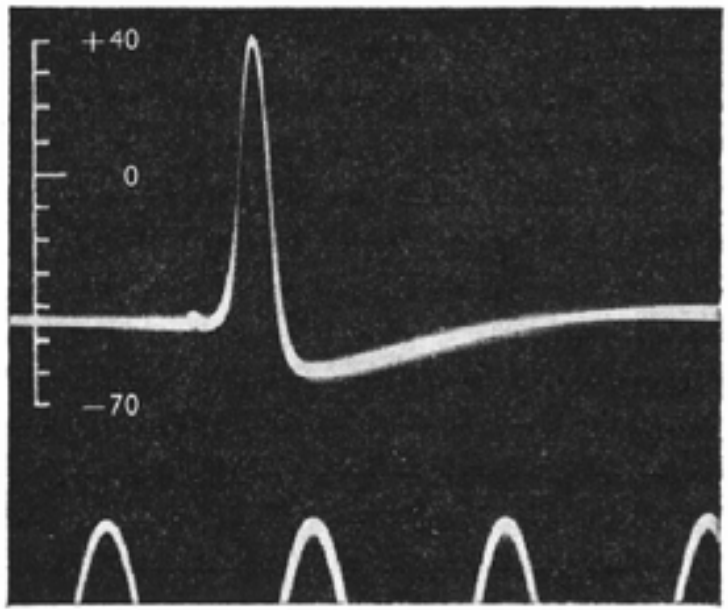


Fig.1: The action potential of squid giant axon recorded by Hodgkin and Huxley.

(Credit: Hodgkin, Alan L., and Andrew F. Huxley)

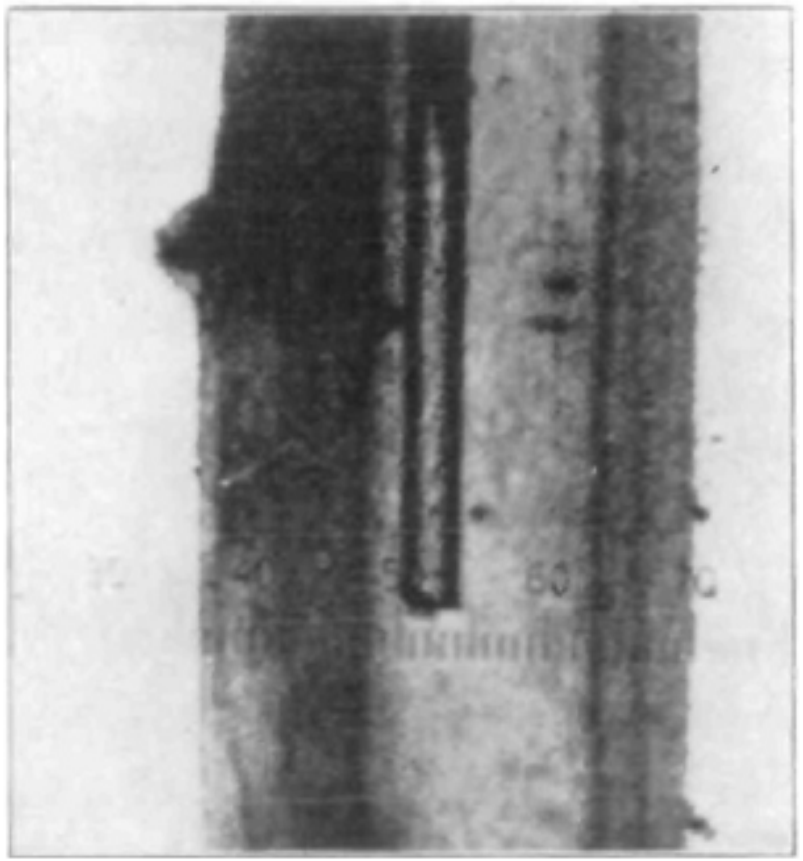
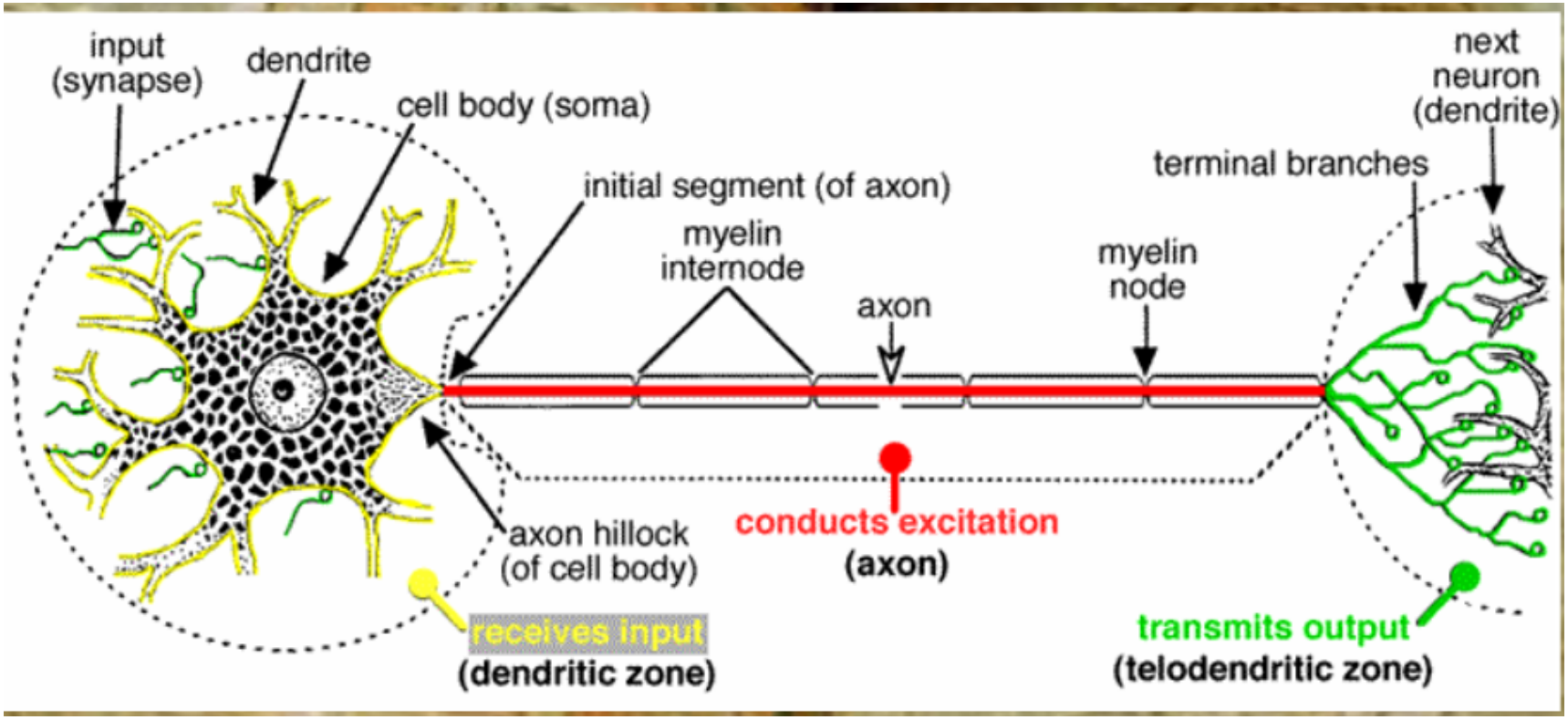
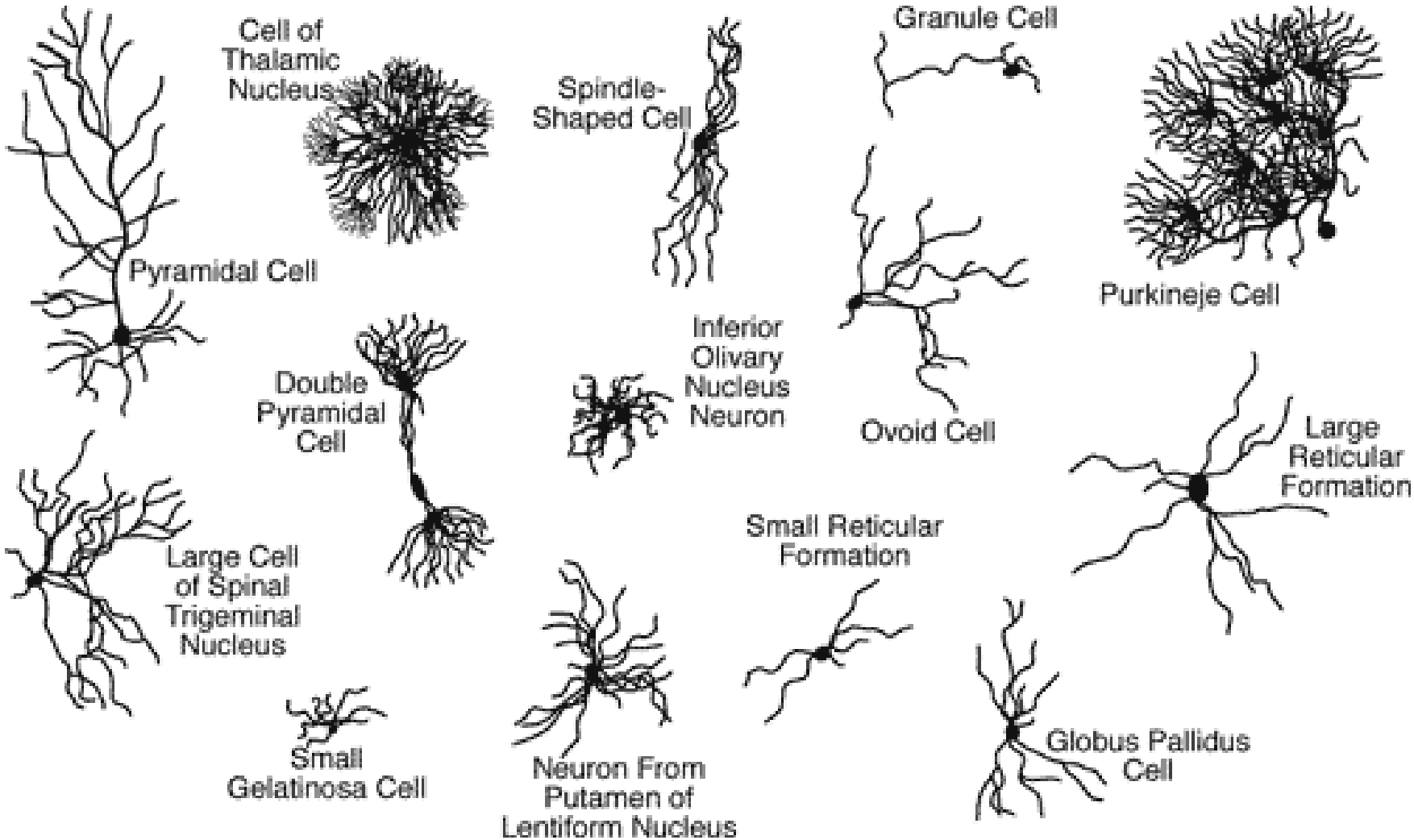


Fig.2: Photomicrograph of electrode inside giant axon.

