Introduction to Computational Cognitive Neuroscience (CCN)

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Institute for Adaptive and Neural Computation,

University of Edinburgh, UK

Spring 2025

- CNS?
- UG4?
- Class only?
- Informatics? PPLS? Other?
- Python?

Welcome to CCN

- Goal of CCN: Understand how the brain works, how cognition and behaviour are generated by the brain, and how it can go wrong (computational psychiatry)

- Highly interdisciplinary field: Combines ideas from computer science, maths, physics, biology, psychology, artificial intelligence, machine learning, etc.

- Learning outcomes: understand computational models of brain function/cognition, implement models in Python, think critically about how to model aspects of brain function and cognition, critically evaluate research articles in the field and write scientific reports, understand current challenges for mental illness.

Is CCN for You?

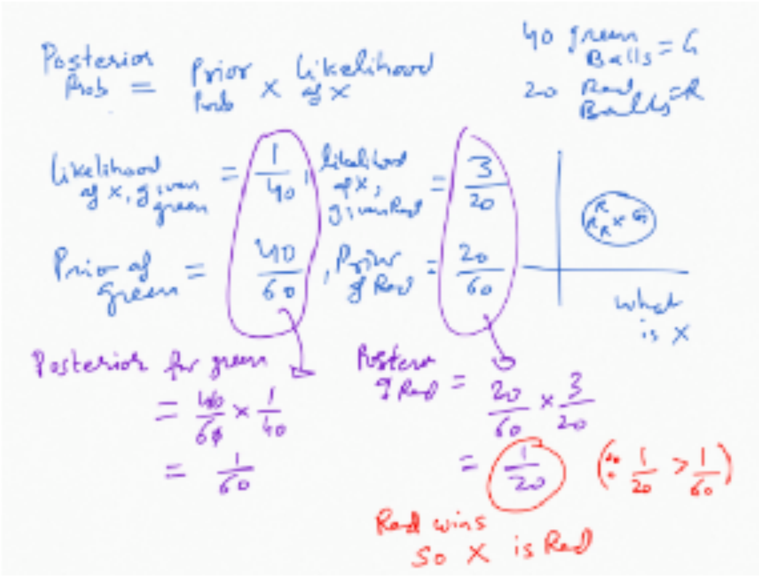
- CCN is a course about the brain, cognition, and mental illness/psychiatry

- We make *extensive* use of (not very advanced) mathematics and computational/ numerical techniques to build and interpret models of brain function and cognition

- CCN is **not** a course that is widely useful for industry or applications (such as AI/ML) - though interest is growing

- Problems in CCN are usually open-ended, the biology is messy, the brain is too complex to modelled exactly – you need to be comfortable with vagueness and uncertainty, and willing to do some independent reading!
- Computational neuroscience/psychiatry an extremely interesting and exciting fields!

Requirements for this Course - Maths



- **Maths:** linear algebra, probability theory, differential equations, optimisation methods
- Not very advanced but used extensively.
- Examples: linear first order ODE, Poisson distribution, matrix/vector algebra, Bayes rule, maximum likelihood

Requirements for this Course - Coding

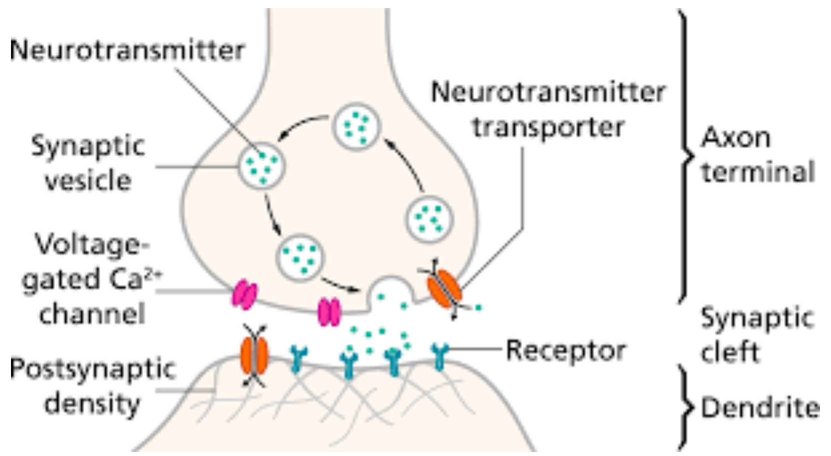
- **Coding:** Numerical computing, typically in Python (previously Matlab)

- The course material assumes Python, but you are free to use any language you choose

- You will need to solve differential equations numerically, plot the results, etc.

Requirements for this Course - Biology

- No formal knowledge of neurobiology is required
- Some background reading is highly recommended (see Learn for basic resources)
- We aim to provide the bare minimum of biology needed to understand the key concepts, but there is a whole world of messy biological details out there!
- Read the Neuroscience Primer on Learn to get started!



Assessment

- 30% Coursework
- 70% Exam

- Assignment: Implement a model in Python. Simulate, critically evaluate, and present results in the format of a scientific report.

- **Deadlines:**

 - Assignment 1 [30%] Released 3/03 - Deadline 24/03

Lectures

- Delivered **in person** - recordings will be available on Learn
  Slides on Opencourse https://opencourse.inf.ed.ac.uk/ccn

  (Note: all recordings from 2020 available on Media Hopper Replay)

- Lectures times: Monday & Thursday @12:10pm
  Monday: McEwan Hall Foyer Room 3-4
  Thursday: LG.09 - 40 George Square Lower Teaching Hub

- Lecturer: Peggy Seriès

Tutorials/Labs

- Labs: Every two weeks (week 2,4,6,8, 10)
  Mondays 3-5 pm 5.05 - West Lab - Appleton Tower

- Format of labs: coding and implementation of models in Python.

Labs are good practice for the assignment and will help with exam!

- *Python tutorial on week 2* – optional but highly recommended if you need a refresher for Python

(available on Opencourse https://opencourse.inf.ed.ac.uk/ccn)

Virtual Office Hours, Discussion, etc.

