Computational Neurobiology

Lecture 1: Introduction

Dmitriy Bozhko
Georgy Galumov
Sofia Kolchanova

Syllabus

- Neuroscience vs Neurobiology
- What do we need to compute here
- Scope of interest
- What won't be in this course (semester)
- What won't ever be in this course
- What will be in this course

Neuroscience vs Neurobiology

- Neuroscience
- Neurobiology
- How do they interact

Definition of Neuroscience:

Neuroscience is the scientific study of the nervous system. It is a multidisciplinary branch of biology that combines physiology, anatomy, molecular biology, developmental biology, cytology, mathematical modeling and psychology to understand the fundamental and emergent properties of neurons and neural circuits.

Modern Neuroscience

- Molecular and cellular neuroscience
- Neural circuits and systems
- Cognitive and behavioral neuroscience
- Computational neuroscience
- Translational research and medicine

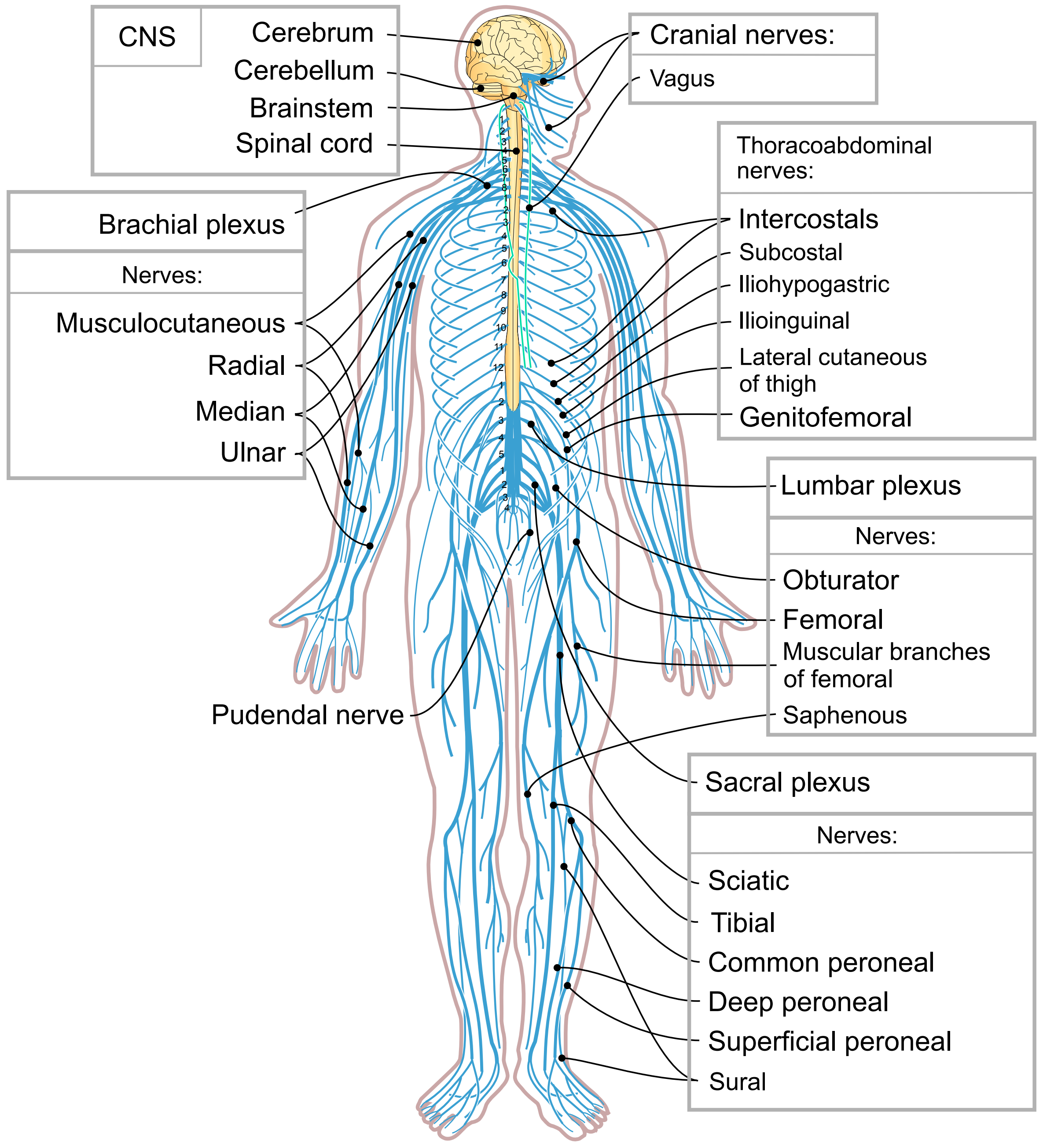
Definition of Neurobiology:

Neurobiology is the study of cells of the nervous system and the organization of these cells into functional circuits that process information and mediate behavior. It is a subdiscipline of both biology and neuroscience.

The scientific study of the nervous system increased significantly during the second half of the twentieth century, principally due to advances in molecular biology, electrophysiology, and computational neuroscience.

This has allowed neuroscientists to study the nervous system in all its aspects:

- How it is structured
- How it works
- How it develops
- How it malfunctions
- How it can be changed



What do we need to compute here and why?

What

- **Theoretical neuroscience** - capturing the essential features of the biological system at multiple spatial-temporal scales, from membrane currents, and chemical coupling via network oscillations, columnar and topographic architecture, all the way up to behavior
- **Neural data science** - electrophysiological or imaging data, the fitting of models to data, and the comparison of models

Why

- Insight
- Prediction
- Integration

Typically sensory input is considered "**bottom-up**", and higher cognitive processes, which have more information from other sources, are considered "**top-down**".