(Credit: Hodgkin, Alan L., and Andrew F. Huxley)

Figure : Potentials recorded on the giant axon of the Atlantic squid,

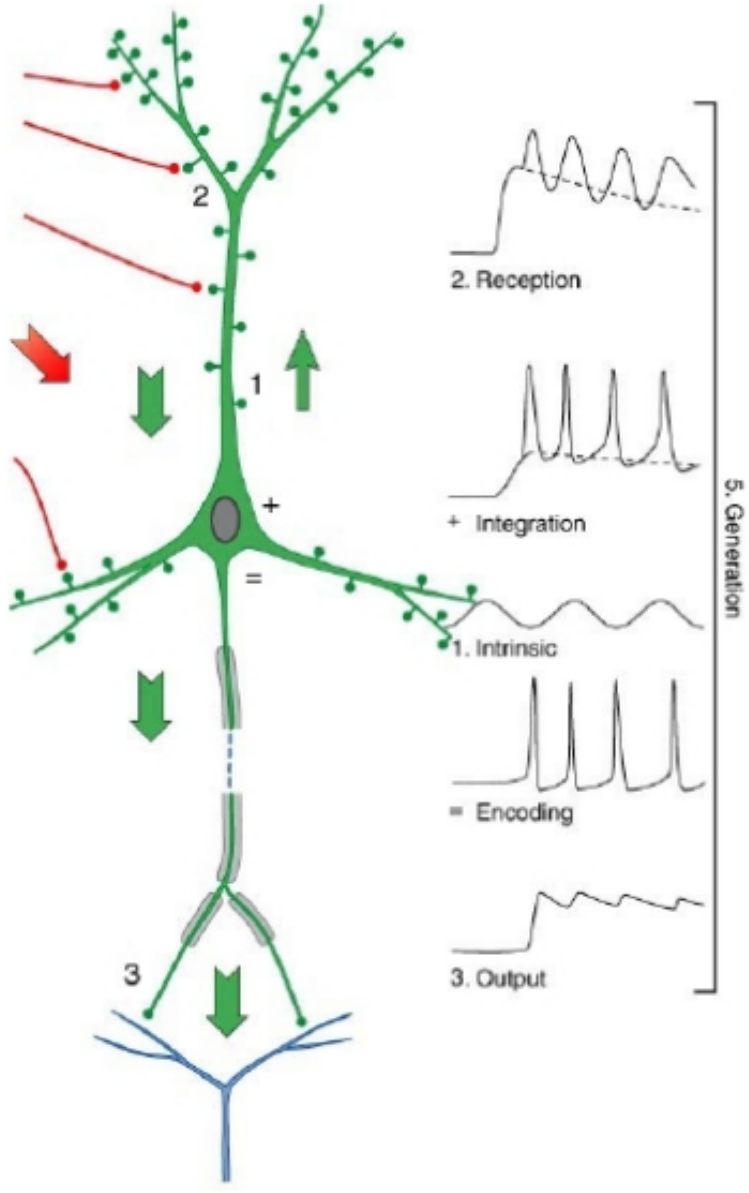

input
(synapse)
dendrite
cell body (soma)
initial segment (of axon)
myelin
internode
axon
myelin
node
terminal branches
next
neuron
(dendrite)
axon hillock
(of cell body)
conducts excitation
(axon)
receives input
(dendritic zone)
transmits output
(telodendritic zone)



[5] *http : //www.mind.ilstu.edu/curriculum/neurons_intro/neurons_intro.php*

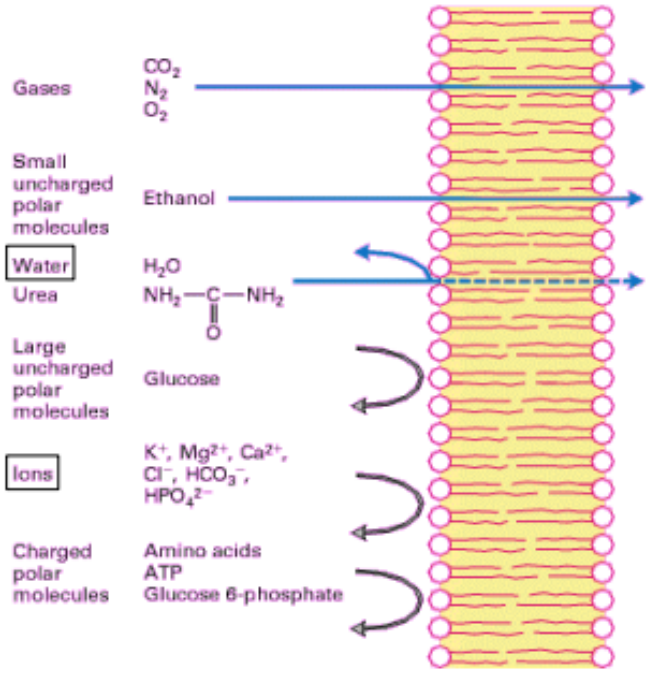
Elementary unit of the nervous system: The neuron

Parts of the neuron:	*Function:*
dendrite	*reception*
soma	*integration*
nucleus	*reproduction*
axon	*transmission*
initial segment	*encoding*
terminal	*output*
synapse	*communication*
glia	*background*
myelin sheath	*speed up*
Ranvier-nodes	*amplification*