- **Office Hour:** Peggy after lectures or with TA Lars Werne (time TBC)
- **On Piazza:** Post questions/discussion about the course

Course Contacts

- **Lecturers: Peggy Series (pseries@inf.ed.ac.uk)**
- **TA: Lars Werne (l.p.j.werne@sms.ed.ac.uk)**

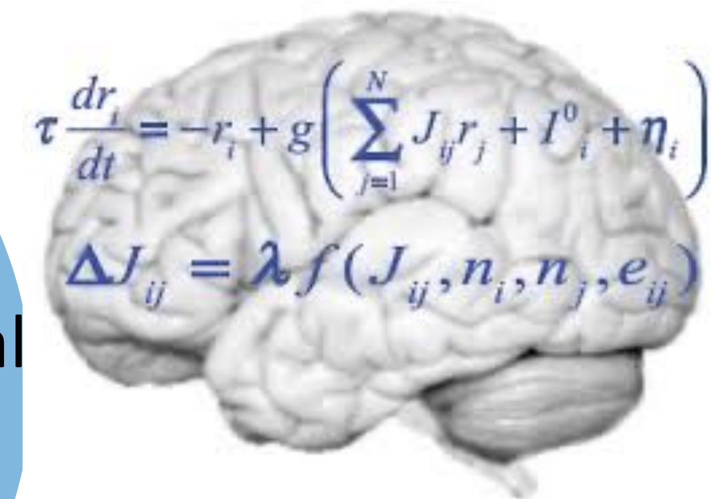
- **Markers:** Jeffrey Scholes (assignment)
  Peggy Series (exam)

What is Computational Cognitive Neuroscience?

Cognitive Science

Computational Cognitive Neuroscience

Computational Neuroscience



Theories/models of cognition

Theories/models of the neural basis of cognition

Theories/models of the brain

Questions of Computational Cognitive Neuroscience

Computational cognitive neuroscience: emphasises understanding how *cognitive processes* are implemented in the brain (a subset of computational neuroscience)

Central question:

How are perception, learning, memory, decision making, language, etc. generated by the concerted action of billions of neurons?

Sub-questions:

What are the underlying principles behind cognition (cognitive science)? How are these principles implemented in the brain (computational neuroscience)?

The Data of Cognitive Neuroscience

Human and animal studies: primates, cats, rodents, birds, insects, etc.

Measurements of behaviour: e.g., psychophysics, memory, linguistic tasks

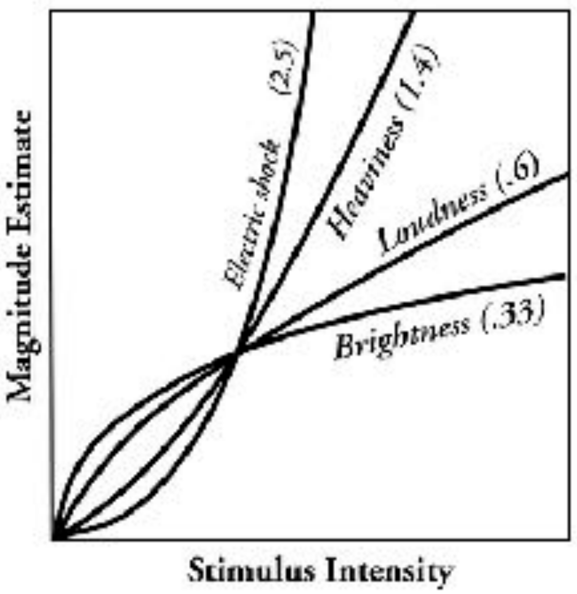
Measurements of neural activity: e.g., EEG, fMRI, intracellular recordings,

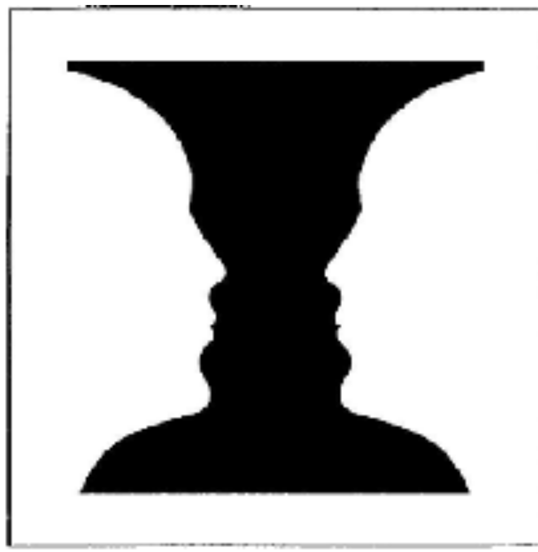
Perturbations of neural activity or behaviour: e.g., pharmacological, electrical, optogenetic

Lesion studies: e.g., accidental injuries (gunshot wounds, WW1), result of brain disease, result of corrective surgery (e.g., split brain patients)

Case studies: neurological disorders (blindsight, hemispatial neglect, face blindness…)