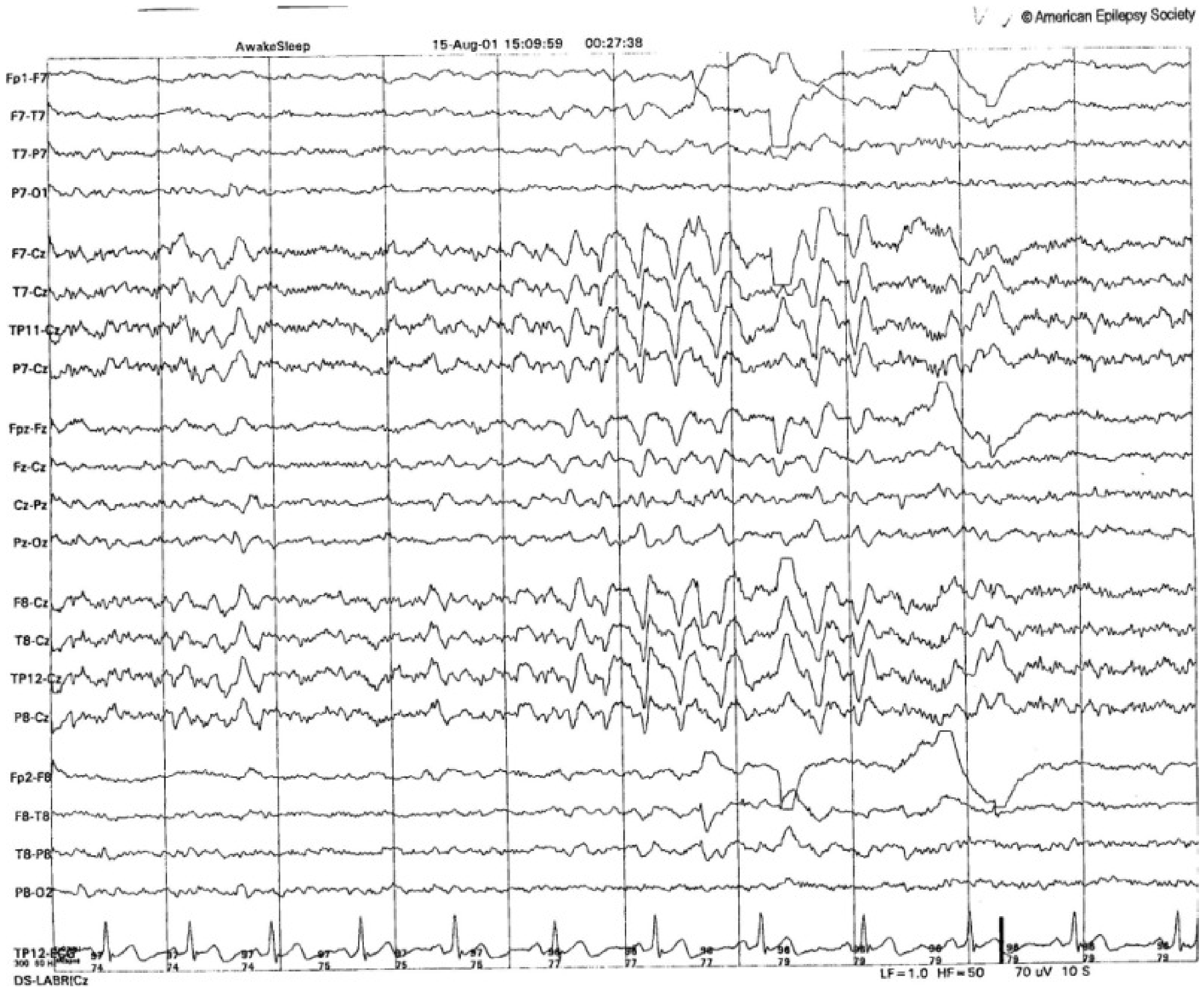
Top-Down — is characterized by a high level of direction of sensory processing by more cognition, such as goals or targets.

Bottom-Up - is characterized by an absence of higher level direction in sensory processing. Psychology defines bottom-up processing as an approach wherein there is a progression from the individual elements to the whole.

Scope of interest

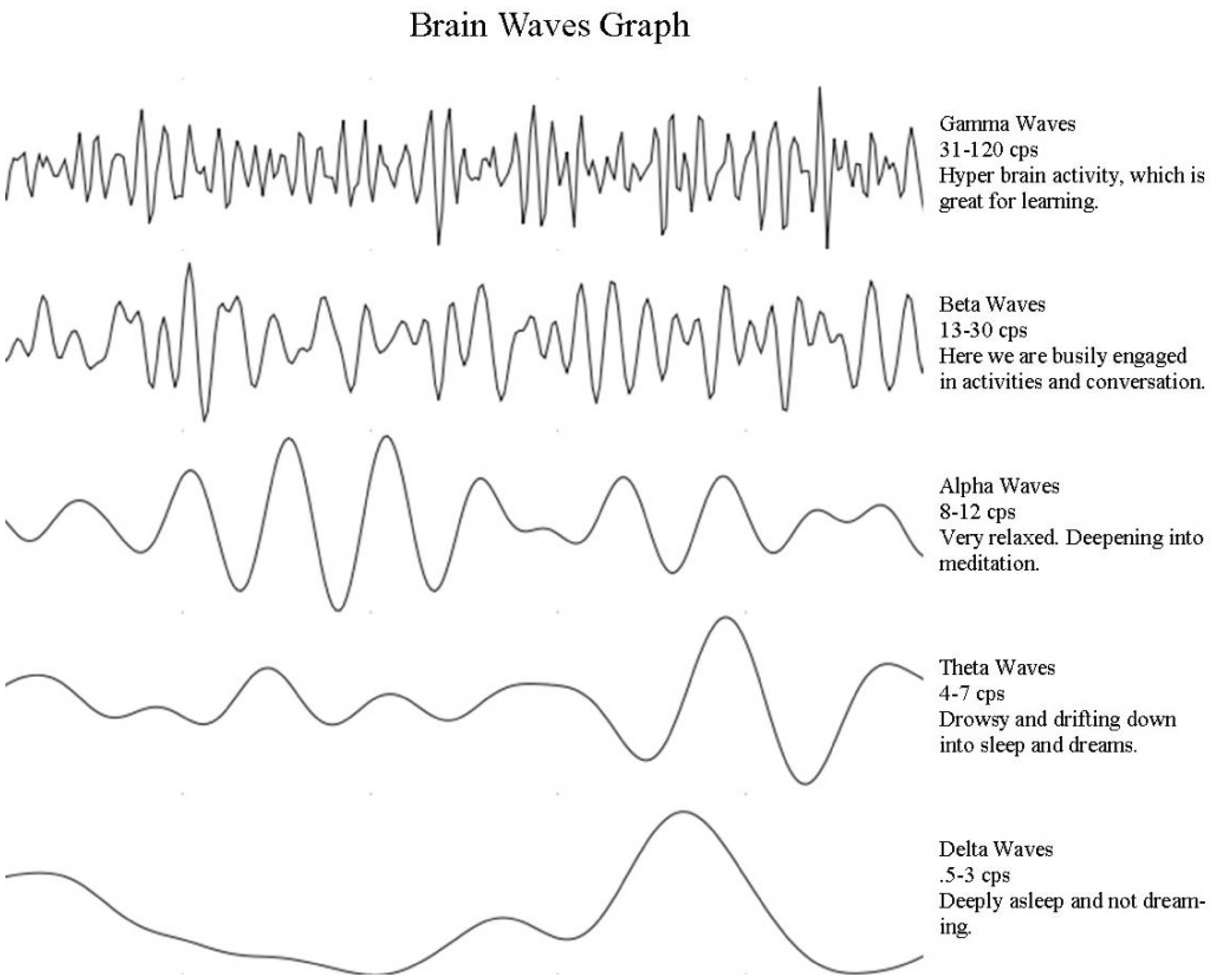
- Data processing and analysis (EEG, PET, fMRI)
- Modeling: neuron, tissue, development, pathology etc.
- Behaviors of networks
- Sensory processing and motor control
- Connectomics and structures mapping
- Memory and synaptic plasticity
- Learning and cognition
- Consciousness
- Computational clinical neuroscience