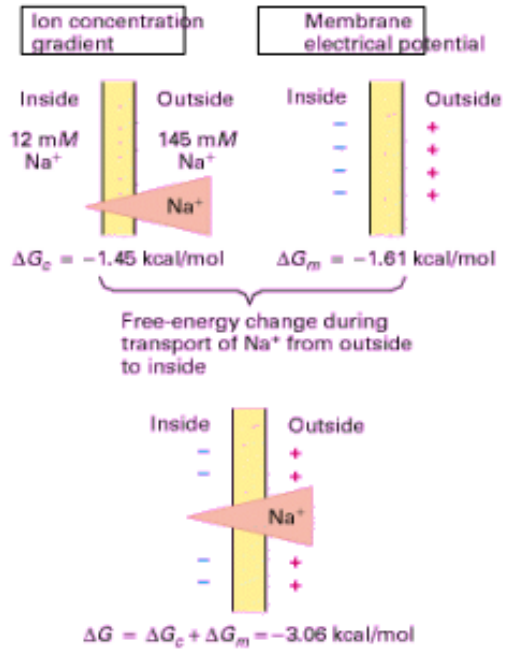


Trough the cell membrane

Different permeability, for different ions and molecules

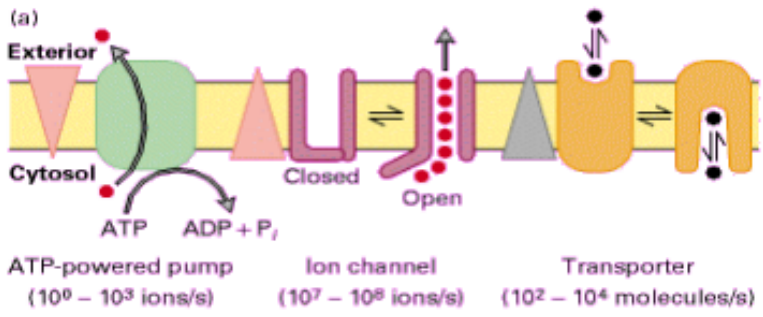


Forces of ion transport

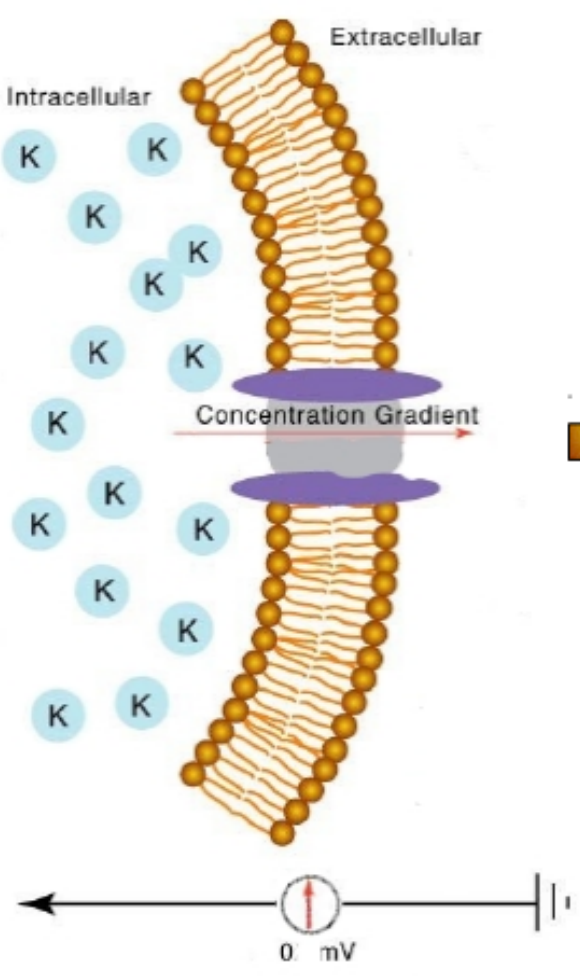


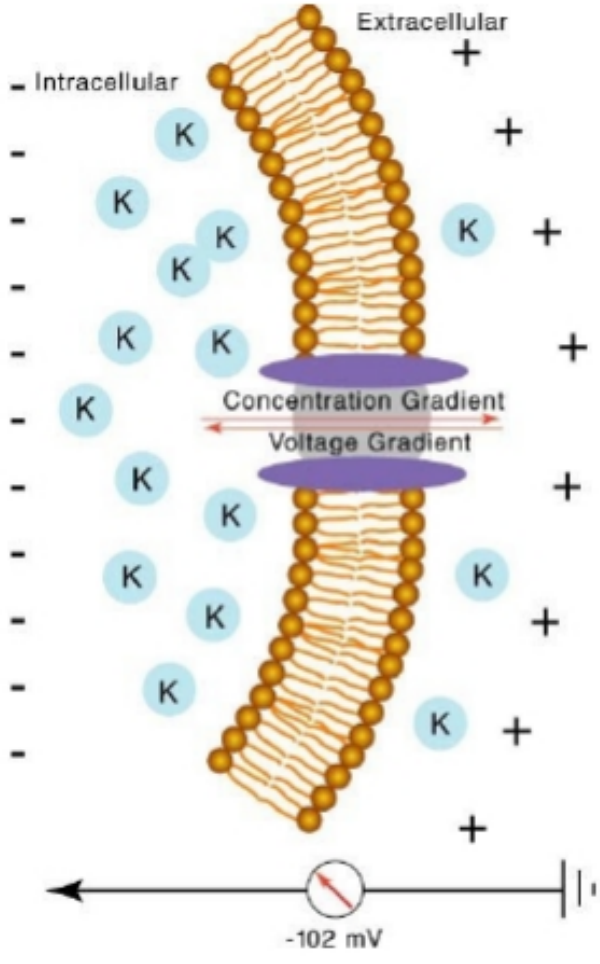
Membrane transport, trough proteins

- pumps (+energy!)
- channels
- transporters



The generation of the resting potential

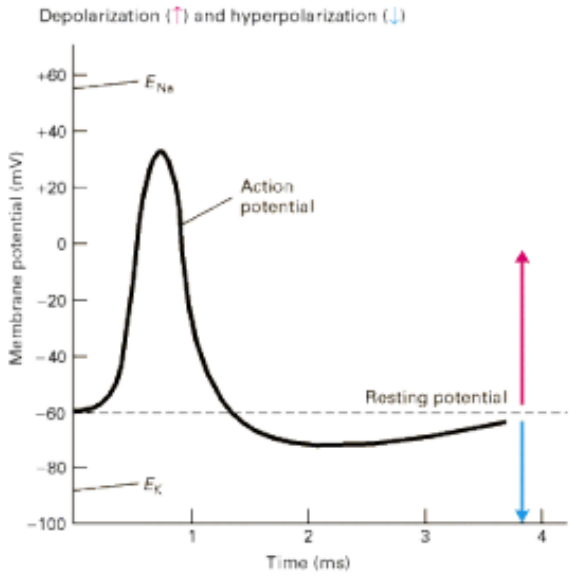


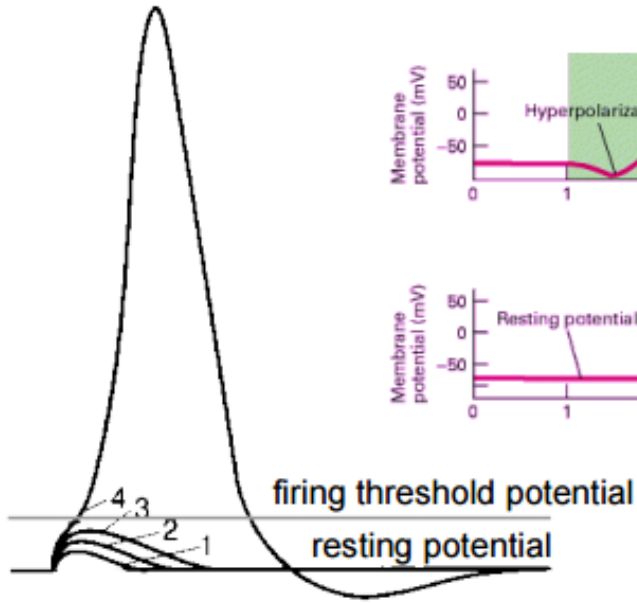


The electric neuron: action potential

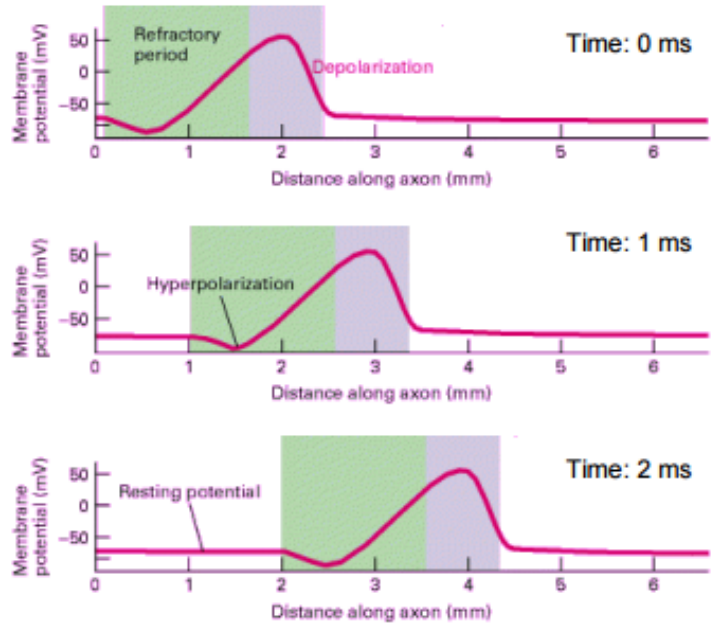
with electrode

What is the action potential?
A short change in the membrane potential



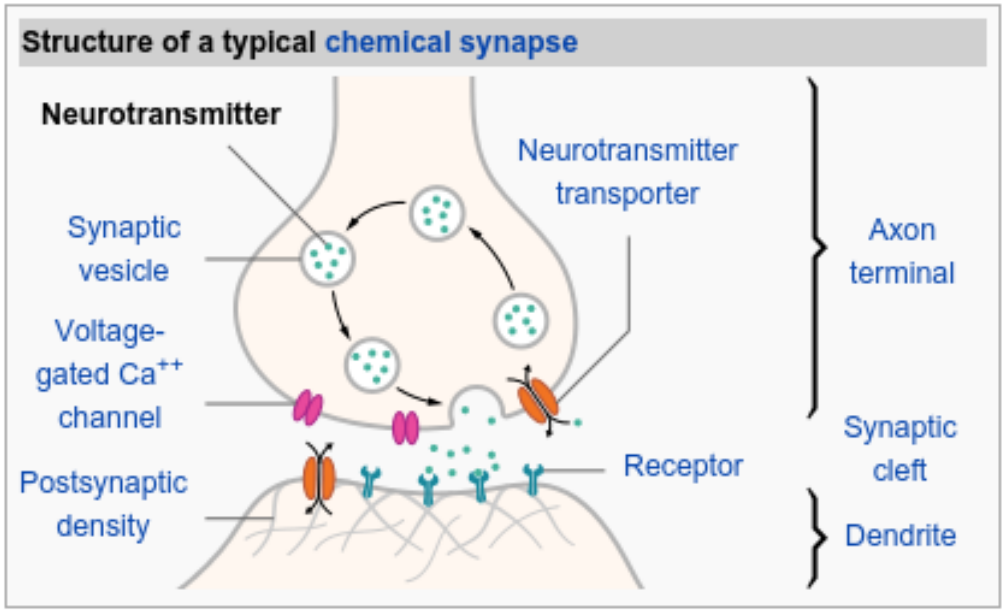


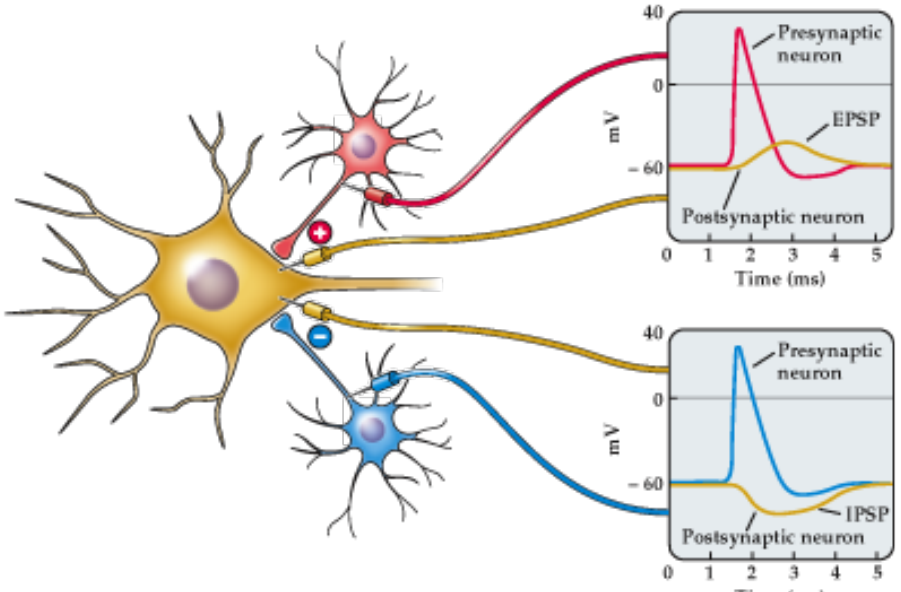
Traveling action potential



The action potential is an 'all or none' phenomenon

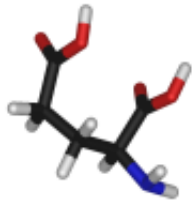
Between Neurons: Synapse



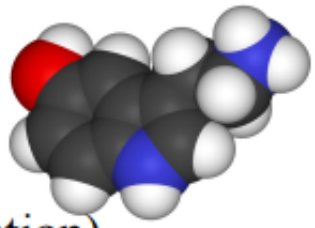


Excitatory and inhibitory neurotransmitters

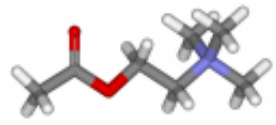
Glutamat
(information transmission)



Serotonin
(mood, wake/sleep)

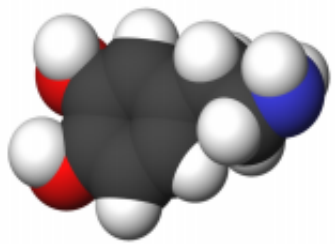


Acetlicholin
(neuromuscular junction)

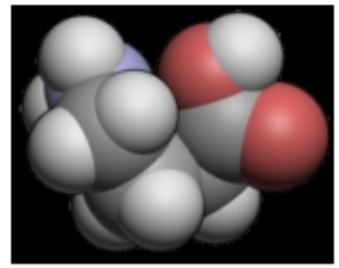


Noradneraline
(arousal)

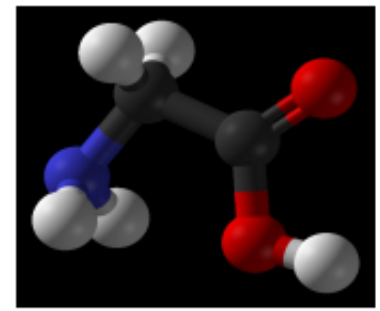
Dopamine
(reward system,
Parkinson disease,
schizophrenia)



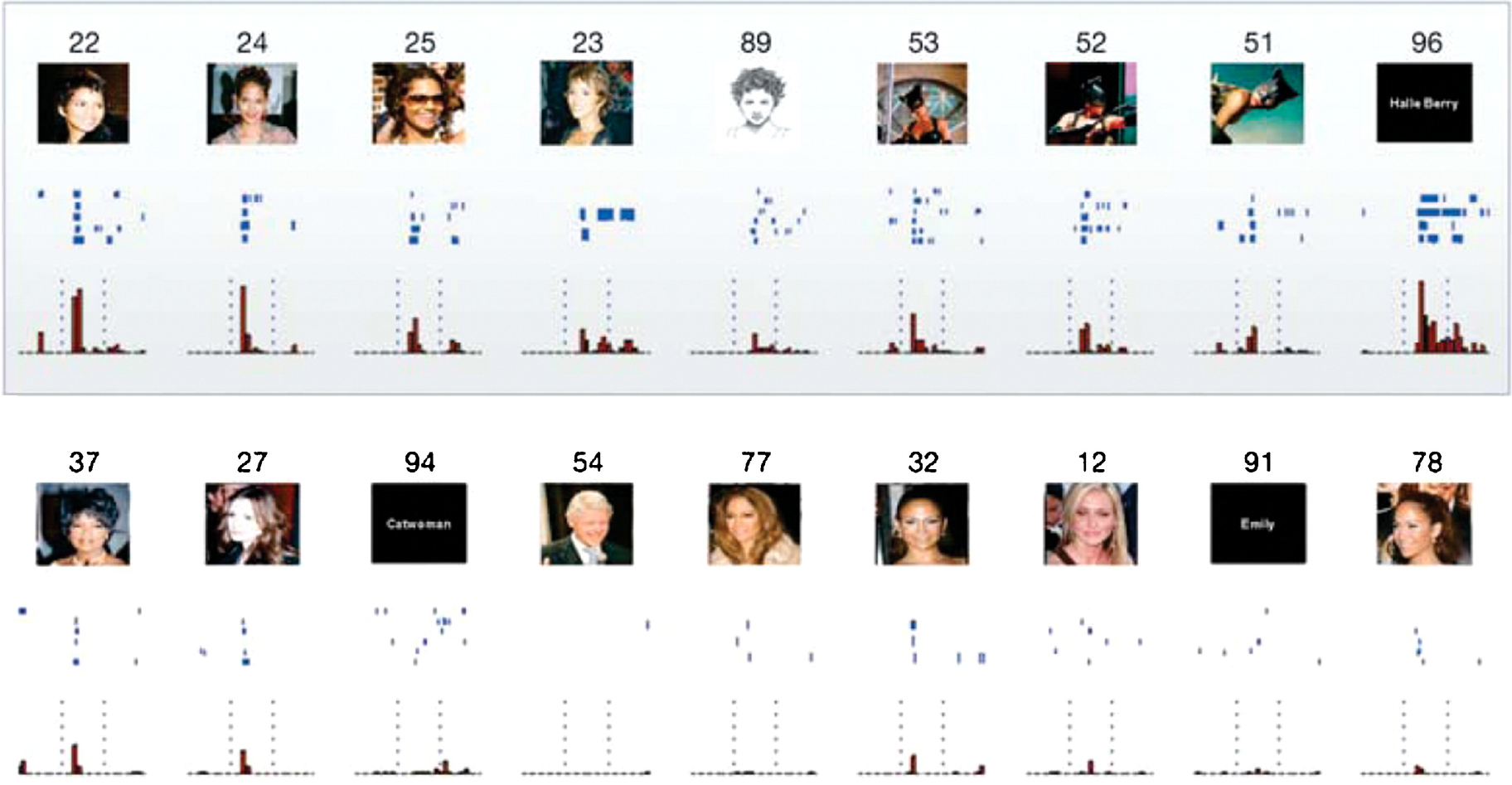
GABA-gamma aminobutyric acid
(in the central neural system)



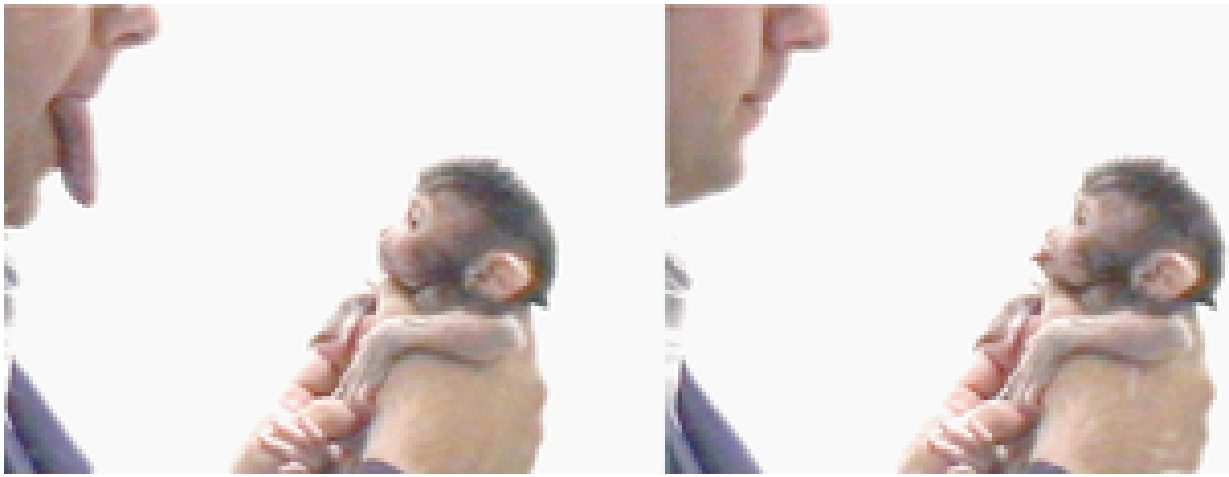
Glycine
(in the periphery)

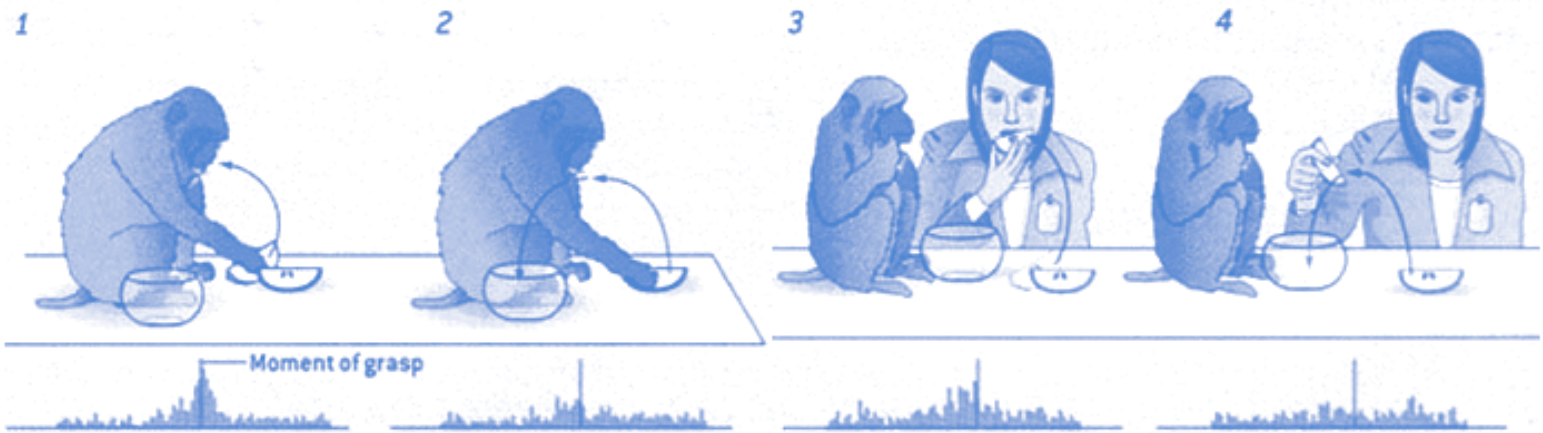


Halle Berry Neuron



Mirror Neuron





Possible roles: understanding intentions, learning facilitation,empathy... [7]