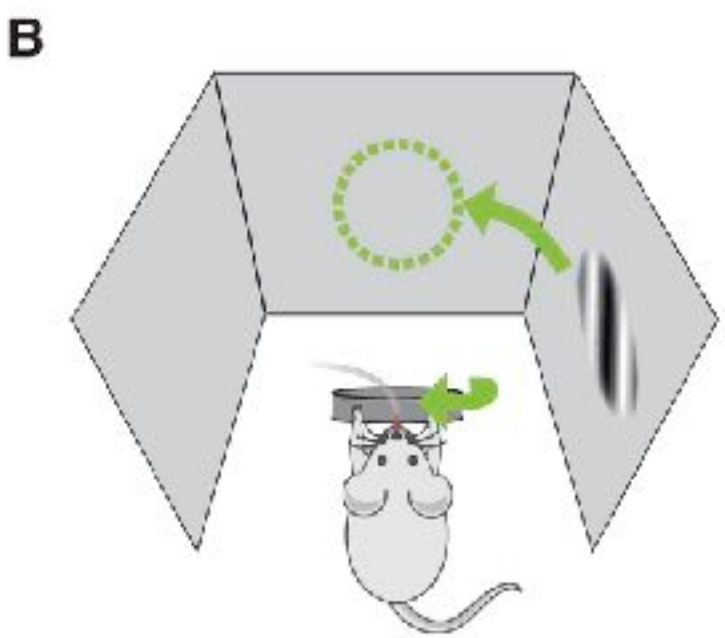
Measuring Behaviour/Perception

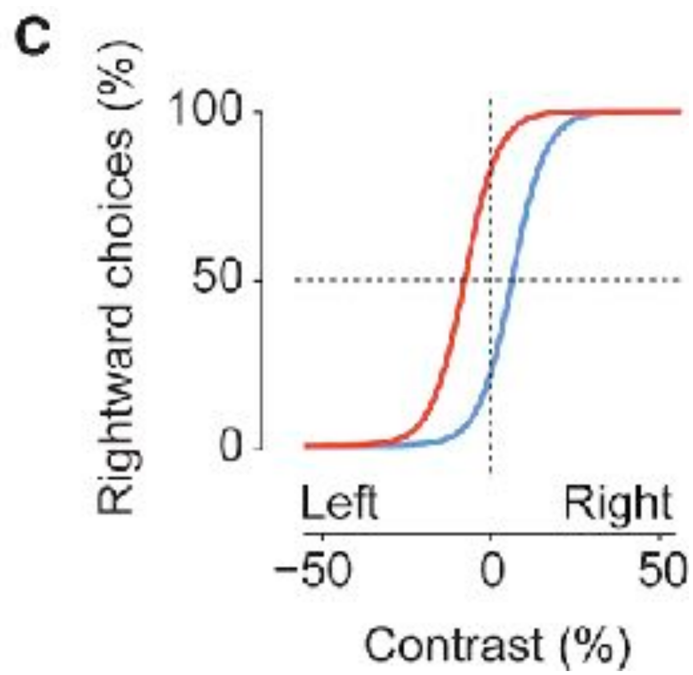




Human Psychophysics:
Behavioural report of perception

Left: How intense? (Fechner's law)
Middle: Face or vase?
Right: Gustav Fechner (1801-1887)

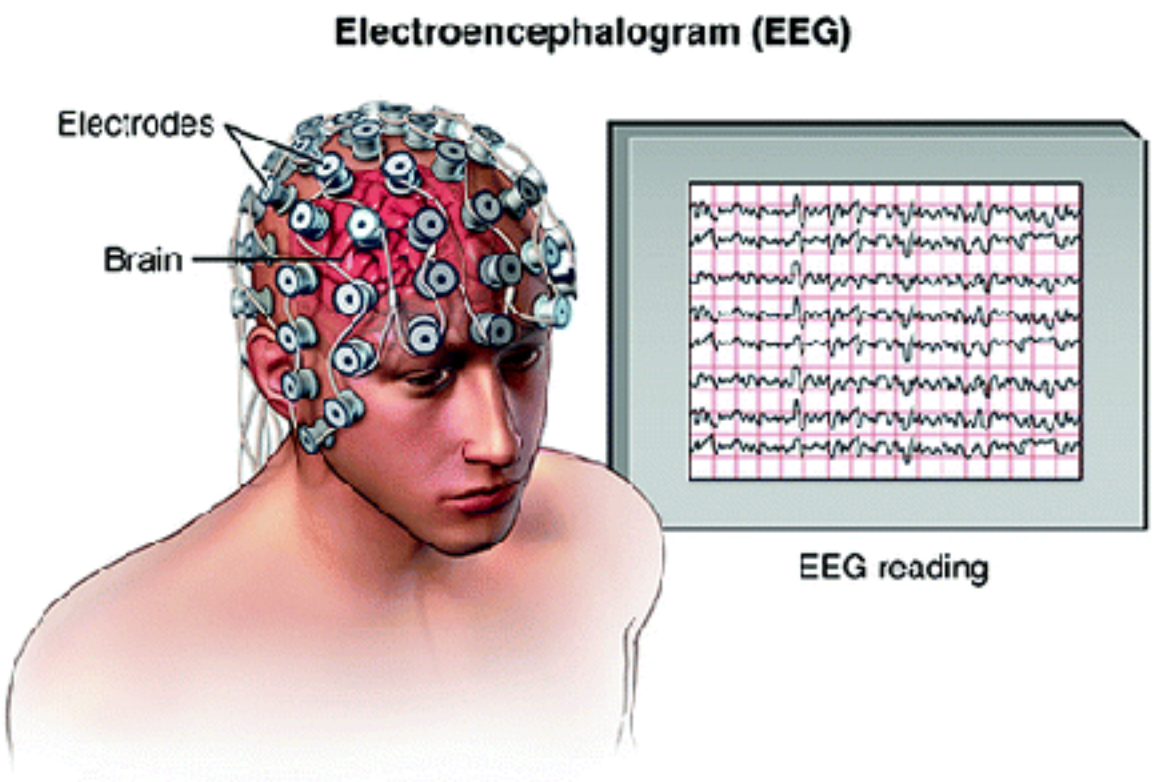




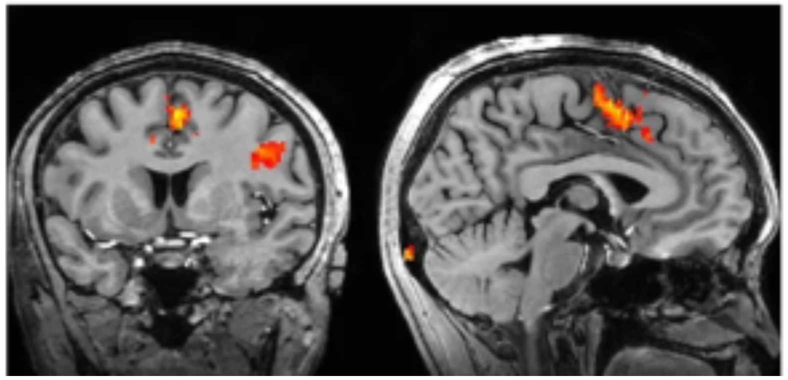
Animal Psychophysics:

Left: Mouse behavioural task
Right: Measured Psychophysical curves

Measuring Neural Activity – Non-invasive Imaging



fMRI

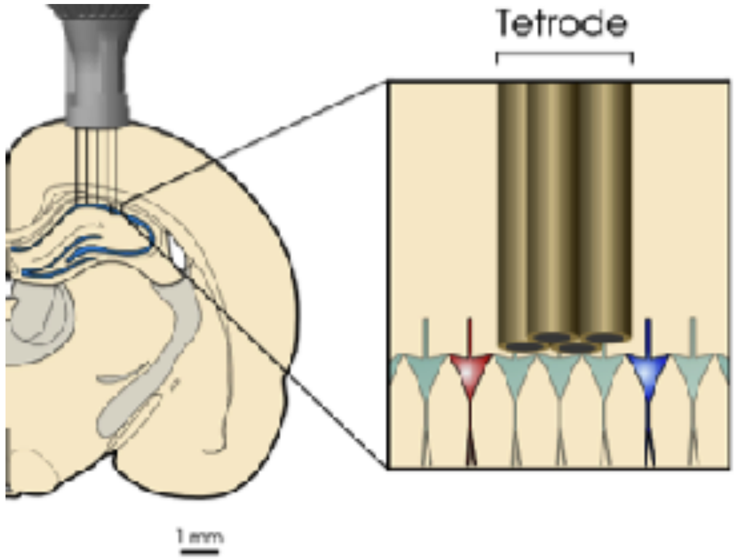


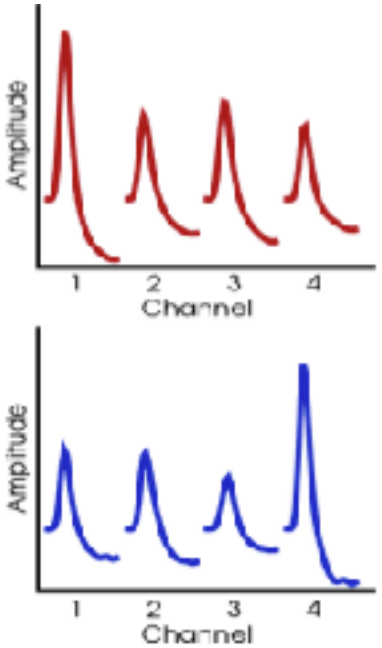
EEG – high temporal but low spatial resolution. Noisy, contaminated, indirect measurement of brain's electrical field.

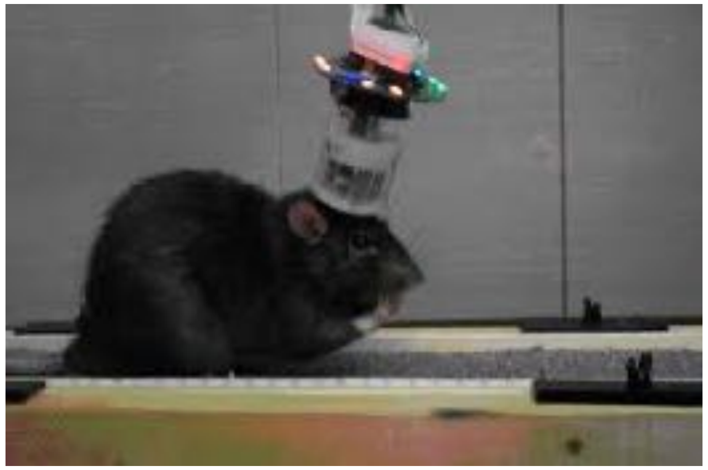
Low temporal but high spatial resolution. Measures BOLD signal (blood flow)

Measuring Neural Activity – Invasive Electrodes

Electrodes: intracellular or extracellular.