EEG Example

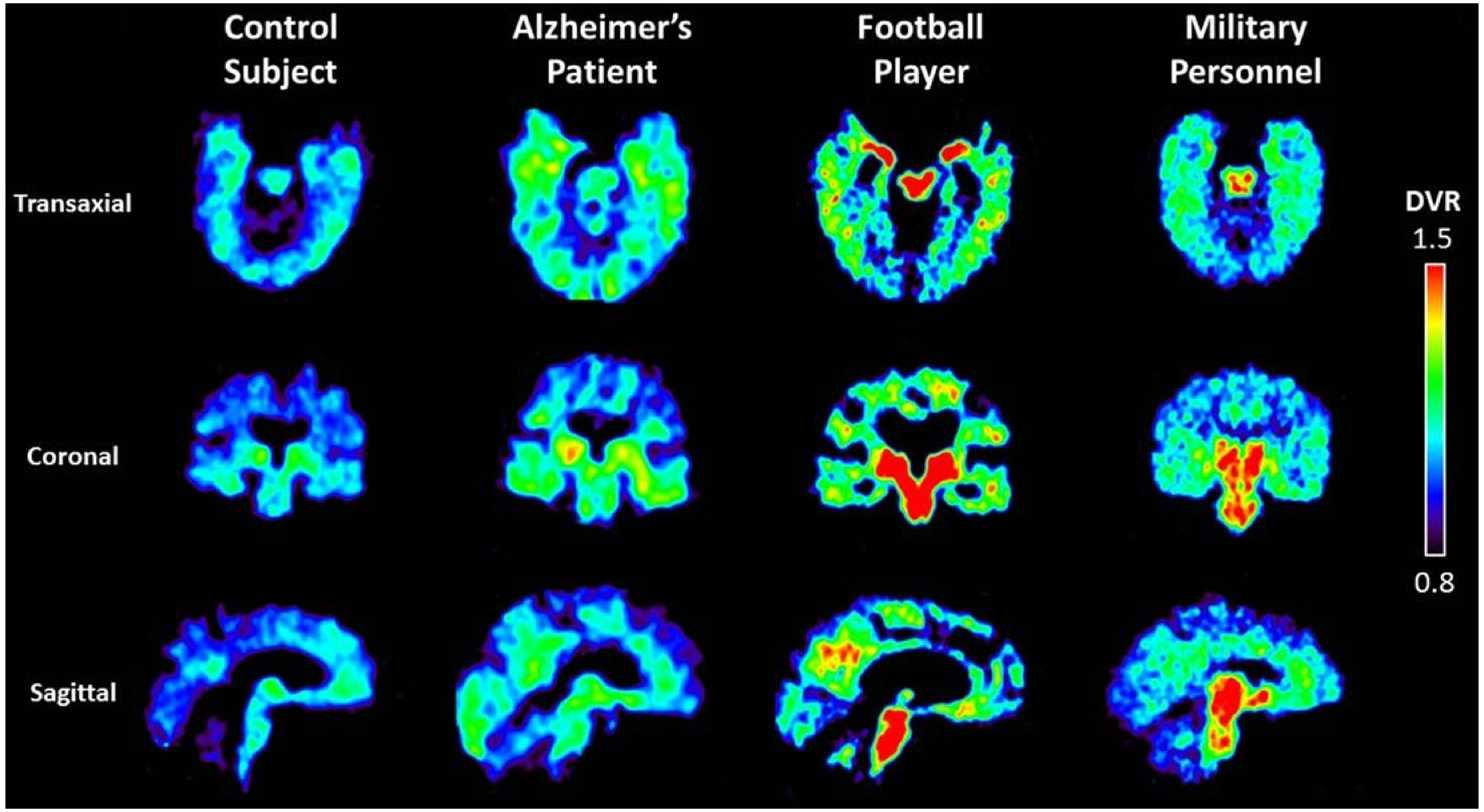


REM sleep EEG.

Electroencephalography (EEG): An Introductory Text and Atlas of Normal and Abnormal Findings in Adults, Children, and Infants


Brain Waves Graph
Gamma Waves
31-120 cps
Hyper brain activity, which is great for learning.
Beta Waves
13-30 cps
Here we are busily engaged in activities and conversation.
Alpha Waves
8-12 cps
Very relaxed. Deepening into meditation.
Theta Waves
4-7 cps
Drowsy and drifting down into sleep and dreams.
Delta Waves
.5-3 cps
Deeply asleep and not dream-ing.