[7] *https://en.wikipedia.org/wiki/Mirror_neuron*

Grid and place cells

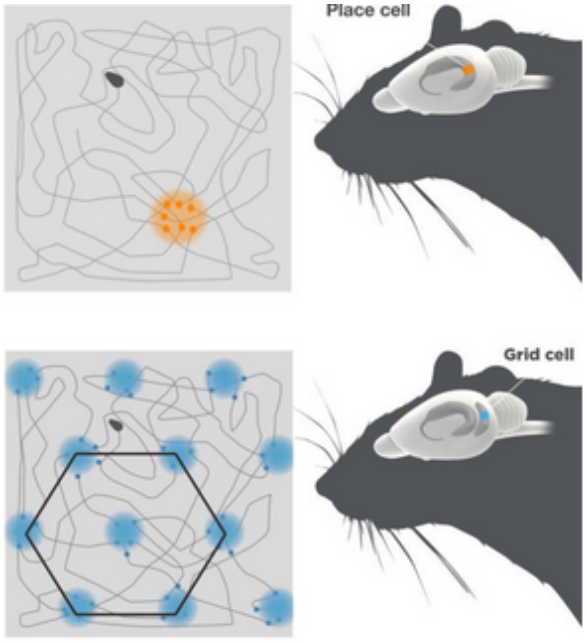


Figure : O'Keefe and the Mosers

Intracellular Recordings

- Voltage clamp
- Current clamp
- The patch-clamp technique
- Sharp electrode technique

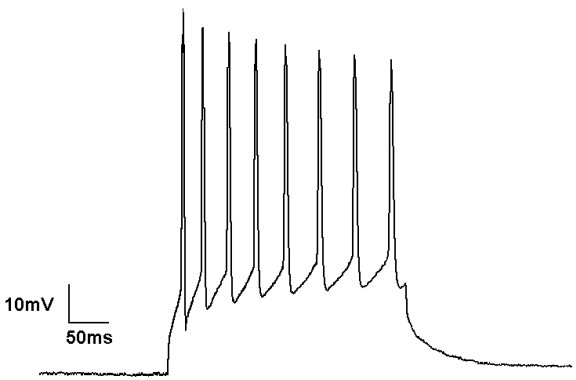


Figure : Current Clamp

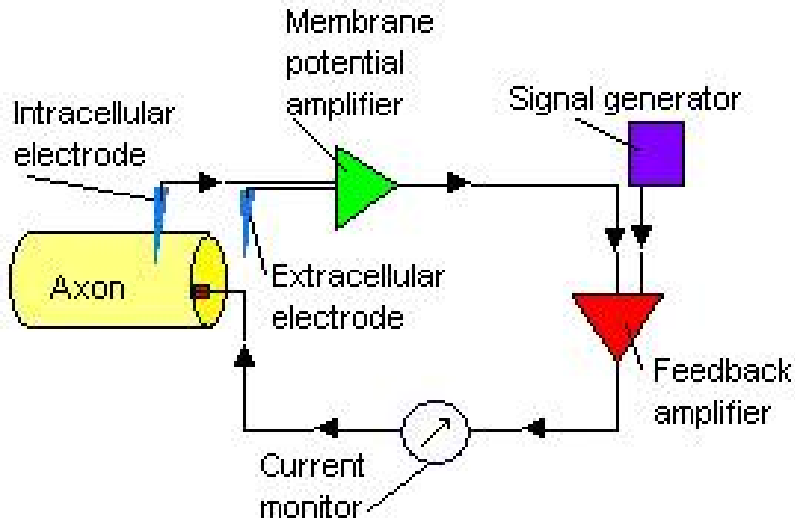
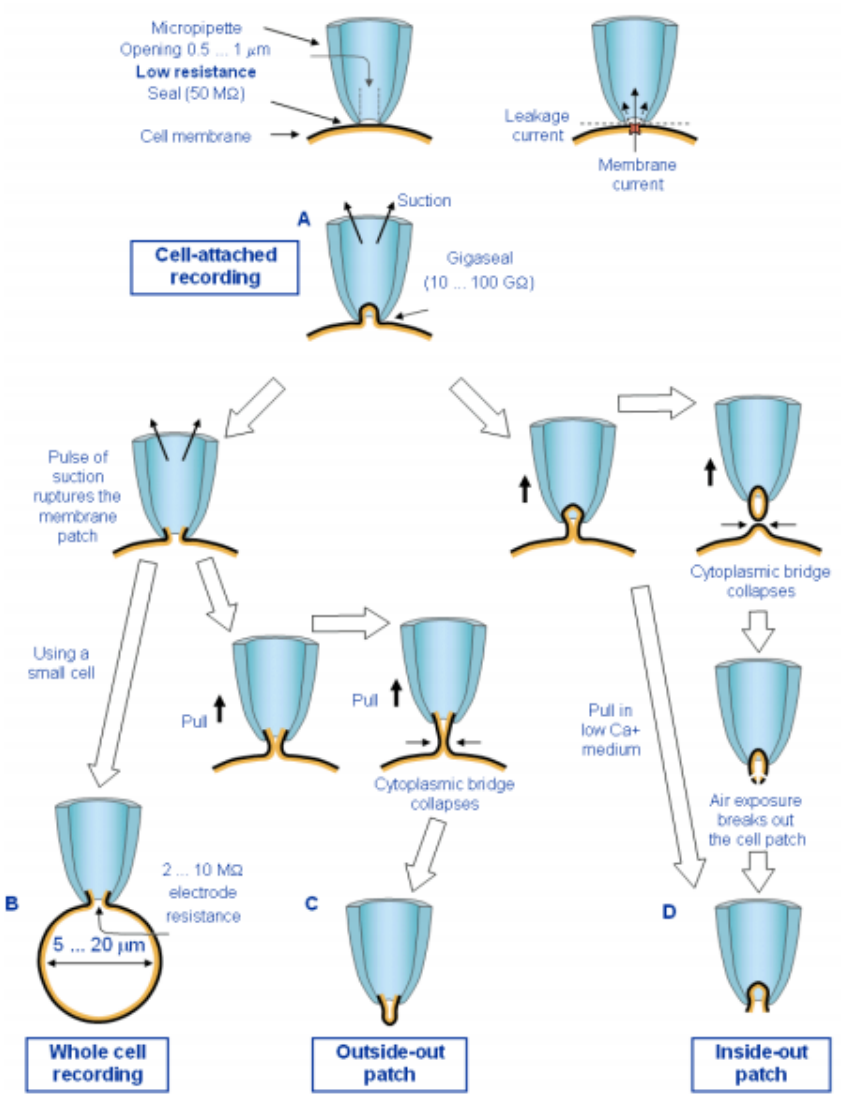


Figure : Voltage Clamp

[8] *https : //en.wikipedia.org/wiki/Electrophysiology*

Patch Clamp



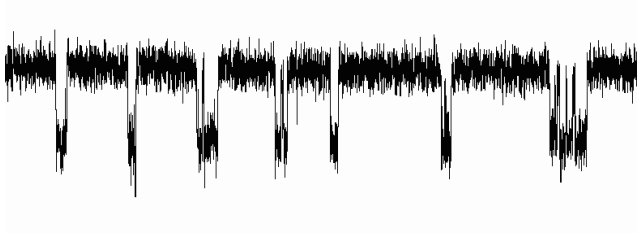


Figure : Clamping an ion channel

Extracellular Recordings

- Single-unit recording
- Field potentials (!)
- Amperometry
- Optical imaging (!) Link