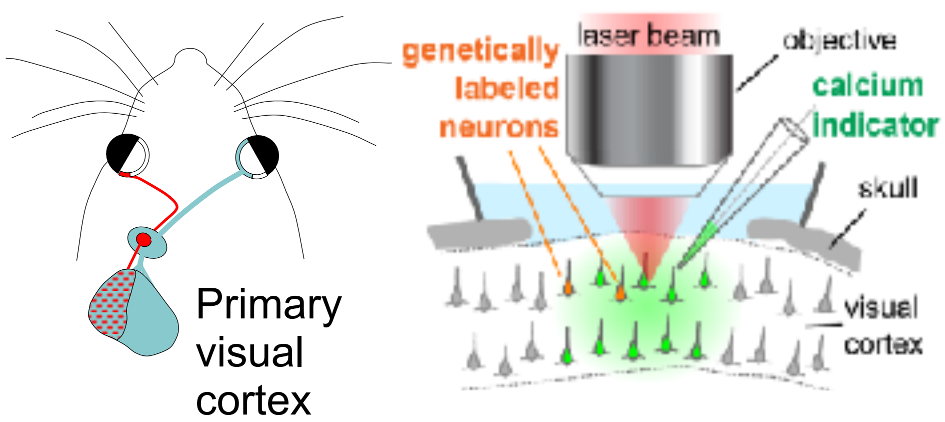


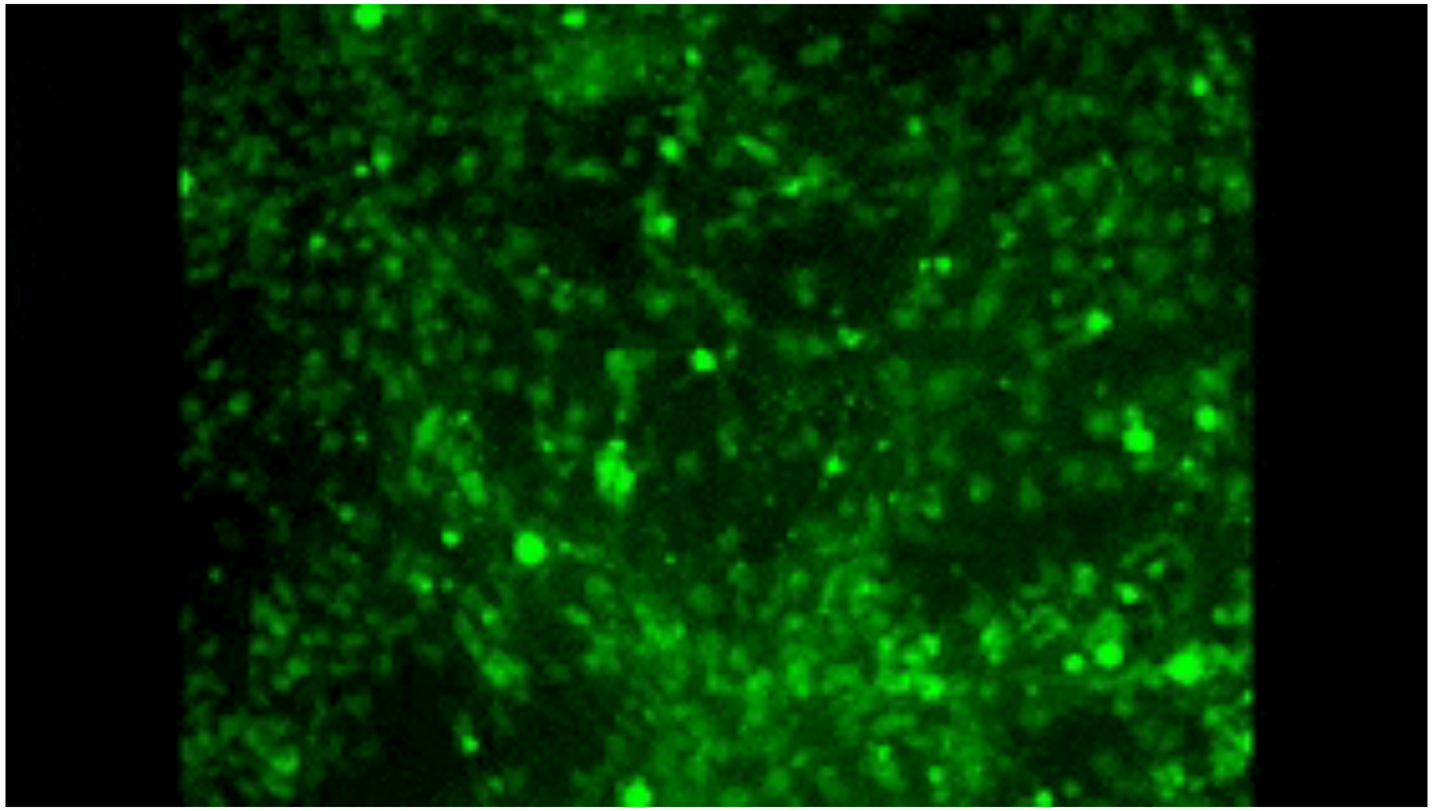
Pros: get signals in single neurons at high temporal resolution, measure electrical activity

Cons: Invasive, limited to working with animals, can't record from many cells simultaneously, data pre-processing tricky

Measuring Neural Activity – Invasive Imaging

Two-photon calcium imaging





Pros: Many cells at once, high spatial resolution

Cons: Invasive, measure calcium fluorescence, low temporal resolution, data pre-processing tricky

Tools of Computational Neuroscience

Computational Neuroscience: uses computational/mathematical tools to understand the brain, by developing:

- Theories about the brain (using maths)
- Computer simulations ("in silico" experiments)
- Data analysis methods (e.g., machine learning)

Try to answer:

What? Descriptive/phenomenological/statistical explanation

How? "Mechanistic" explanation, i.e. *causal* or *physical* explanation in terms of biology

Why? "Teleological"/functional/normative explanation (in terms of *optimality*, i.e. evolution)

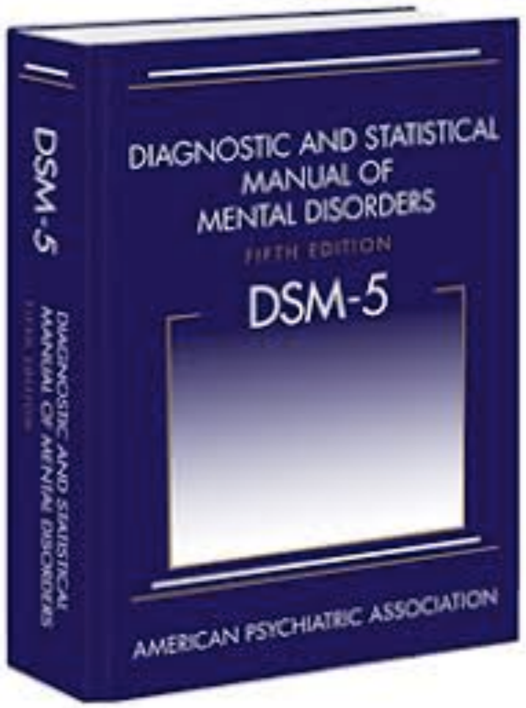
Why a focus on Mental Illness ?

- In the UK, mental ill health is recognised as the single largest cause of disability, contributing almost 23% of the disease burden and costing over £100 billion a year in services, lost productivity, and reduced quality of life.

- Every year in the EU, about 27% of adults are affected by mental disorder of some kind.

- In the US, almost one in two people will meet the criteria for a mental disorder in the course of their lifetime.

A Crisis in Psychiatry



- Diagnosis based on DSM leads to heterogenous patient groups
- comorbidity
- stagnation in drug development
- symptoms- based no link with potential causal factors (neuroscience)

Table 1 DSM-5 criteria for MDE

- At least five of the following symptoms that cause clinically significant distress or impairment in social, occupational, or other important area of functioning
- At least one of the symptoms is 1) depressed mood or 2) loss of interest or pleasure
- Symptoms must be present almost every day for at least 2 weeks
  1. Depressed mood most of the day
  2. Diminished interest or pleasure in all or most activities
  3. Significant unintentional weight loss or gain
  4. Insomnia or sleeping too much
  5. Agitation or psychomotor retardation noticed by others
  6. Fatigue or loss of energy
  7. Feelings of worthlessness or excessive guilt
  8. Diminished ability to think or concentrate, or indecisiveness
  9. Recurrent thoughts of death
- Diagnosis of recurrent MDD requires ≥2 MDEs separated by at least 2 months in which criteria are not met for an MDE

Abbreviations: DSM-5, Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition; MDD, major depressive disorder; MDE, major depressive episode.

