NEUR3041
Neural computation: Models of brain function
2018 provisional timetable.

Module organisers: Dr Caswell Barry & Prof. Neil Burgess

Contact details
Dr Caswell Barry: caswell.barry@ucl.ac.uk
Prof. Neil Burgess: n.burgess@ucl.ac.uk

Further course information available on: http://www.icn.ucl.ac.uk/nburgess/teaching.htm
NEUR3041 – Half unit.

Module aims and objectives

Aims

1. To introduce the consideration of neurons and synapses in terms of their computational properties and interpretation of their action in terms of information processing.

2. To introduce the analysis of an animal’s ability to learn, remember or act in terms of the action of neurons and synapses within the animal’s nervous system.

3. To understand several examples of how the action of individual neurons and synapses in various parts of the central nervous system contribute to the learning, memory or behaviour of an organism.

Method of assessment

NEUR3041 is a ½ unit module

Undergraduate BSc and 4th year MSci students: There is a course essay and a 3 hour exam. The course essay consists of analysing a research paper (papers for essay available under ‘Teaching’ on: http://www.ucl.ac.uk/icn/neilburgess), max. 2,000 words. The essay constitutes 10% of the final mark for the course. The exam constitutes the remaining 90% of the final mark for the course.

MSc students, and affiliate students (leaving before May): One 3,000 word essay, chosen from these titles:

Can a mechanistic neuron-level understanding of some aspects of cognition be attained?

Discuss the approximations made in computational approaches to understanding the functional properties of networks of neurons, including when and how they have proved to be useful.

Describe examples where understanding of the electrophysiological behaviour of neurons allows increased understanding of the behaviour of the organism.

The deadline for essays is Monday January 7th 2019.
NEUR3041 Neural computation: Models of brain function

**Provisional Timetable Autumn 2018**

Lectures: Wednesday 11-1 and Friday 10-11. NB the order/topic of lectures may change.

<table>
<thead>
<tr>
<th>Day</th>
<th>Time</th>
<th>Subject</th>
<th>Lecturer</th>
<th>Venue</th>
<th>Week</th>
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</thead>
<tbody>
<tr>
<td>12 Oct</td>
<td>10:00 – 11:00</td>
<td>Introduction to artificial neural networks &amp; unsupervised learning.</td>
<td>Prof. Neil Burgess</td>
<td>Chadwick Building G07</td>
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<tr>
<td>17 Oct</td>
<td>11:00 – 12:00</td>
<td>Intro to artificial neural networks &amp; unsupervised learning, cont.</td>
<td>Prof. Neil Burgess</td>
<td>Medawar Building G02 Watson LT</td>
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<td></td>
<td>12:00 – 13:00</td>
<td>Intro to artificial neural networks &amp; unsupervised learning, cont</td>
<td>Prof. Neil Burgess</td>
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<td>19 Oct</td>
<td>10:00 – 11:00</td>
<td>Computational properties of individual neurons</td>
<td>Dr Andrej Bicanski</td>
<td>Chadwick Building G07</td>
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<tr>
<td>24 Oct</td>
<td>11:00 – 12:00</td>
<td>Artificial neural networks, feedback &amp; simple supervised learning.</td>
<td>Prof. Neil Burgess</td>
<td>Medawar Building G02 Watson LT</td>
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<td></td>
<td>12:00 – 13:00</td>
<td>More advanced learning algorithms in artificial neural networks.</td>
<td>Prof. Neil Burgess</td>
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<td>26 Oct</td>
<td>10:00 – 11:00</td>
<td>More advanced learning algorithms in artificial neural networks, cont.</td>
<td>Prof. Neil Burgess</td>
<td>Chadwick Building G07</td>
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<tr>
<td>31 Oct</td>
<td>11:00 – 12:00</td>
<td>Computational properties of individual neurons</td>
<td>David Attwell</td>
<td>Medawar Building G02 Watson LT</td>
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<td></td>
<td>12:00 – 13:00</td>
<td>Neural bases of sensory decision making.</td>
<td>Prof Peter Latham</td>
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<td>2 Nov</td>
<td>10:00 – 11:00</td>
<td>Hippocampal and striatal navigation.</td>
<td>Dr Caswell Barry</td>
<td>Chadwick Building G07</td>
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<td>Reading Week</td>
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<td>11</td>
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<td>14 Nov</td>
<td>11:00 – 12:00</td>
<td>Hippocampus and associative memory</td>
<td>Dr Andrej Bicanski</td>
<td>Medawar Building G02 Watson LT</td>
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<td></td>
<td>12:00 – 13:00</td>
<td>Hippocampus and associative memory</td>
<td>Dr Andrej Bicanski</td>
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<td>Date</td>
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<td>16</td>
<td>10:00 –</td>
<td>Path integration, continuous attractors and grid cells.</td>
<td>Dr Daniel Bush</td>
<td>Chadwick Building G07</td>
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<td>21</td>
<td>11:00 –</td>
<td>Reinforcement learning.</td>
<td>Prof. Neil Burgess</td>
<td>Medawar Building G02 Watson LT</td>
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<td>12:00</td>
<td>13:00</td>
<td>Reinforcement learning, cont.</td>
<td>Prof. Neil Burgess</td>
<td>Medawar Building G02 Watson LT</td>
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<tr>
<td>23</td>
<td>10:00 –</td>
<td>Models of prefrontal cortex.</td>
<td>Dr Sam Gilbert</td>
<td>Chadwick Building G07</td>
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<td>28</td>
<td>11:00 –</td>
<td>Learning, performing and remembering serially ordered actions.</td>
<td>Dr Caswell Barry</td>
<td>Medawar Building G02 Watson LT</td>
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<td>Nov</td>
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<td>12:00</td>
<td>13:00</td>
<td>Spatial processing in the spine and motor cortex.</td>
<td>Caswell Barry</td>
<td>Watson LT</td>
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<tr>
<td>30</td>
<td>10:00 –</td>
<td>Temporal processing in audition and olfaction.</td>
<td>Dr Caswell Barry</td>
<td>Chadwick Building G07</td>
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<td>5</td>
<td>11:00 –</td>
<td>Filtering and normalization in sensory systems.</td>
<td>Prof Matteo Carandini</td>
<td>Medawar Building G02 Watson LT</td>
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<td>Dec</td>
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<td>12:00</td>
<td>13:00</td>
<td>Theories of the cerebellum.</td>
<td>Dr Peter Gilbert</td>
<td>Malet Place Engineering Building 1.03</td>
<td>16</td>
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<td>7</td>
<td>11:00 –</td>
<td>Computing with spike timing and delays; course review.</td>
<td>Prof. Neil Burgess</td>
<td>Malet Place Engineering Building 1.03</td>
<td>16</td>
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<tr>
<td>Dec</td>
<td>12:00</td>
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General reading list