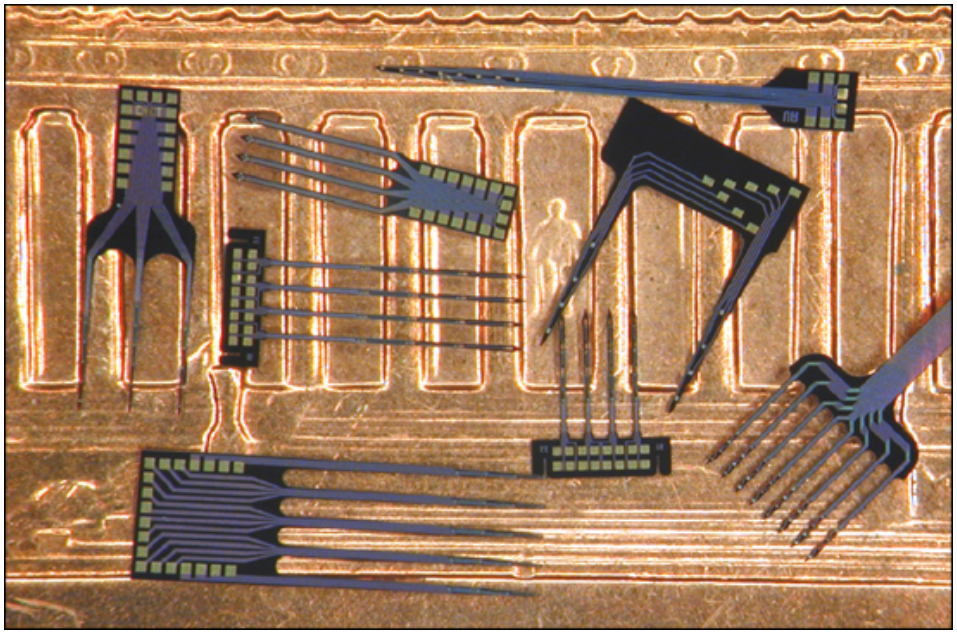
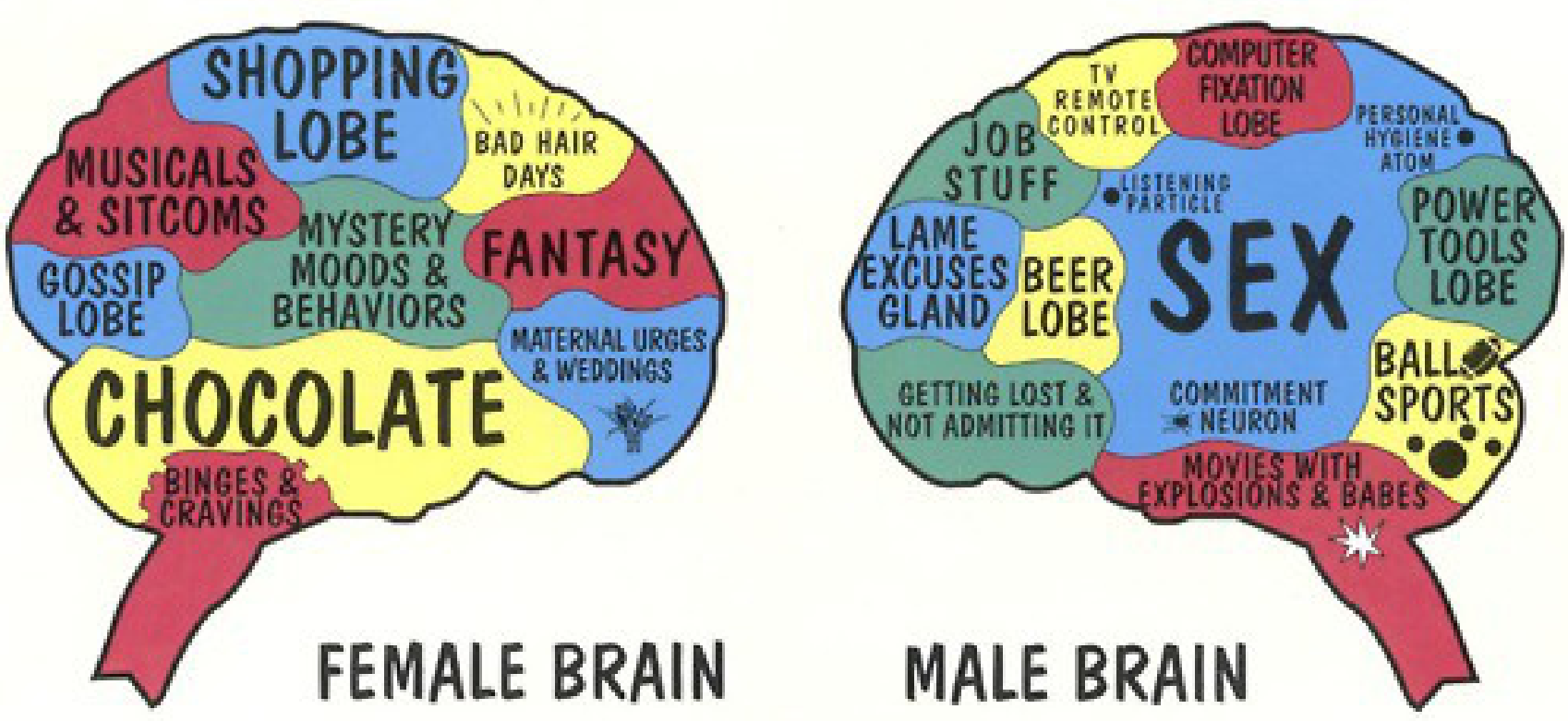
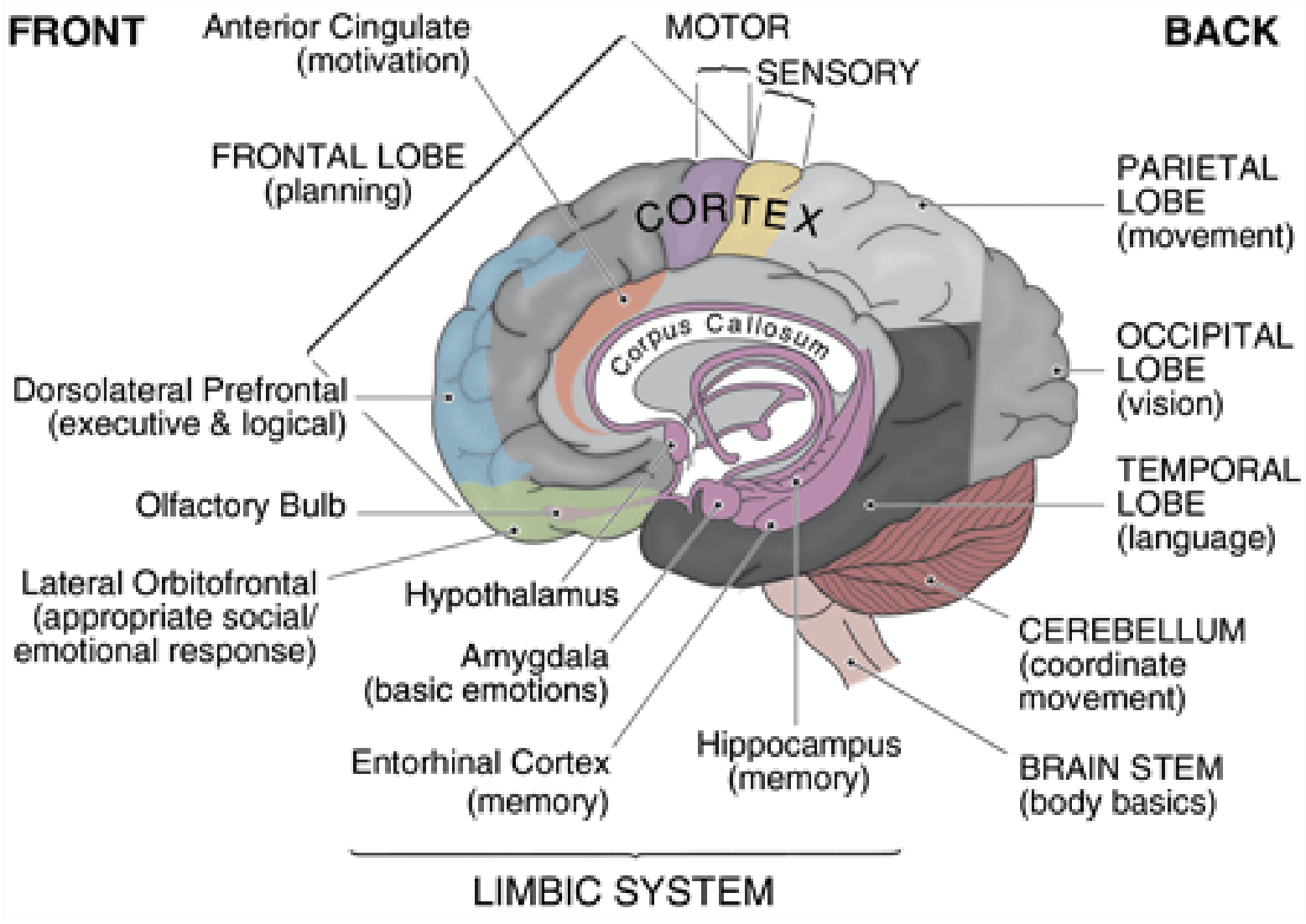
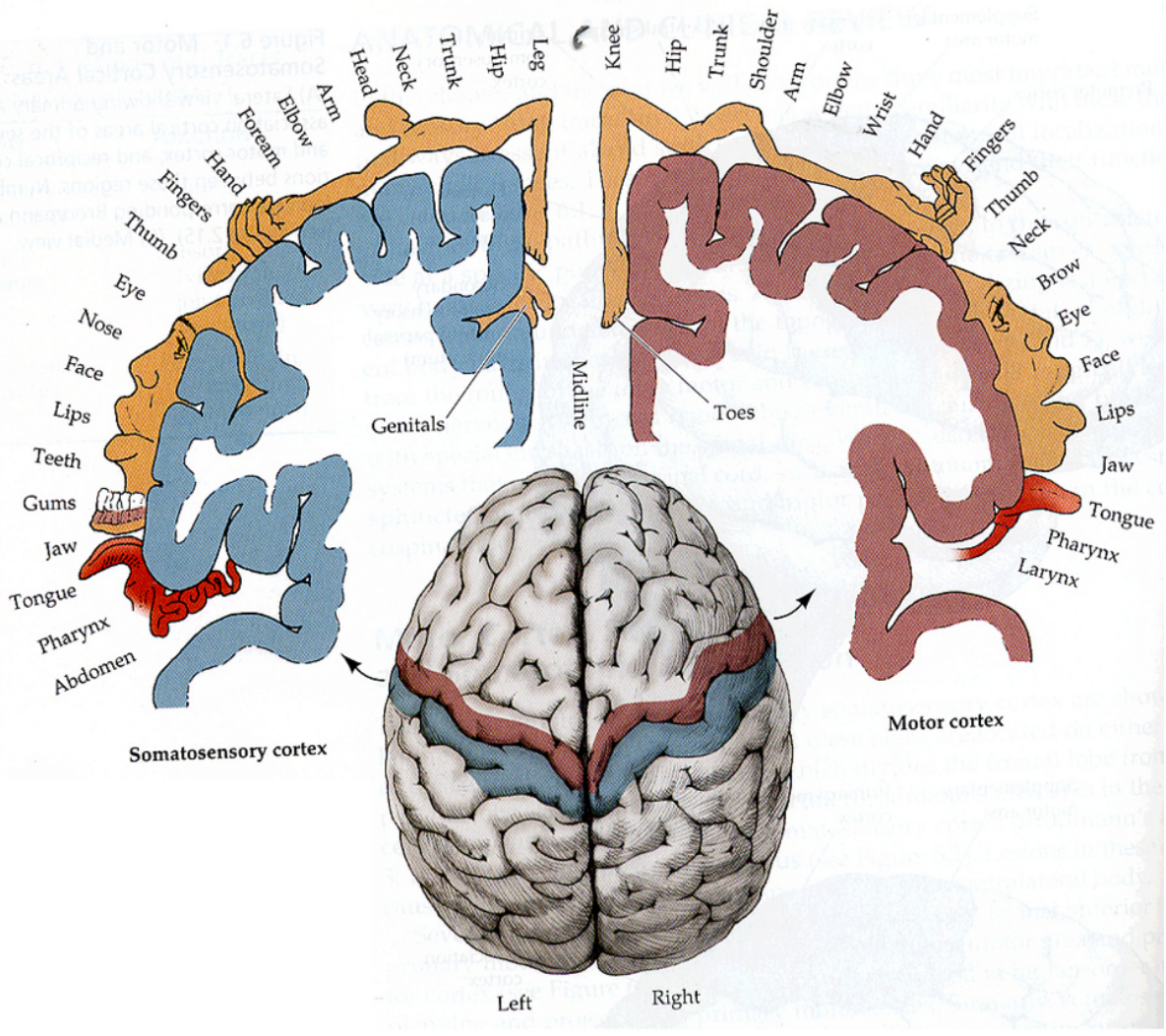


Figure : Several different probe designs shown on the back of a U.S. penny.

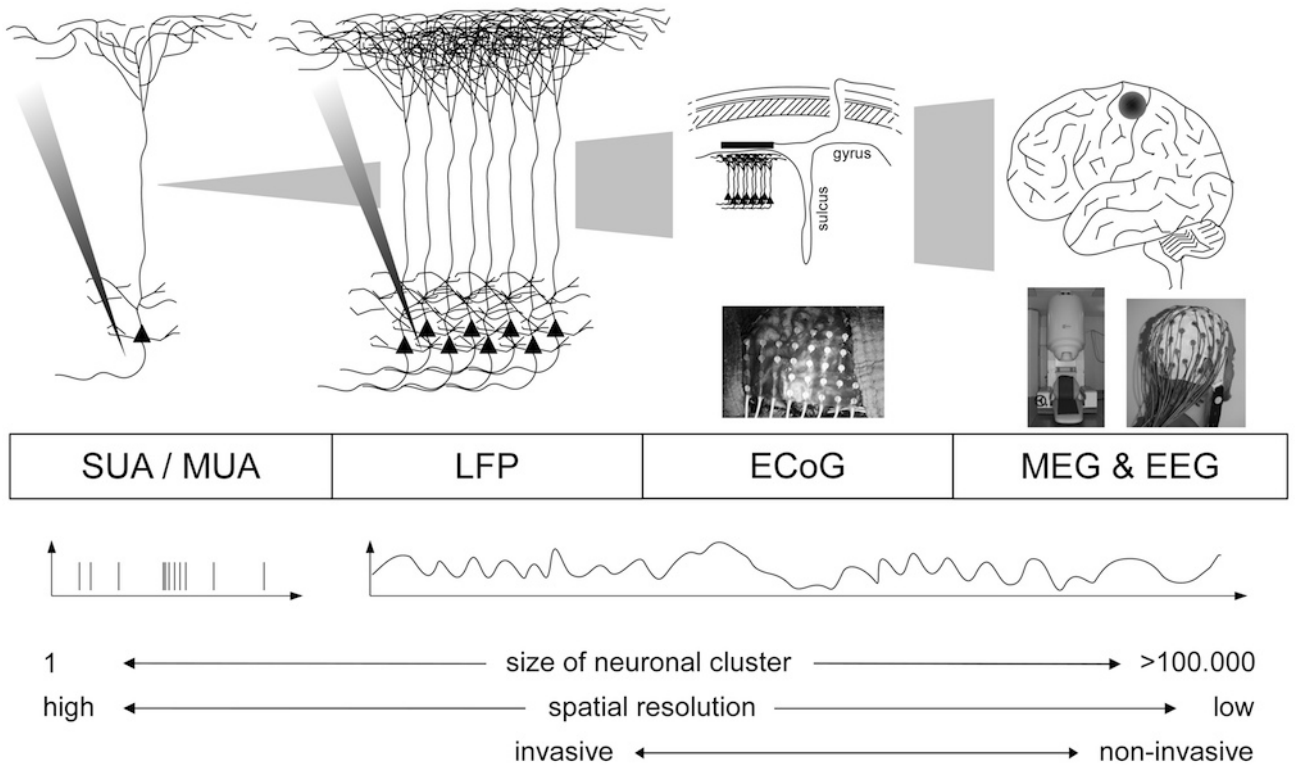
Brain Areas


SHOPPING LOBE
BAD HAIR DAYS
MUSICALS & SITCOMS
MYSTERY MOODS & BEHAVIORS
FANTASY
GOSSIP LOBE
MATERNAL URGES & WEDDINGS
CHOCOLATE
BINGES & CRAVINGS
FEMALE BRAIN
TV REMOTE CONTROL
COMPUTER FIXATION LOBE
PERSONAL HYGIENE ATOM
JOB STUFF
LISTENING PARTICLE
POWER TOOLS LOBE
LAME EXCUSES GLAND
BEER LOBE
SEX
BALL SPORTS
GETTING LOST & NOT ADMITTING IT
COMMITMENT NEURON
MOVIES WITH EXPLOSIONS & BABES
MALE BRAIN


FRONT
BACK
Anterior Cingulate
(motivation)
MOTOR
SENSORY
FRONTAL LOBE
(planning)
CORTEX
PARIETAL
LOBE
(movement)
Corpus Callosum
OCCIPITAL
LOBE
(vision)
Dorsolateral Prefrontal
(executive & logical)
TEMPORAL
LOBE
(language)
Olfactory Bulb
Lateral Orbitofrontal
(appropriate social/
emotional response)
Hypothalamus
Amygdala
(basic emotions)
CEREBELLUM
(coordinate
movement)
Entorhinal Cortex
(memory)
Hippocampus
(memory)
BRAIN STEM
(body basics)
LIMBIC SYSTEM


Head
Neck
Trunk
Hip
Leg
Arm
Elbow
Forearm
Hand
Fingers
Thumb
Eye
Nose
Face
Lips
Teeth
Gums
Jaw
Tongue
Pharynx
Abdomen
Genitals
Midline
Knee
Hip
Trunk
Shoulder
Arm
Elbow
Wrist
Hand
Fingers
Thumb
Neck
Brow
Eye
Face
Lips
Jaw
Tongue
Pharynx
Larynx
Toes
Somatosensory cortex
Motor cortex
Left
Right