RDOC framework in Psychiatry

National Institute of Mental Health

- Building upon ongoing advances in the behavioural and neurobiological sciences
- "RDoC is an attempt to create a new kind of taxonomy for mental disorders by bringing the power of modern research approaches in genetics, neuroscience, and behavioral science to the problem of mental illness.” [Elevag et al 2016]
- From a categorical to a dimensional approach.

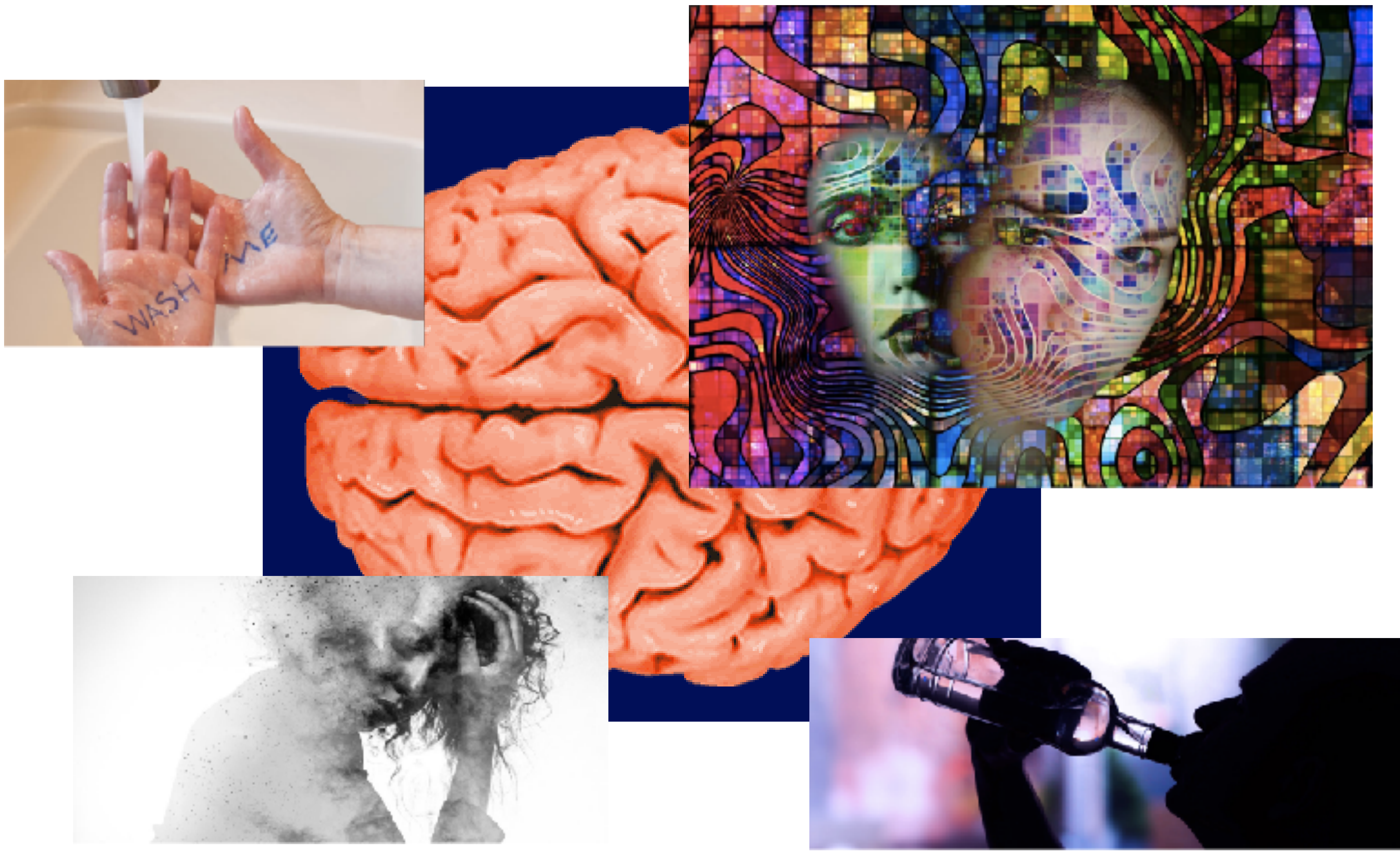
NIMH Research Domain Criteria (RDoC)

Functional Domains				
Negative Valence Systems (e.g., fear, anxiety, loss)	**Positive Valence Systems** (e.g., reward, learning, habit)	**Cognitive Systems** (e.g., attention, perception, memory)	**Systems for Social Processes** (e.g., attachment, communication, perception of self & others)	**Arousal and Regulatory Systems** (e.g., arousal, circadian rhythms)

Units of Analysis									
Genes	Molecules	Cells	Circuits	Physiology	Behavior	Self-Reports	Paradigms	Genes	Molecules

Computational Psychiatry

Can computational approaches help us understand
how the brain generates dysfunctional behaviours?



The Emerging Rise of Computational Psychiatry

Neuropsychiatry

OPEN ACCESS

REVIEW

Computational Psychiatry: towards a mathematically informed understanding of mental illness

Rick A Adams,[1,2] Quentin J M Huys,[3,4] Jonathan P Roiser[1]

[1]Institute of Cognitive Neuroscience, University College London, London, UK
[2]Division of Psychiatry, University College London, London, UK
[3]Translational Neuromodeling Unit, University of Zürich and Swiss Federal Institute of Technology, Zürich, Zürich, Switzerland
[4]Department of Psychiatry, Psychotherapy and

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REVIEW FOCUS ON NEURAL COMPUTATION AND THEORY

nature neuroscience

Computational psychiatry as a bridge from neuroscience to clinical applications

Quentin J M Huys[1,2,5], Tiago V Maia[3,5] & Michael J Frank[4]

Translating advances in neuroscience into benefits for patients with mental illness presents enormous challenges because it involves both the most complex organ, the brain, and its interaction with a similarly complex environment. Dealing with such complexities demands powerful techniques. Computational psychiatry combines multiple levels and types of computation with multiple types of data in an effort to improve understanding, prediction and treatment of mental illness. Computational psychiatry, broadly defined, encompasses two complementary approaches: data driven and theory driven. Data-driven approaches apply machine-learning methods to high-dimensional data to improve classification of disease, predict treatment outcomes or improve treatment selection. These approaches are generally agnostic as to the underlying mechanisms. Theory-driven approaches, in contrast, use models that instantiate prior knowledge of, or explicit hypotheses about, such mechanisms, possibly at multiple levels of analysis and abstraction. We review recent advances in both approaches, with an emphasis on clinical applications, and highlight the utility of combining them.