**General:** Fundamentals of Computational Neuroscience by Thomas Trappenberg (OUP, 2002)

**Artificial Neural Networks:**
1. An Introduction to Neural Networks, James A. Anderson (MIT Press, 1995);
2. An Introduction to Neural Networks, Kevin Gurney (UCL Press, 1997);

**Biological neural networks:**

**Models of brain systems/ systems neuroscience:**

**Computational Neuroscience** (includes most things, but v. v. mathematical)
Specific reading lists

For students interested in the details of a particular lecture (lecturers may also give additional references during the lecture).

Introduction to artificial neural networks and unsupervised learning.
- Books 1,2,8.

Artificial neural networks, feedback & simple supervised learning
- Books 1,2,5.

Computational properties of neurons
- Books 8,9,10.

More advanced learning algorithms in artificial neural networks
- Books 1,2,4,6

Spatial processing in the spine and motor cortex

The hippocampus and spatial representation
- Book 13

Path integration, continuous attractors & grid cells
- Zhang 1996 Representation of spatial orientation by the intrinsic dynamics of the head-direction

Hippocampal and striatal navigation

The hippocampus and associative memory

Reinforcement learning
• See also Book 14, chapter 9.

Learning, performing and remembering serially ordered actions

Models of prefrontal cortex
Temporal processing: Models of audition and olfaction


Computing with spike timing and delay


Filtering and normalization in sensory systems


Theories of the cerebellum


Neural bases of sensory decision making

Objectives

By the end of the following lectures the students should be able to:

Introduction to artificial neural networks and unsupervised learning (2hrs)

- Understand simple mathematical models of how a neuron’s firing rate depends on the firing rates of the neurons with synaptic connections to it.
- Describe how Hebbian learning rules relate change in synaptic weights to the firing rates of the pre- and post-synaptic neurons.
- Describe how application of these rules can lead to self-organisation in artificial neural networks.
- Relate self-organisation in artificial neural networks to organisation of the brain, such as in topographic maps.