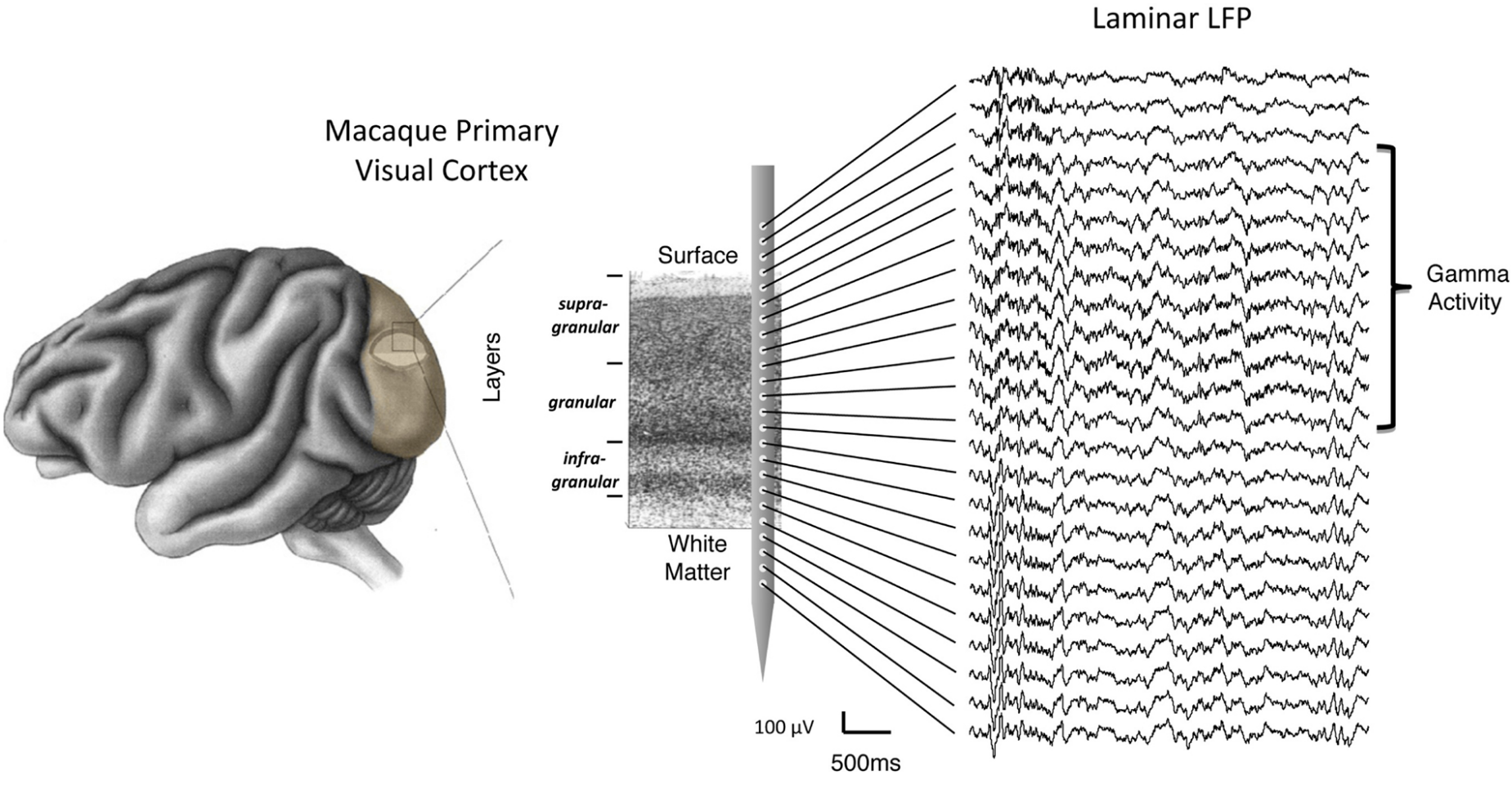
Scales in recording from the brain



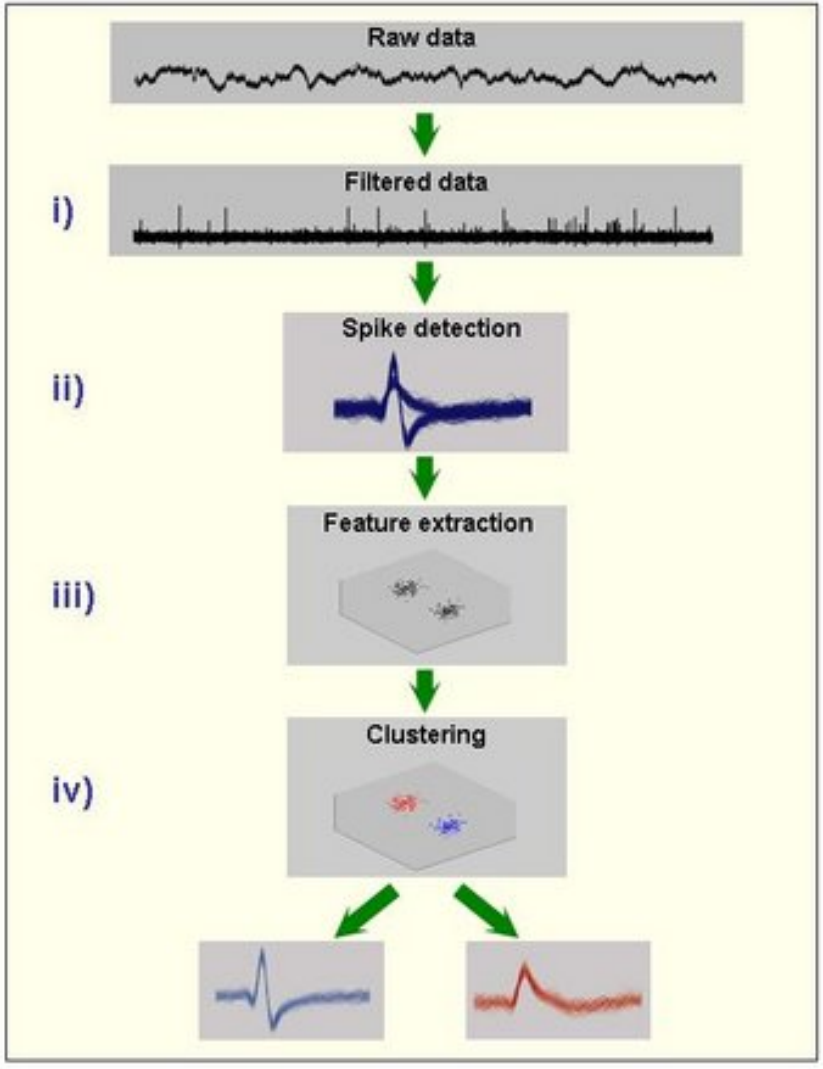
- SUA/MUA: "Single/Multi Unit Activity"
- LFP: "Local Field Potential"
- ECoG: "Electrocorticograph"
- MEG/EEG: "Magneto-/Electroencephalograph" [10]

[10] *http://www.neurotechnology.uni-freiburg.de/research/clinic/bmi-overview/box-bmi-scales*

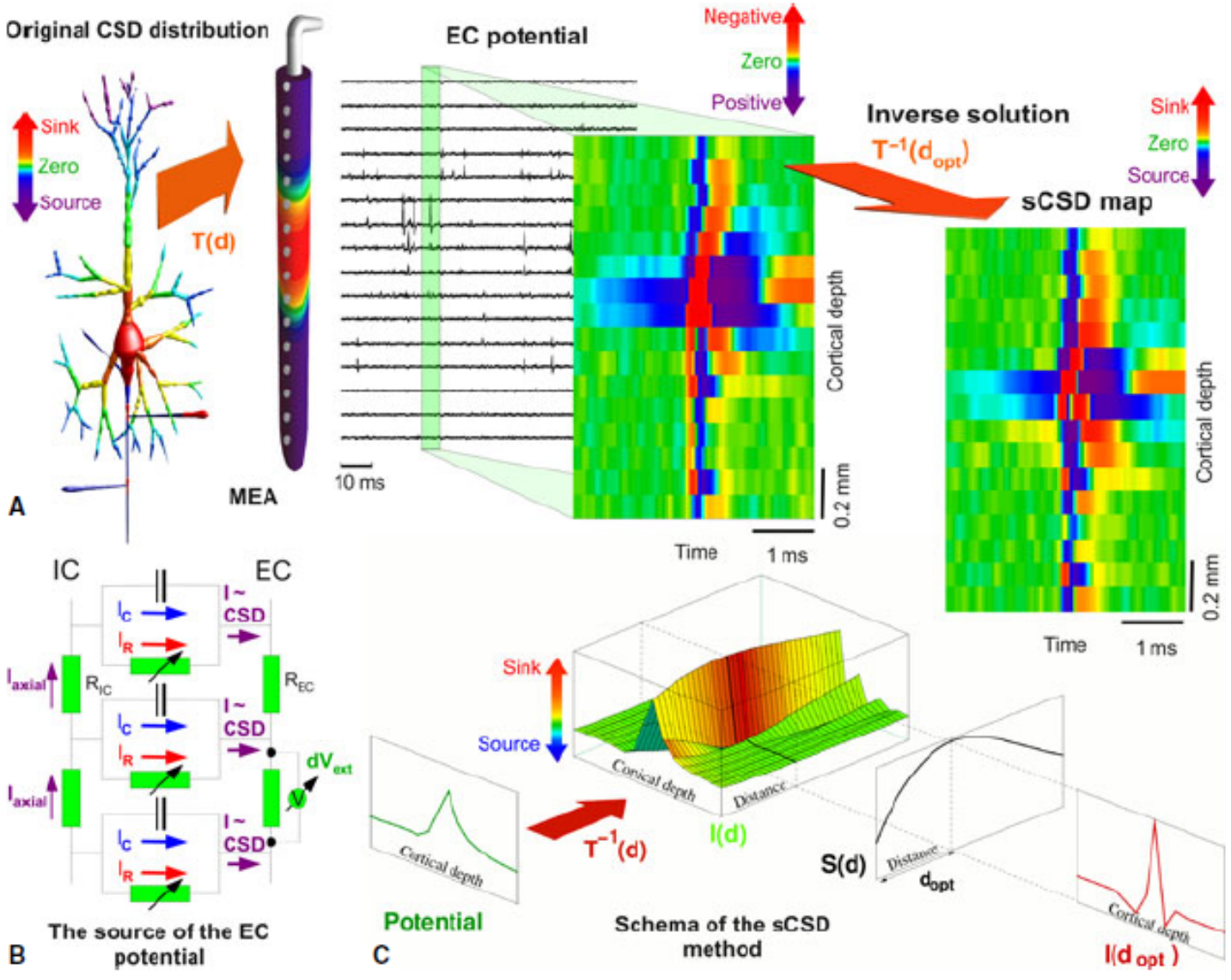
LFP


Laminar LFP
Macaque Primary
Visual Cortex
Layers
Surface
supra-
granular
granular
infra-
granular
White
Matter
Gamma
Activity
100 µV
500ms

Spikes - $> 300Hz$



sCSD Method


Original CSD distribution
Sink
Zero
Source
T(d)
MEA
A
EC potential
Negative
Zero
Positive
10 ms
Cortical depth
0.2 mm
Time
1 ms
Inverse solution
$T^{-1}(d_{opt})$
Sink
Zero
Source
sCSD map
Cortical depth
0.2 mm
Time
1 ms
IC
EC
I_C
I_R
I_{axial}
R_{IC}
R_{EC}
I ~ CSD
dV_{ext}
V
The source of the EC potential
B
Sink
Source
Cortical depth
Distance
I(d)
$T^{-1}(d)$
Potential
C
Schema of the sCSD method
S(d)
Distance
d_{opt}
Cortical depth
$I(d_{opt})$