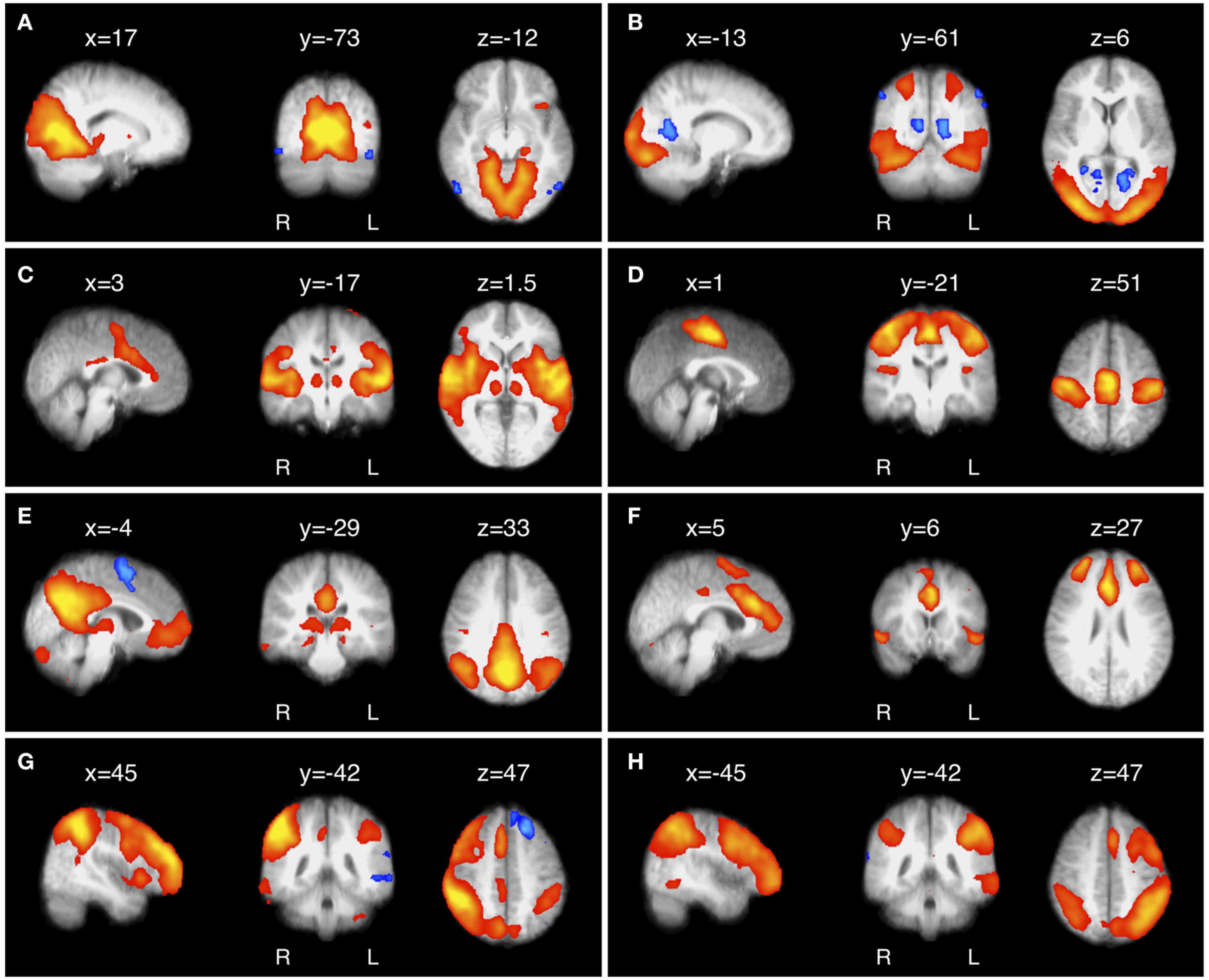
PET Example



Examples of FDDNP-PET DVR transaxial, coronal, and sagittal images of a cognitively healthy individual, Alzheimer's disease patient, football player, and a military subject.

J Alzheimers Dis. 2018; 65(1): 79–88.doi: 10.3233/JAD-171152

fMRI Example



Eight of the most common and consistent RSNs identified by ICA.

Front. Syst. Neurosci., 06 April 2010 | https://doi.org/10.3389/fnsys.2010.00008

Modeling: Neuron level

Electrical input–output membrane voltage models

- Integrate-and-fire/Leaky integrate-and-fire
- Hodgkin–Huxley
- Galves-Löcherbach
- Compartmental models

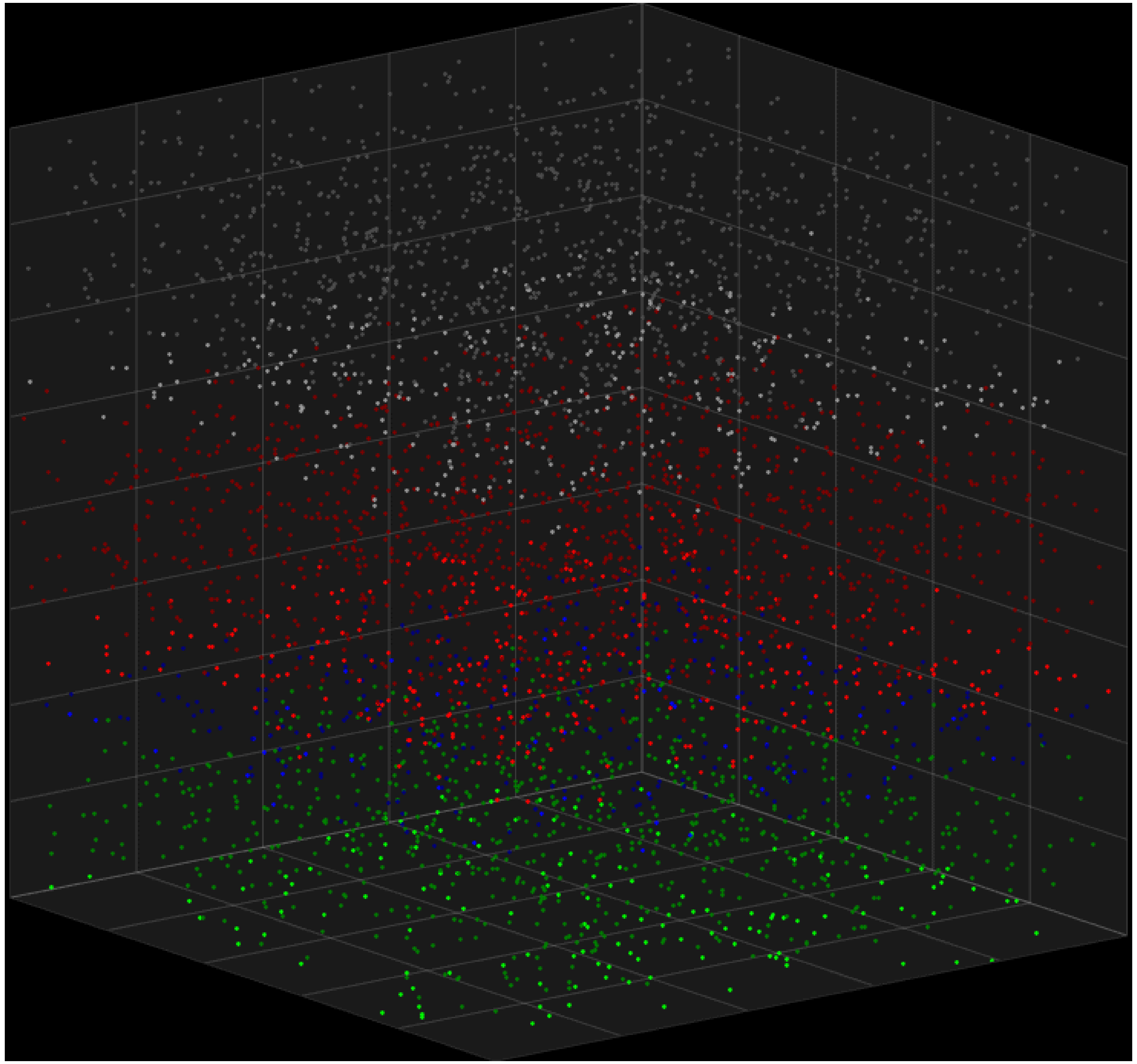
Natural input stimulus neuron models

- The non-homogeneous Poisson process model (Siebert)
- The two state Markov model (Nossenson & Messer)
- Non-Markovian models (Johnson and Swami, Berry and Meister)

Pharmacological input stimulus neuron models

- Synaptic transmission (Koch & Segev)
- The two state Markov model (Nossenson & Messer)