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Continuous Publication
8 1/2 x 11
Founded: 2017

Computational Psychiatry

Peter Dayan and Read Montague, Editors

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that involve the application, analysis, or invention of theoretical,
computational and statistical approaches to mental function and dys
Topics include brain modeling over multiple scales and levels of ana
and the use of these models to understand psychiatric dysfunction, i
remediation, and the sustenance of healthy cognition through the lif
The journal also has a special interest in computational issues perta
related areas such as law and education.

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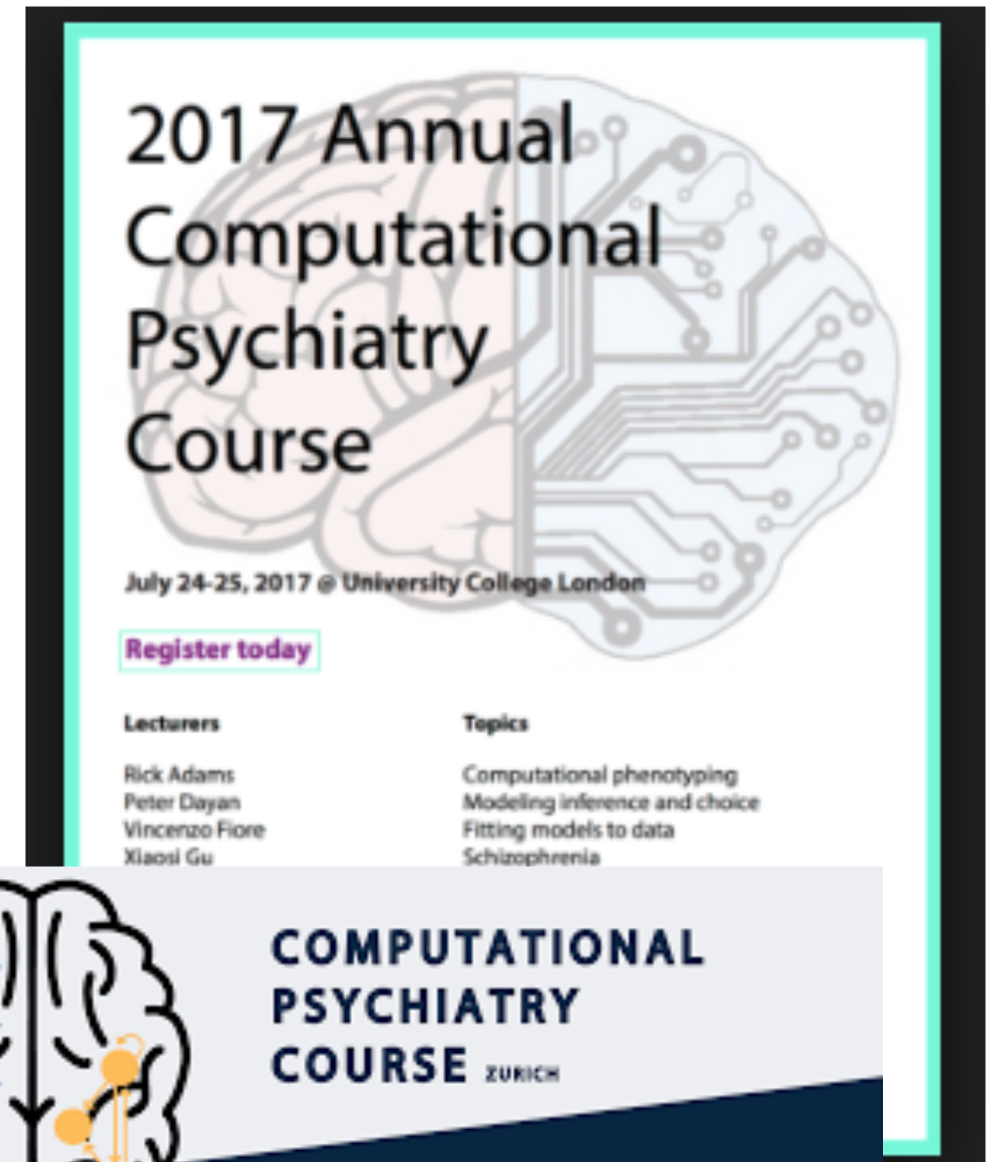