Brain Rhythms

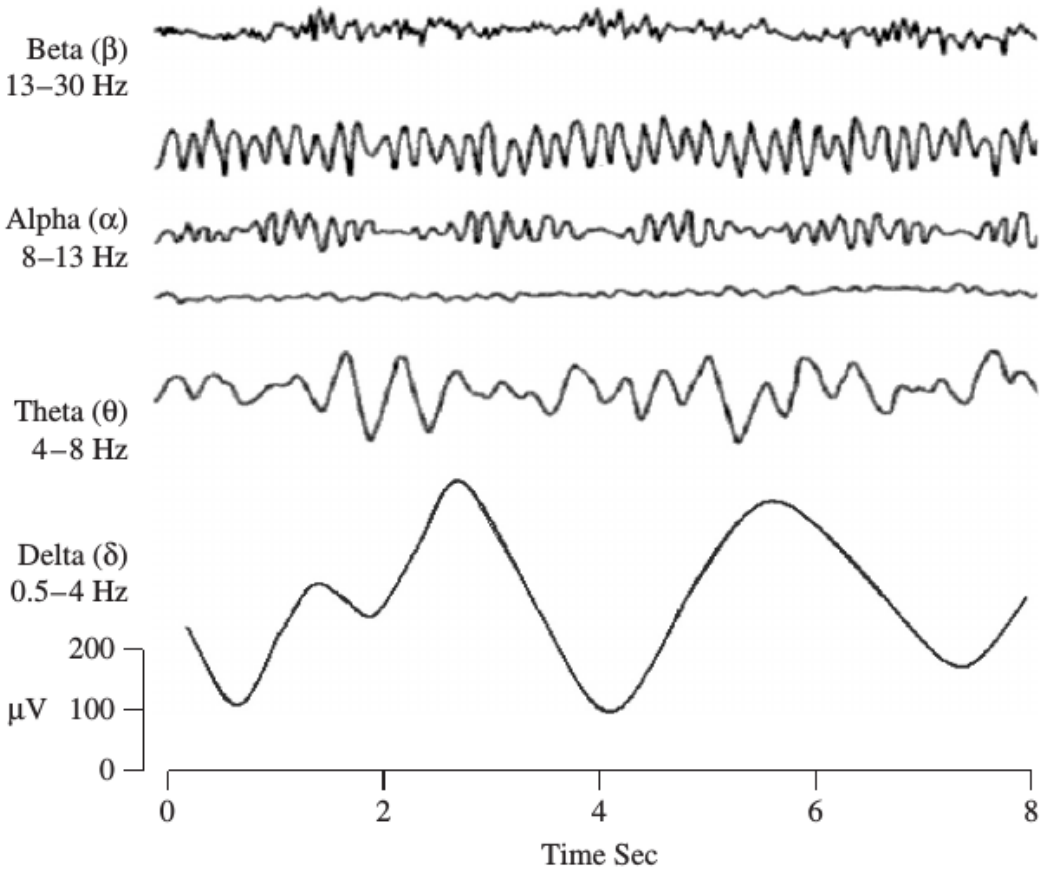
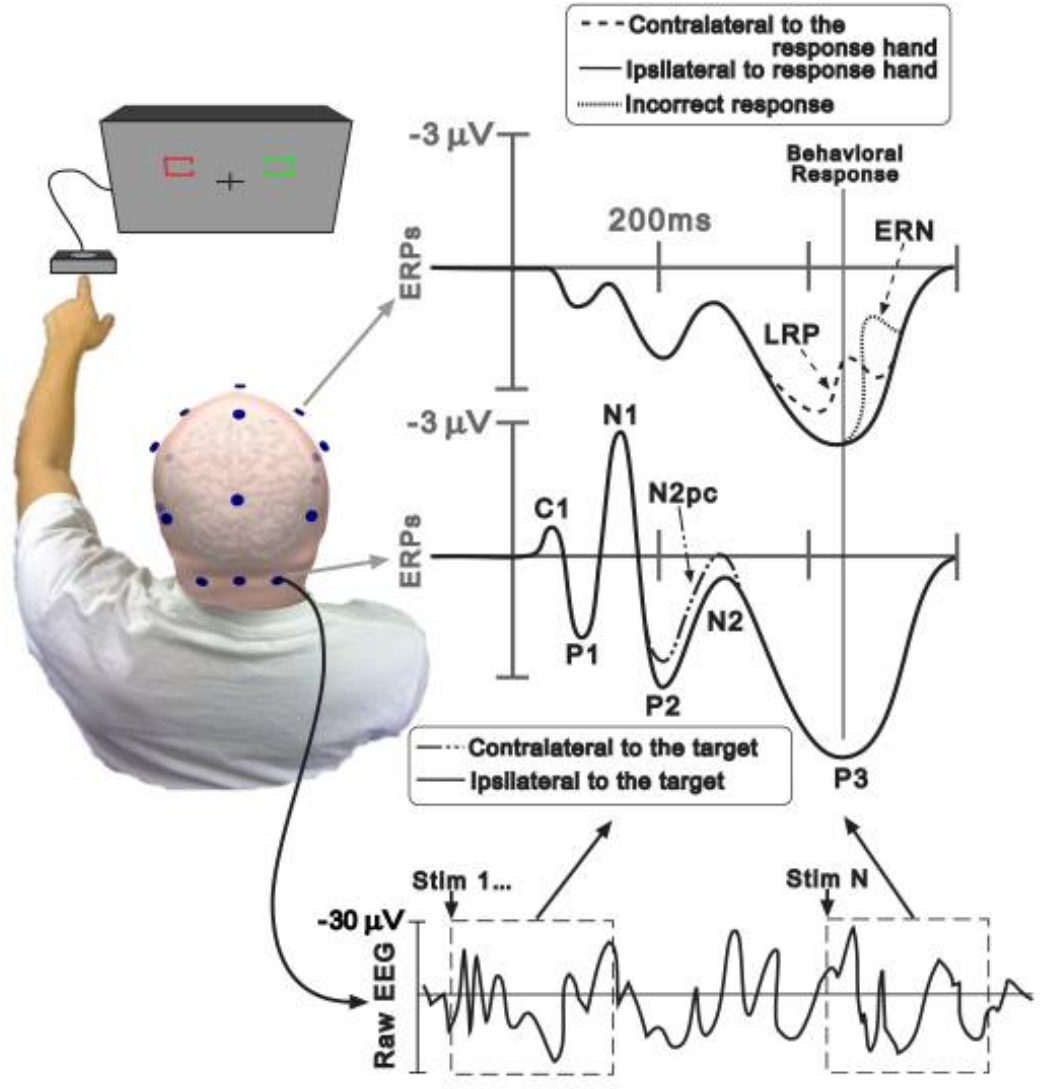


Figure : Four typical dominant brain normal rhythms, from high to low frequencies. The delta wave is observed in infants and sleeping adults, the theta wave in children and sleeping adults, the alpha wave is detected in the occipital brain region when there is no attention, and the beta wave appears frontally and parietally with low amplitude.

Event related potentials -stimulus

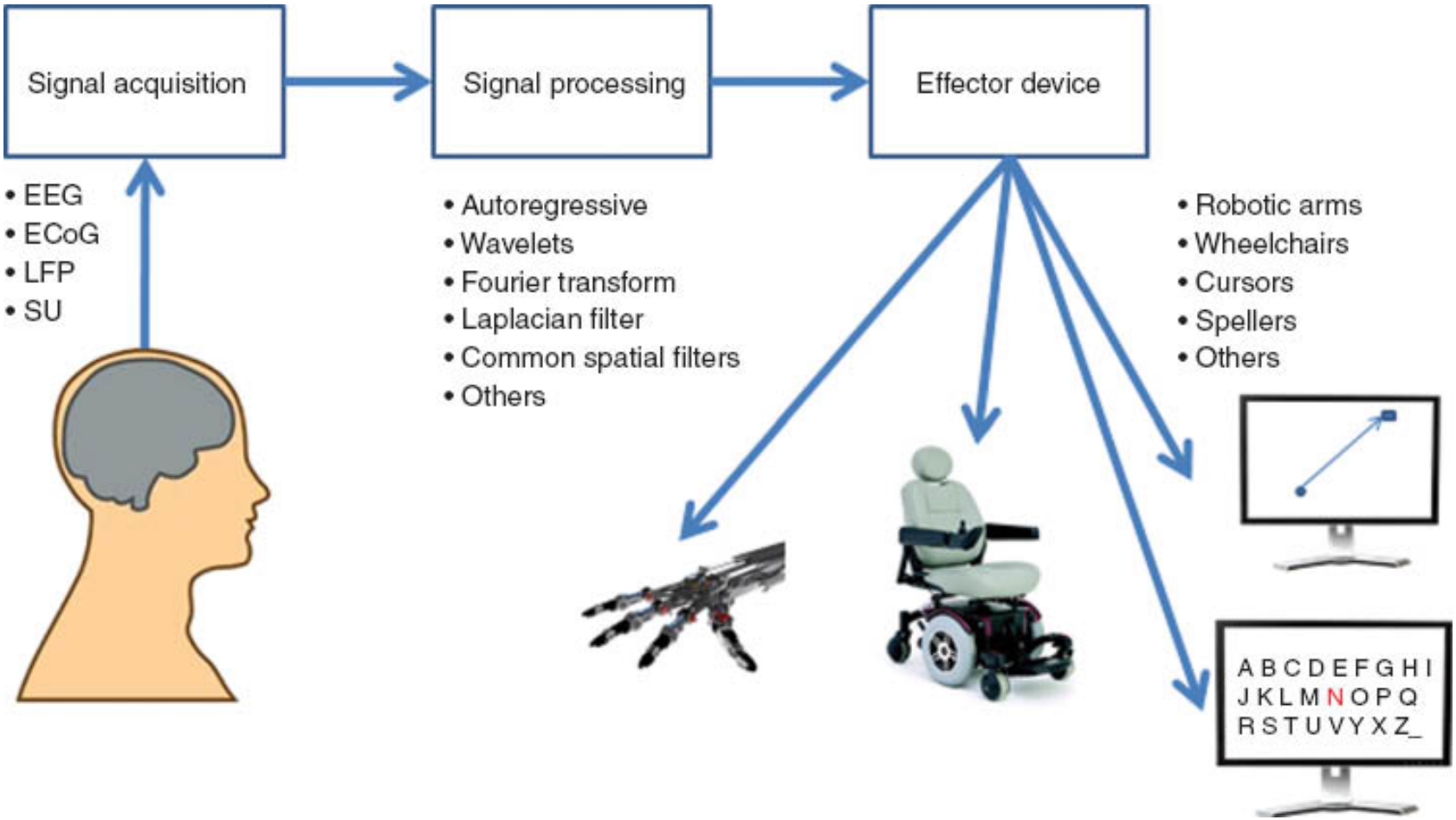
Respononse to a specific sensory, cognitive or motor event.



Nomenclature	Ordinal	Latency (peak)	Scalp Distribution	Task/Stimulus Specificity	Hypothesized Process(es) Indexed	Useful Reference
Components Preceding a Stimulus				CNV (O- & E-waves)	Anticipation, Cognitive & Motor Preparation	(Brunia, van Boxtel, & Bocker, in press)
Components Following a Stimulus	C1	P/N50-70			Sensory Processing	(Pratt, in press)
	P1	P90-100			Sensory/Perceptual Processing	(Pratt, in press)
	N1	N170-200	Posterior versus Anterior N1	N170 for faces	Perceptual Processing, Expert Recognition, Visual Discrimination	(Hillyard, Vogel, & Luck, 1998; Rossion & Jacques, in press; Vogel & Luck, 2000)
	P2				Not Well Understood	(Crowley & Colrain, 2004)
	N2	N225-250			Object Recognition, Categorization	(Folstein & Van Petten, 2008; Pritchard et al., 1991)
	N2pc		PCN		Deployment of Covert Attention	(Luck, in press)

	P3	P300	P3a/P3b	P3a/P3b	Stimulus Evaluation Time, Categorization, Context (Working Memory) Updating, Cognitive Load	(Polich, in press)
			SPCN	CDA	Maintenance in Visual Working Memory	(Perez & Vogel, in press)
				LRP	Response Preparation	(Smulders & Miller, in press)
Components Following a Response			Medial Frontal Negativity	ERN/Ne & FBN	Error Processing, Reinforcement Learning or Response Conflict Signal	(Gehring, Liu, Orr, & Carp, in press)
				Pe	Affective or Conscious Assessment of Task Performance	(Falkenstein et al., 2000)

Brain-Computer Interfaces



Monkey controlling robotic arm ▸ Link [12]

[12] *http://www.degruyter.com/view/j/revneuro.2013.24.issue-5/revneuro-2013-0032/graphic/revneuro-2013-0032_fig1.jpg*