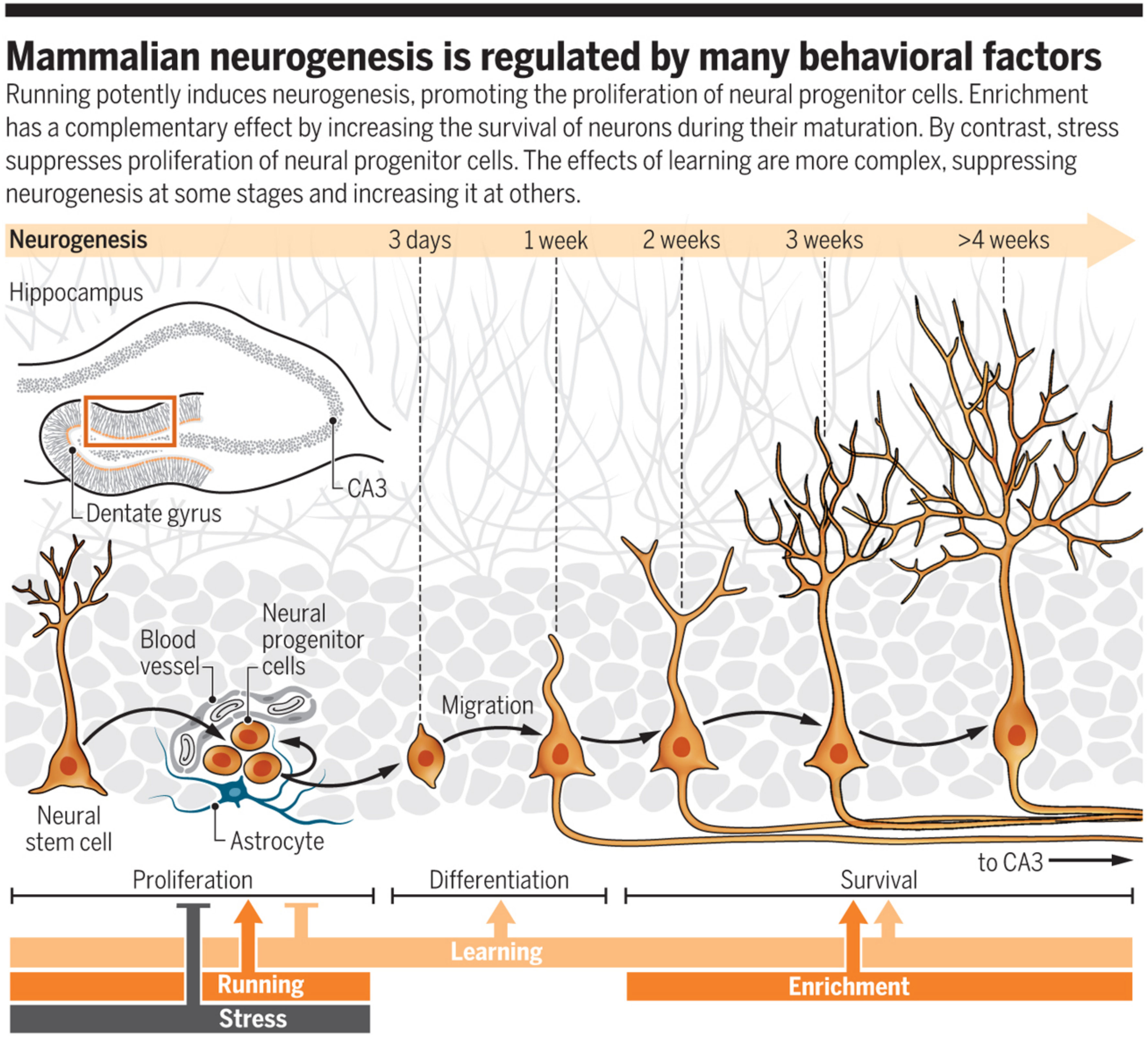
HTM Neuron Model



3D visualization of the Galves-Löcherbach model for biological neural nets.

Modeling: Development

- How do neuron precursor cells know how to differentiate?
- How do neurons migrate to the proper position in the central and peripheral systems?
- How do axons and dendrites form during development?
- How do axons know where to target and how to reach these targets?
- How do synapses form?



Adult neurogenesis in mammals. doi: 10.1126/science.aav6885

Modeling: Pathology

- Cellular level pathologies (osmosis, signaling pathways, gene expression etc)
- Tissue pathologies (prolifiration, differentiation, apoptosis etc)
- Infectious diseases
- Chemicals/drugs interaction

Modeling: Tissue and Behaviors of networks

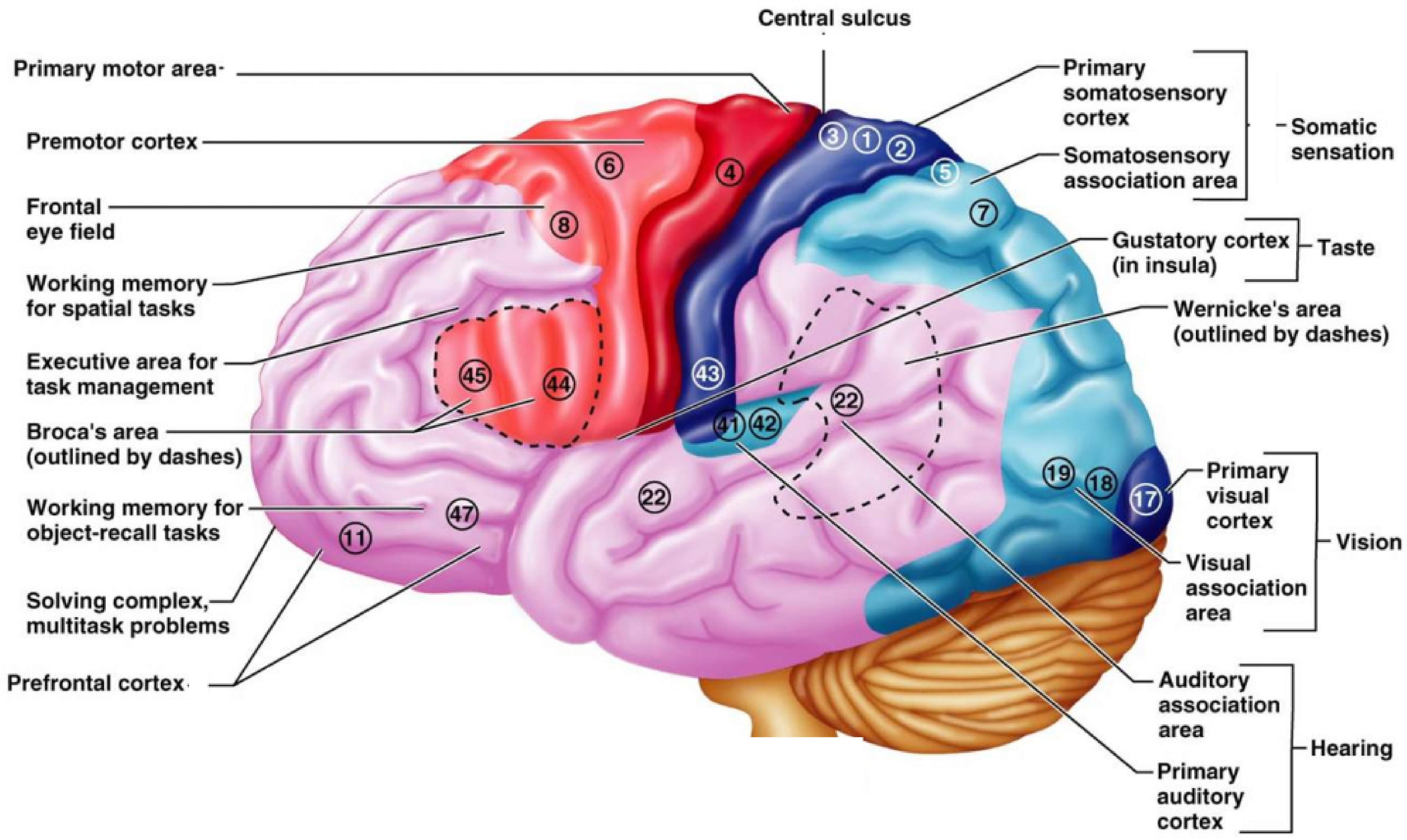
- Mean field theory (Ising model)
- Population model (Wilson–Cowan model)
- Neural tissue simulation (organoids)
- Spiking neural networks