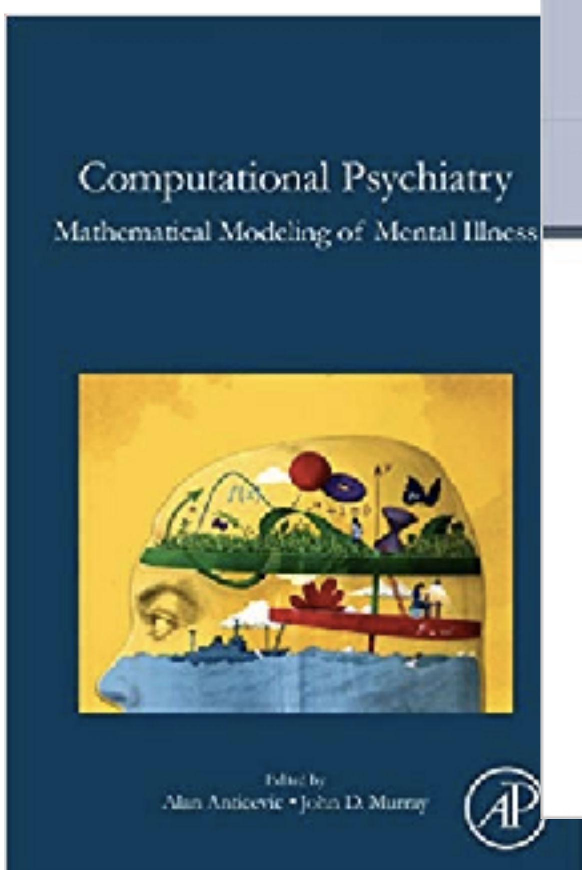

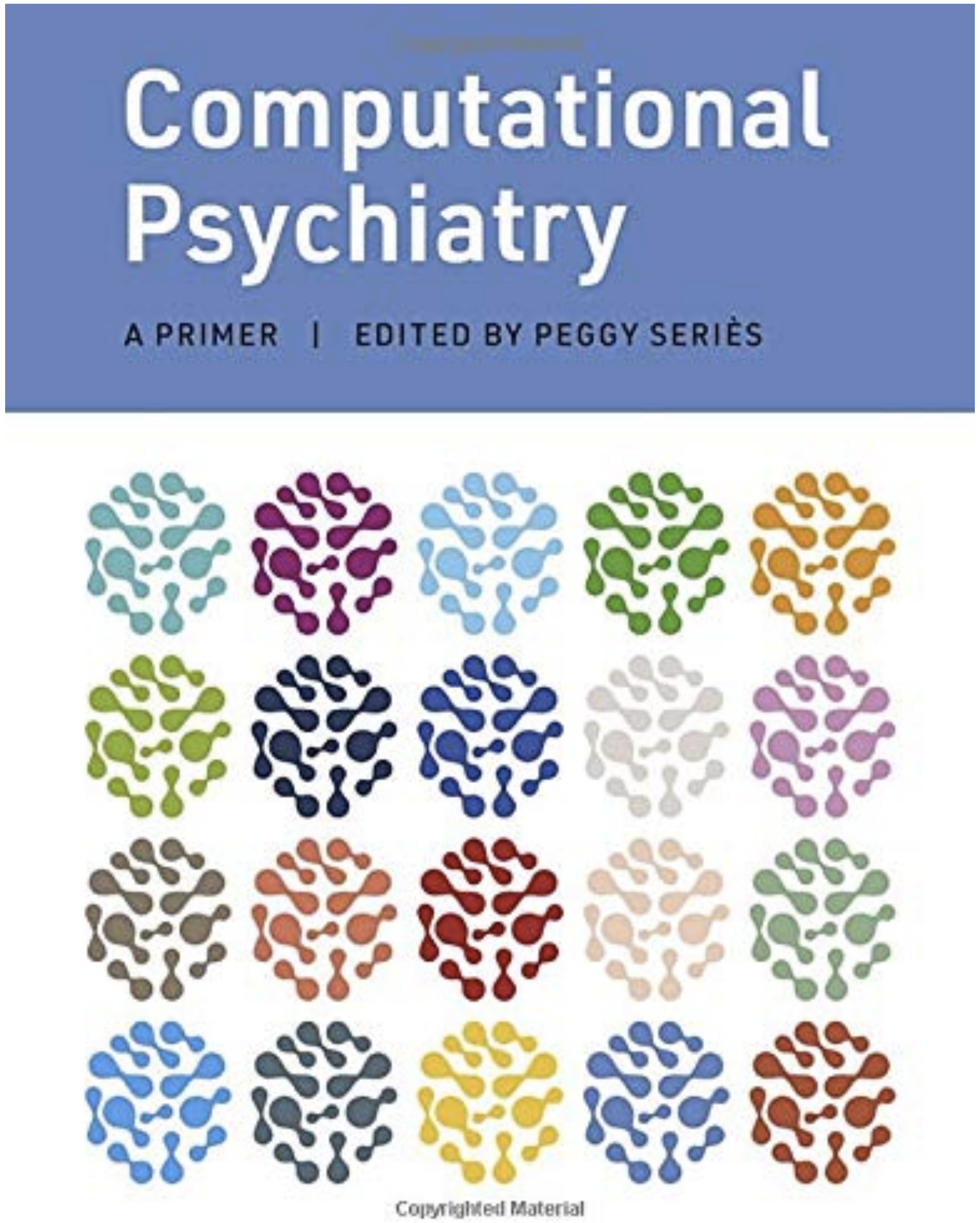

2020

COMPUTATIONAL PSYCHIATRY: A PRIMER

Edited by Peggy Seriès

Chapter 1: Introduction: Toward a Computational Approach to Psychiatry

Janine M. Simmons, Bruce Cuthbert, Joshua A. Gordon, & Michele Ferrante.

Chapter 2: Methods of Computational Psychiatry: A brief Survey

Peggy Seriès

Chapter 3: Biophysically Based Neural Circuit Modeling of Working Memory and Decision Making and Related Psychiatric Deficits

Xiao-Jing Wang and John D. Murray

Chapter 4: Computational Models of Cognitive Control: Past and Current Approaches

Debbie M. Yee and Todd S. Braver

Chapter 5: The Value of Almost Everything: Models of the Positive and Negative Valence Systems and their relevance to Psychiatry

Peter Dayan

Chapter 6: Psychosis and Schizophrenia from a Computational Perspective

Rick A Adams

Chapter 7: Depressive Disorders from a Computational Perspective

Samuel Rupprechter, Vincent Valton, Peggy Seriès

Chapter 8: Anxiety Disorders from a Computational Perspective

Erdem Pulcu and Michael Browning

Chapter 9: Addiction from a Computational Perspective

David Redish

Chapter 10: Tourette Syndrome from a Computational Perspective

Vasco A. Conceição and Tiago V. Maia

Chapter 11: Perspectives and Further Study in Computational Psychiatry

Peggy Seriès

A New Model for Mental Illness

Mental illness is the result of an impairment in prediction, due to having a distorted internal model of the world, possibly due to abnormal exposure (trauma) or to an impairment in learning.

Overview of Upcoming Lectures

- Introduction to Neuroscience
- Foundations of Computational Neuroscience (1): Models of Neurons
- Foundations of Computational Neuroscience (2): Models of Networks - Neural network models
- Schizophrenia, Attractors and Working Memory
- Multi-sensory integration and causal inference
- Decision making and drift diffusion models (DDM)
- Reinforcement learning models
- Bayesian models

and application to psychiatry: addiction, schizophrenia, autism, depression and anxiety, PTSD.

Questions?