Emotive Epoc

Neurogaming ▸ Link

Brain Imaging Technics

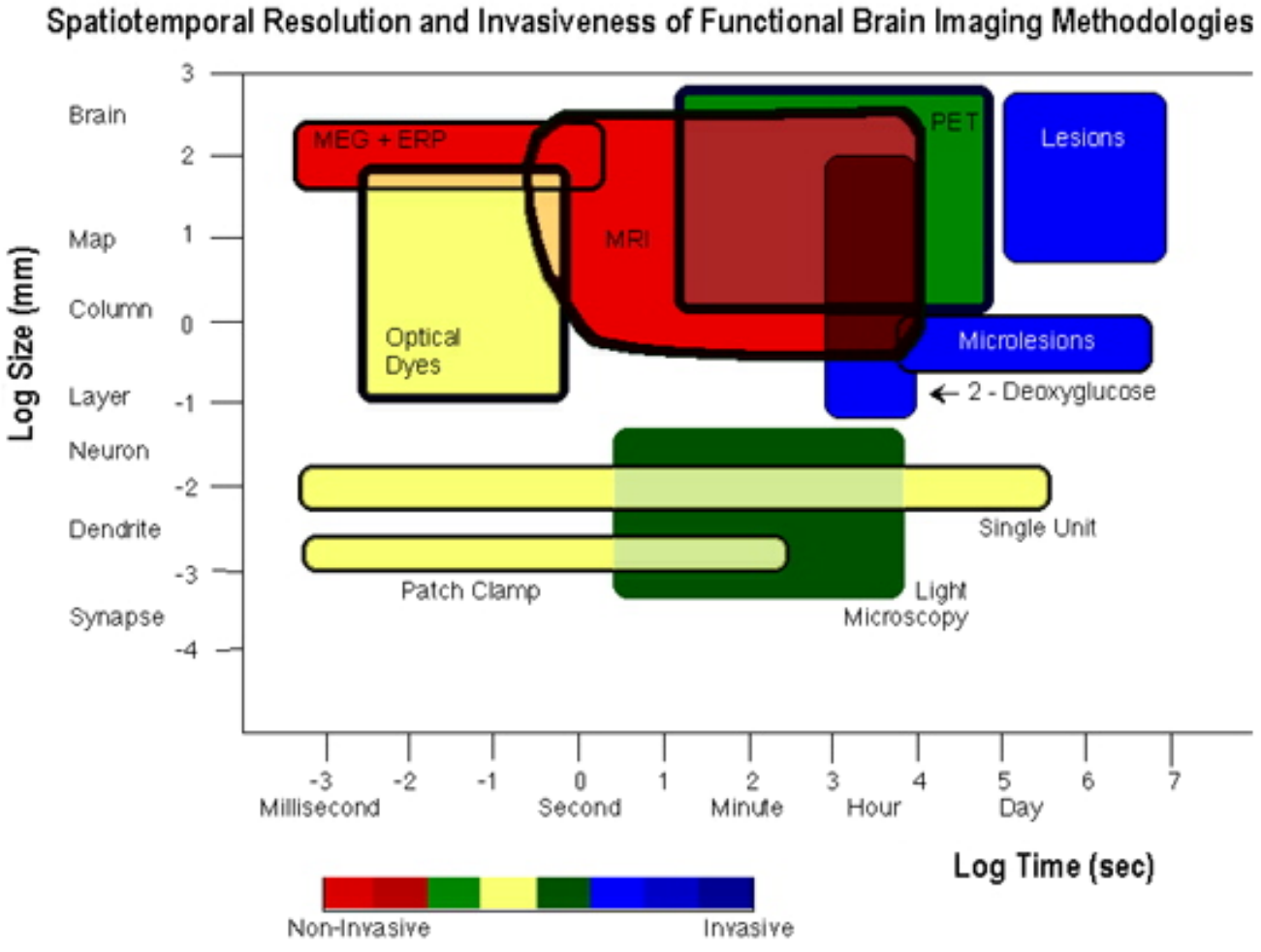
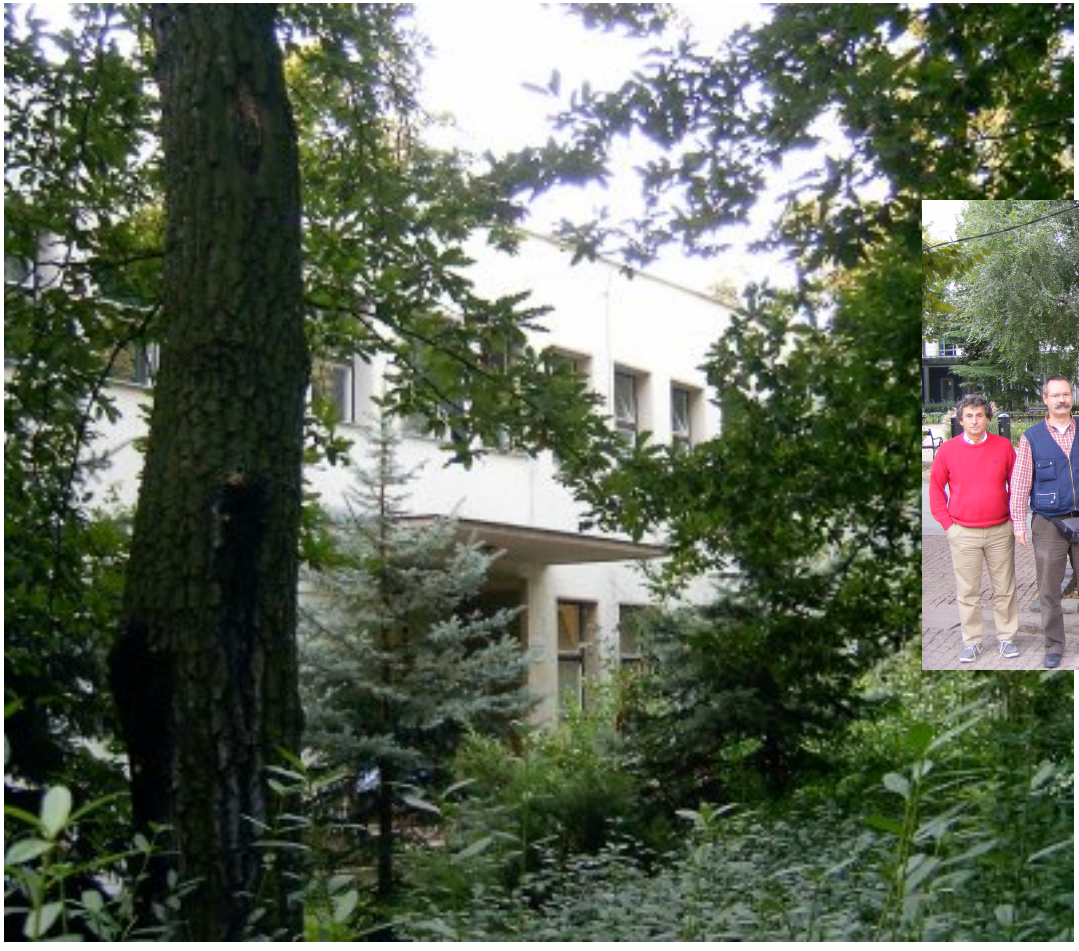


Figure : Spatial and temporal resolution of brain imaging technincs

Take home messages

?



Summary

- Single neuron morphology, signal propagation
- Single neuron imaging
- Neuron populations
- Population activity imaging

Multielectrode Probes

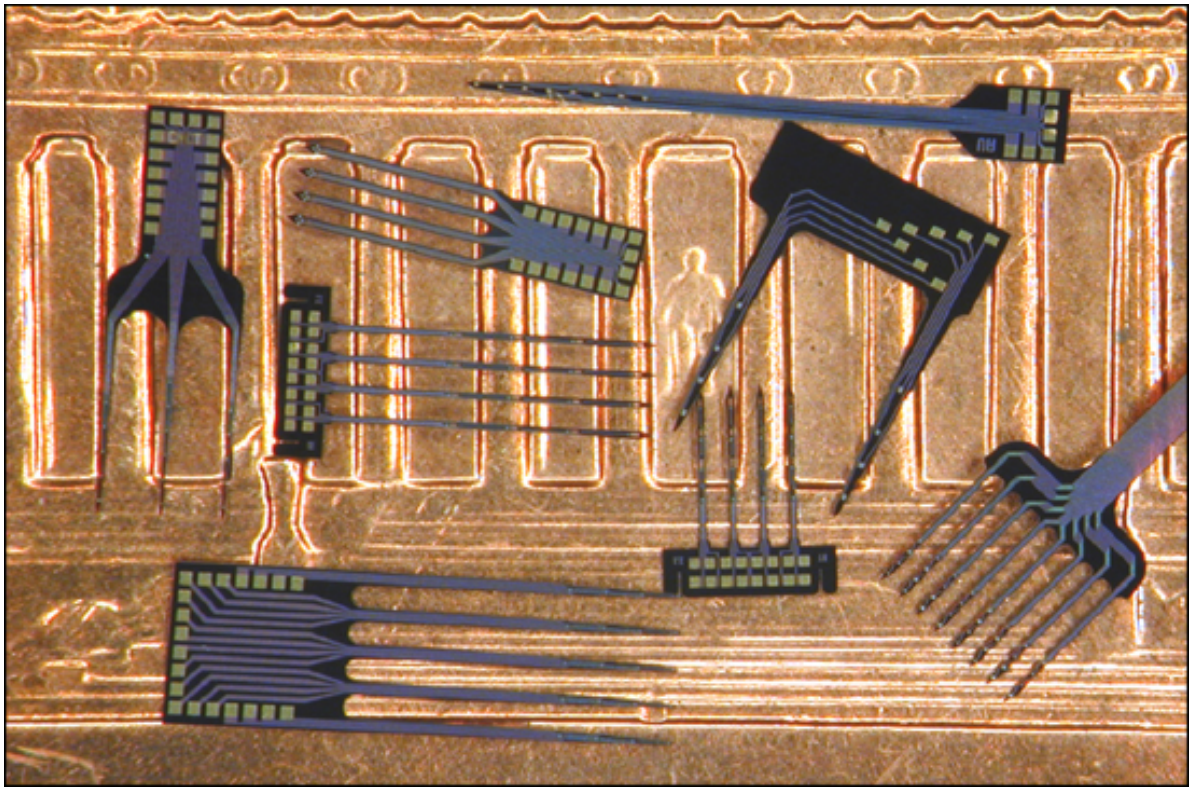
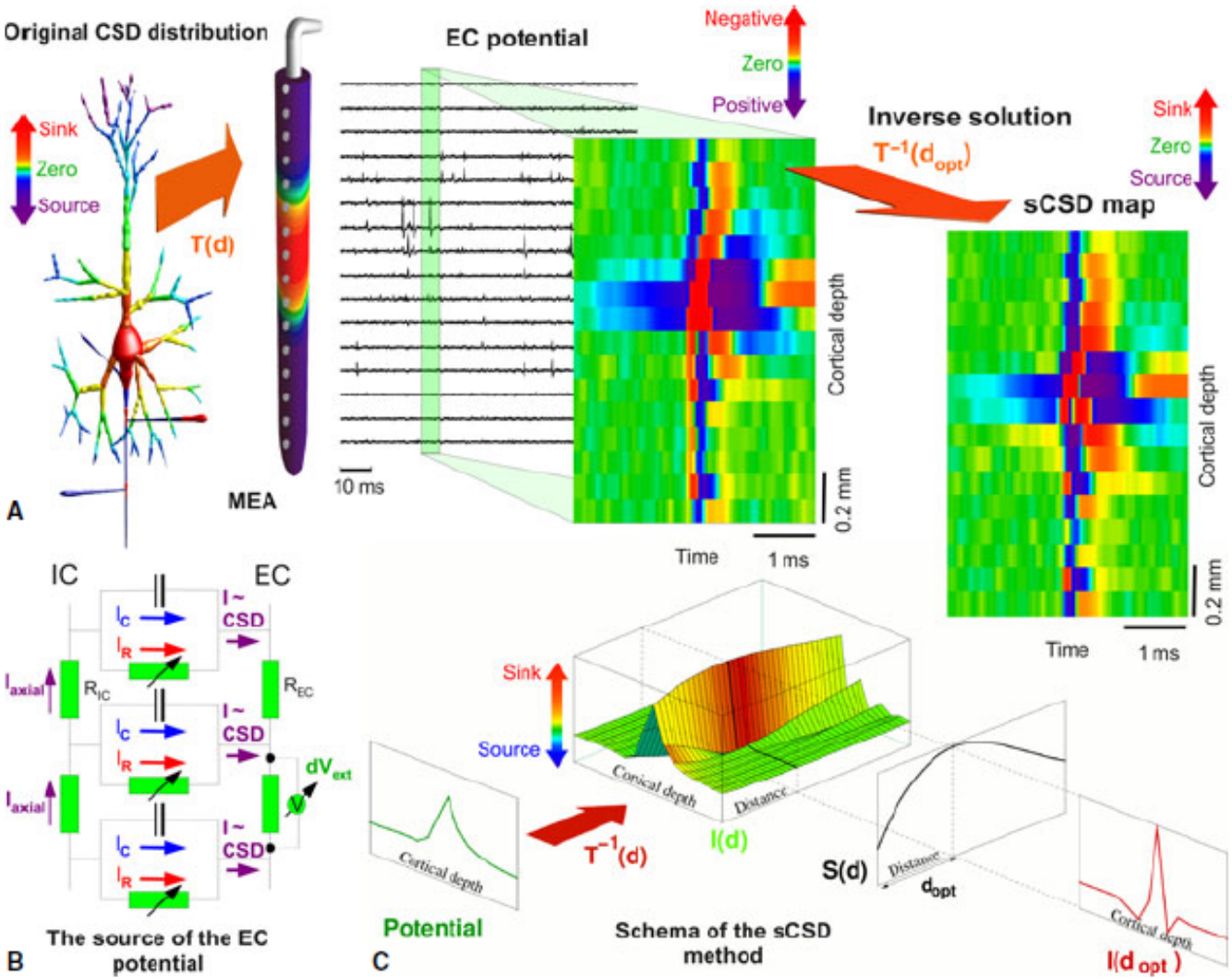


Figure : Several different probe designs shown on the back of a U.S. penny.

14

[14] Wise, K.D.; Sodagar, A.M.; Ying Yao; Gulari, M.N.; Perlin, G.E.; Najafi, K., "Microelectrodes, Microelectronics, and Implantable Neural Microsystems," Proceedings of the IEEE , vol.96, no.7, pp.1184,1202, July 2008

Previous approaches - sCSD method



15

[15] Somogyvári Z, Cserpán D, Ulbert I, Érdi P 2012