Sensory processing approaches

- Biophysical modelling of different subsystems (honest physiology)
- Theoretical modelling of perception (some form of Bayesian inference)

Visual information is a major one, but not the only!

Brain Diagram



Motor control models

- Cerebellum's role for error correction
- Skill learning in motor cortex and the basal ganglia
- Control of the vestibulo ocular reflex

Connectomics and structures mapping

Connectomics and structures mapping

Connectomics is the study of the brain's structural and functional connections between cells, which is visualized as a connectome.

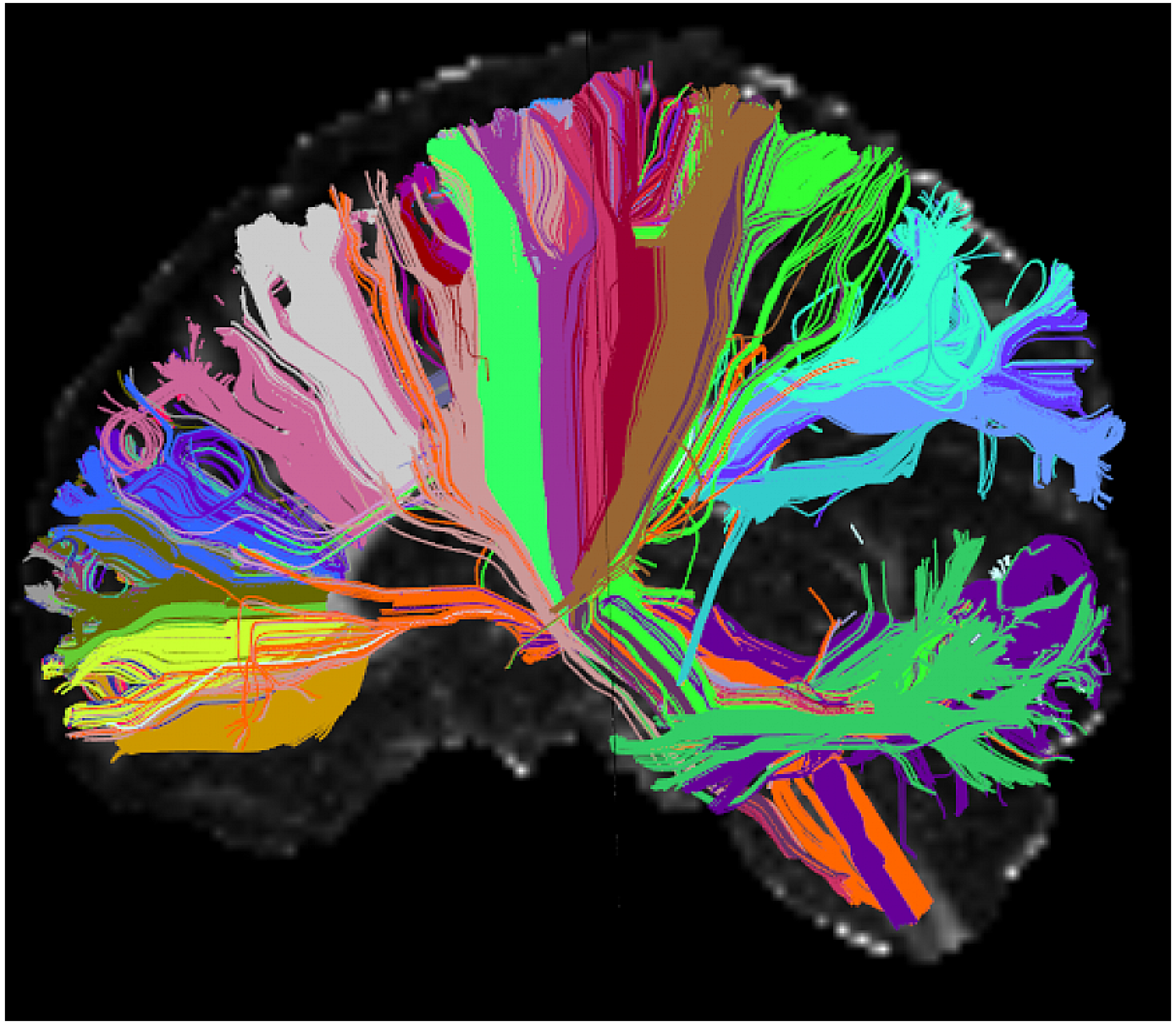
Model systems

- Nematode C. elegans
- Fruit fly
- Barn owl
- Mouse/rat
- Human BRAIN!

Instruments

- Neural imaging
- 3D electron microscopy
- Graph theory

Human Connectome Project



Memory and synaptic plasticity

Hebb's postulate

When an axon of cell A is near enough to excite a cell B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is increased.

Directions

- Hebbian learning
- Working memory or short-term memory models (Baddeley and Hitch, Prefrontal cortex basal ganglia working memory)
- Short-term + long-term memory (Atkinson–Shiffrin memory model)
- Search of associative memory (SAM) models
- Stereochemically detailed models of the acetylcholine receptor-based synapse

Learning and Cognition

- Visual attention
- Identification
- Categorization
- Decision making
- Reaction
- Reinforcement (molecular level)
- Default-mode networks

Consciousness

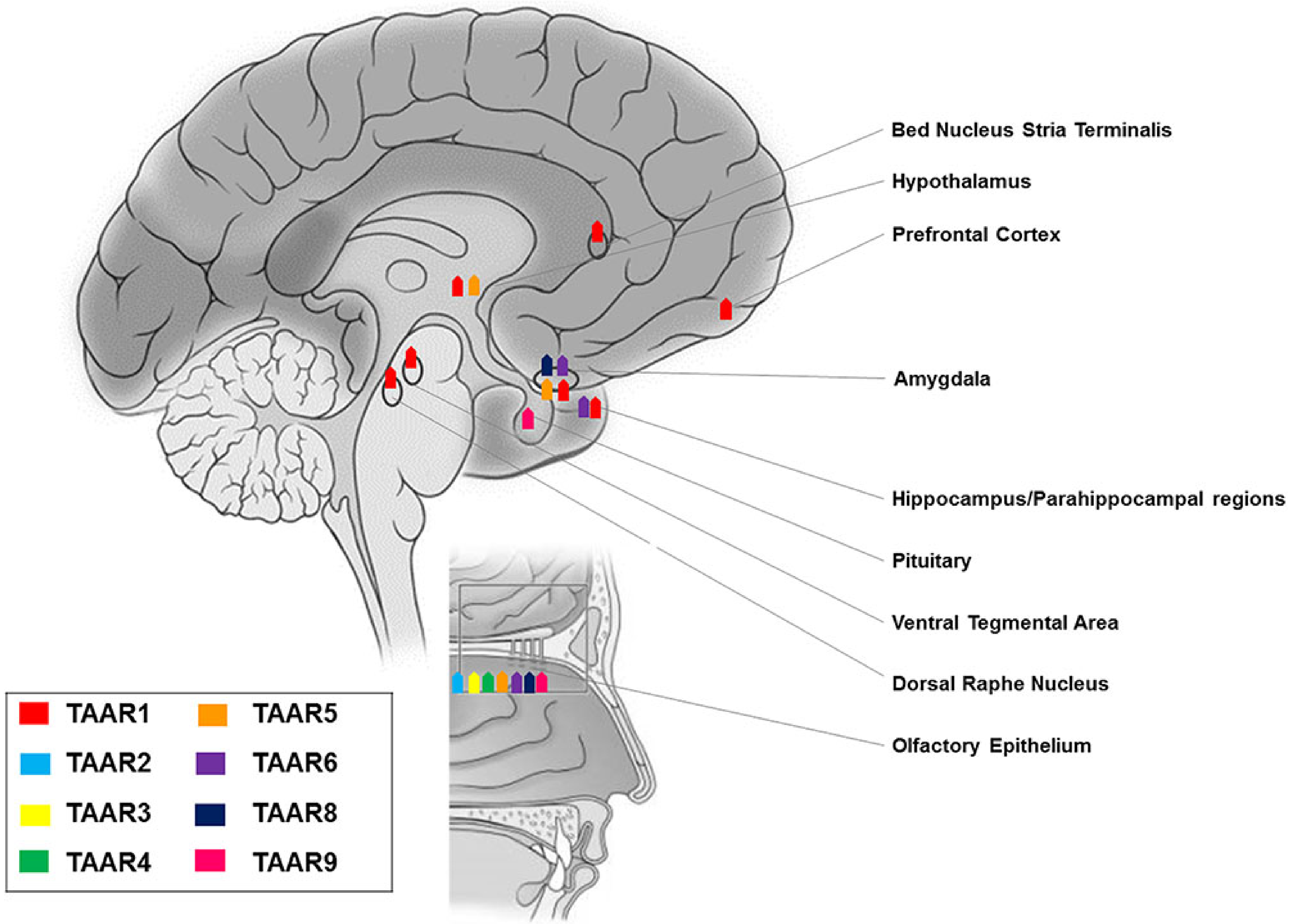
One of the ultimate goals of psychology/neuroscience is to be able to explain the everyday experience of conscious life. Francis Crick, Giulio Tononi and Christof Koch made some attempts to formulate consistent frameworks for future work in neural correlates of consciousness **(NCC)**, though much of the work in this field remains speculative.

Computational clinical neuroscience

- Mental diseases
- Neurodegenerative deseases
- Regenerative medicine
- Psychopharmacology
- Neural-control interfaces

Mental/psychiatric deseases

- Anxiety disorders (panic disorder, PTSD, OCD)
- Neurodevelopmental disorders (autism spectrum disorders, motor disorders, ADHD)
- Personality disorders (odd or eccentric disorders, dramatic, emotional or erratic disorders, anxious or fearful disorders)
- Psychotic disorders (schizophrenia, bipolar disorder, sleep deprivation)



TAAR1 may contribute an etiological role to the pathogenesis of schizophrenia, amongst a multiplicity of genetic and environmental risk factors.

Front. Pharmacol., 10 January 2018 | https://doi.org/10.3389/fphar.2017.00987

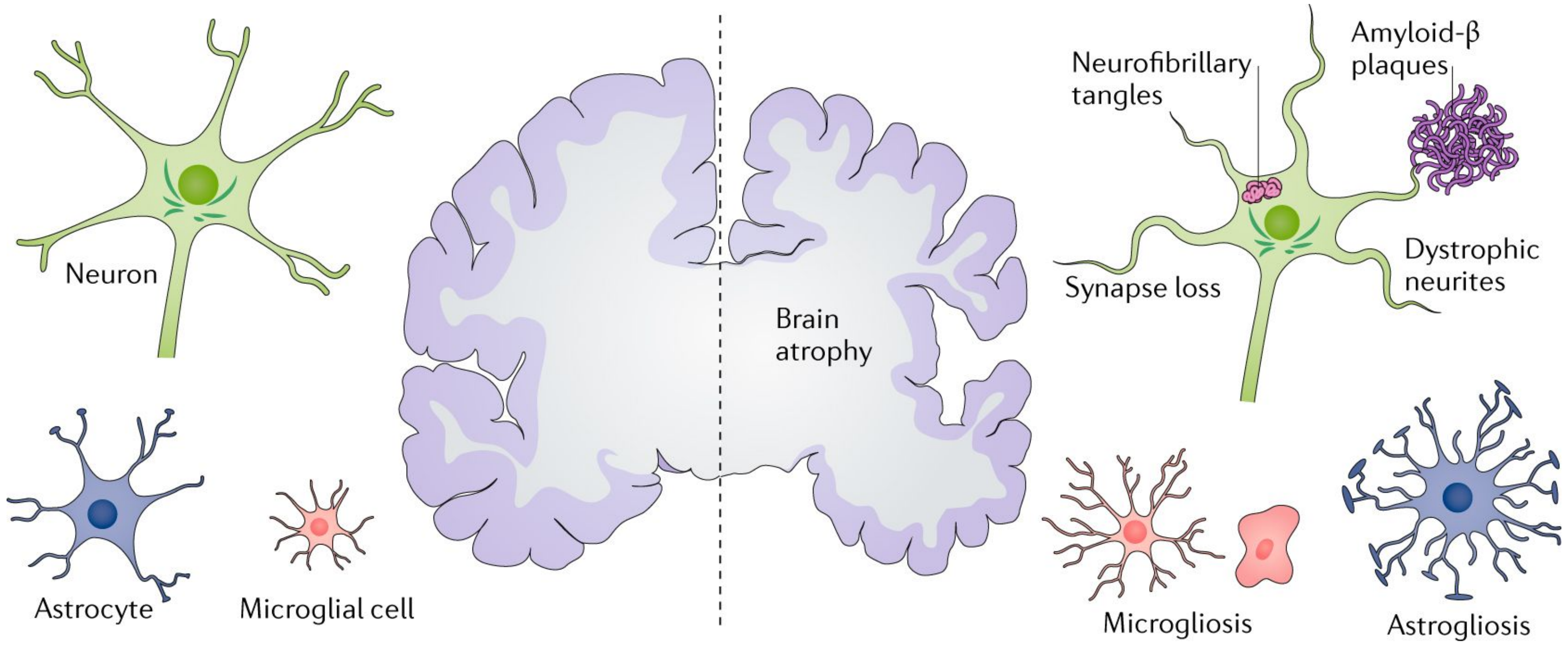
Neurodegenerative deseases

- Amyotrophic lateral sclerosis
- Parkinson's disease
- Alzheimer's disease
- Huntington's disease

Mechanisms

- Genetics/epigenetics
- Protein misfolding
- Intracellular mechanisms
- PCD

Tau-targeting therapies for Alzheimer disease



The defining pathological hallmarks of Alzheimer disease.

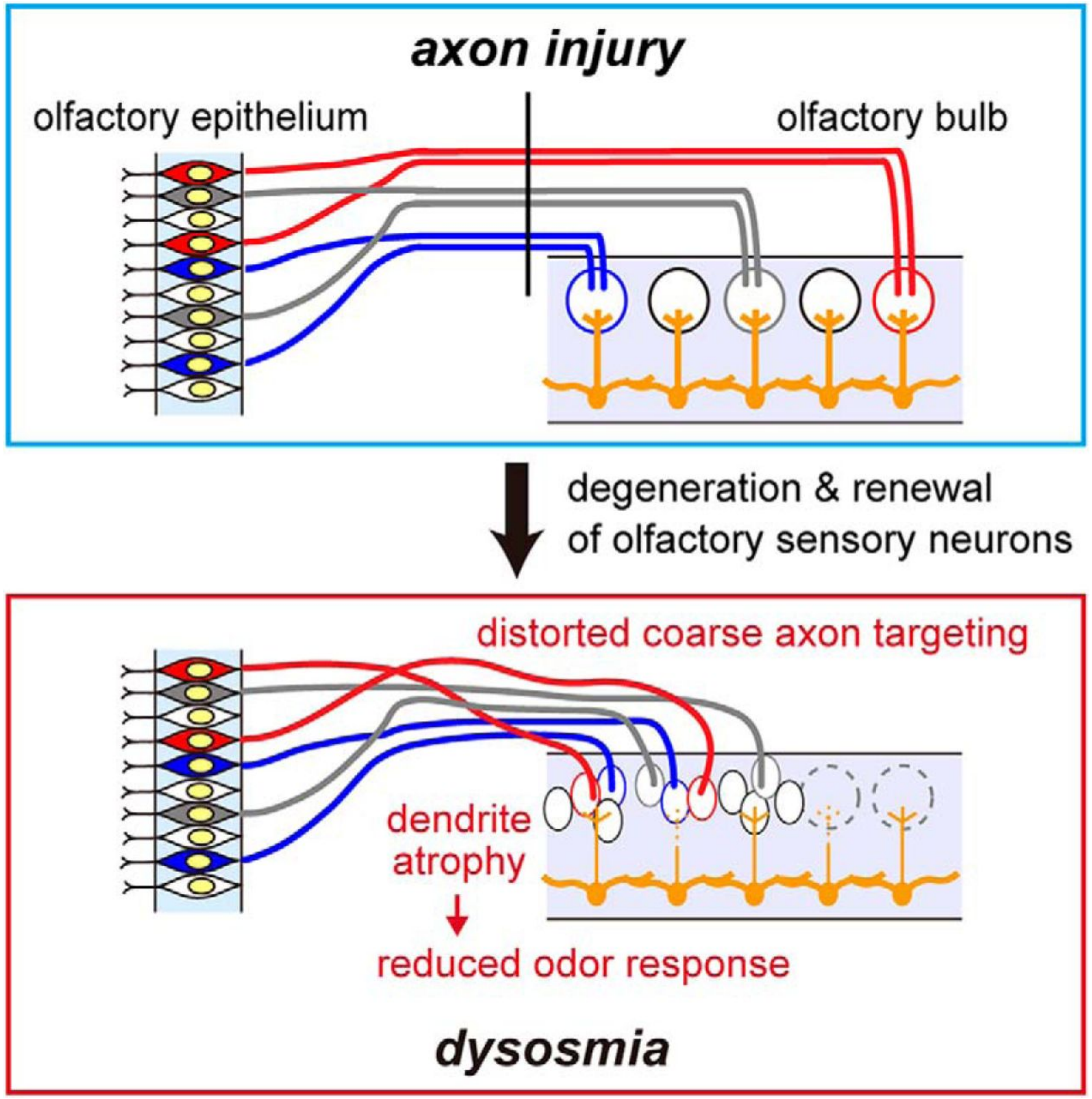
Nat Rev Neurol. 2018 Jul;14(7):399-415. doi: 10.1038/s41582-018-0013-z.

Regenerative medicine

- Trauma
- Injury
- Neurodegenerative disease
- Aging

Michael Levin. Bioelectricity in regeneration processes

Example of axon injury



Psychopharmacology

- Drug development/neurotoxicity tests
- Clinical trials
- Addiction models

Neural-control interfaces

- Invasive NCIs (vision, movement)
- Partially invasive NCIs
- Non-invasive NCIs

Emotiv and WoW

What won't be in this course (semester)

- Connectomics
- Learning models
- Memory models

What won't ever be in this course

- Pathologies modeling (because of biology)
- Clinical data processing (becuase it's more data science)
- Consciousness (guess why :))

What will be in this course

- Course programm
- Course structure

Course programm

- Neuron physiology and biophysics
- Electrical input–output membrane voltage models
- Biological perspective
- Neurotransmitters and receptors
- Neural encoding and decoding
- Network models
- Developmental models. Ties to computational and systems biology
- Regulation of neuron functioning
- How you can build your own model and why

Course structure

- 11 lections
- 2 seminars
- 5 homeworks
- final quiz

Assessment criteria

In this course students can get a maximum of 10 points in total. Each task is graded based on the scale from 1 to 10 where 1-3 is unsatisfactory, 4-5 is satisfactory, 6-7 is good, 8-10 is excellent.

Tasks coeffcients:

- Hodgkin-Huxley Model (blocking): 0.1
- Chemical synapse model (blocking): 0.15
- Stochastic network model (blocking): 0.1
- Free choice network model: 0.1
- Axon growth model (blocking): 0.2
- Final quiz (blocking): 0.35

Questions?