Artificial neural networks, feedback & simple supervised learning (2 hr)

- Explain how Hebbian learning in recurrent connections between neurons can create an associative memory.
- Describe how a set of examples of stimuli and correct responses can be used to train an artificial neural network to respond correctly via changes in synaptic weights governed by the firing rates of the pre- and post-synaptic neurons and the correct post-synaptic firing rate.
- Describe how this type of learning rule is used to perform pattern recognition in a perceptron.

Computational properties of neurons (1 hr)

- Discuss how information can be coded by a neuron’s membrane potential as graded potentials or action potentials.
- Explain how processing of synaptic signals as graded potentials allows the operations of addition, subtraction, multiplication and division to be carried out by an individual neuron.

More advanced learning algorithms in artificial neural networks (2hrs)

- Discuss the limitation of simple supervised learning algorithms such as the perceptron, and the use of multi-layered networks to overcome them.
- Explain the problems posed to learning by the credit assignment problems caused by correct responses not being provided for each neuron, or for each stimulus.
- Discuss how reinforcement learning and genetic algorithms overcome the problems of temporal credit assignment and how error back-propagation and the use of forward models can overcome the problem of credit assignment for neurons contributing indirectly to the network’s output.
- Discuss the relative biological plausibility of these learning algorithms.

Spatial processing in the spine and motor cortex (1hr).

- Explain the idea of a ‘convergent force field’ and how the combination of a small number of these could used to control limb movements to an arbitrary end point.
- Understand how a large number of broadly tuned neurons can provide an accurate code via their net ‘population vector’.
- Discuss how the spine and motor cortex together could control movement, with motor cortex providing a population vector of reaching direction and the spine solving the complex transformation to muscle tensions by producing convergent force fields.

The hippocampus and associative memory (1hr)

- Understand how an associative memory matrix stores information by switching synapses on such
that a pattern of activation in the output is reproduced by representation of the pattern of activation in the inputs.
- Explain what is meant by the terms content-addressable, pattern completion, error correction, interference, hetero-association and auto-association.
- Describe how the Chadwick of the hippocampal region CA3 is consistent with a role as an associative memory matrix.

**The hippocampus and spatial representation (1 hr)**
- Explain how unsupervised competitive learning could lead to the formation of location-specific firing in hippocampal 'place cells', and how the rat’s movement during learning would determine the effect the rat’s orientation has on their firing rates (Sharp, 1991).
- Discuss Sharp’s model & subsequent expts. Inputs sensitive to the distance of landmarks appear to be present (O’Keefe & Burgess, 1996), but place cell firing is probably non-directional to start with (not learned) & a fixed feed-forward model is sufficient to model the firing of cells (Hartley et al., 2000; Zipser, 1986). Synaptic plasticity may be required, but for stability and robustness of place cell representation (Kentros et al., 2000; Nakazawa et al., 2002).

**Path integration, continuous attractors & grid cells (1 hr)**
- Understand the idea of path integration, and how it might contribute to navigation and place cell firing.
- Discuss the continuous attractor model of place cell firing
- Describe the firing pattern of grid cells in entorhinal cortex and why they might be suitable to produce the path integration input to place cells.

**Hippocampal and striatal navigation (1 hr)**
- Describe how place cells could be used as a spatial memory for the proximity of a goal by synaptic change at the goal location.
- Describe how routes to a goal could be learned by modifying connections between the hippocampus and nucleus accumbens (Brown & Sharp, 2000), including the relevance of the limitations of perceptrons to linearly-separable functions and the problem of temporal credit-assignment

**Models of prefrontal cortex (1 hr)**
- Discuss computational and behavioral studies of contextual control deficits in Schizophrenia and frontal lobe patients, e.g. in the Stroop task.
- Explain a computational hypothesis for the impairment of Schizophrenics and frontal lobe patients in override automatic but inappropriate response tendencies.

**Reinforcement learning (2hrs)**
- Discuss formal models of classical and instrumental conditioning in animals
- Describe how the involvement of neuromodulators, such as dopamine, in reward and punishment learning is included in these models.

**Learning, performing and remembering serially ordered actions (1hr)**
- Explain how asymmetric recurrent connections can be used to learn a chain of association.
- Discuss the limitation of associative chaining as a model for response selection.
- Describe the competitive queuing model of response selection, and how it applies to human short-term memory for serial order.

**Temporal processing: Models of audition and olfaction (1hr)**
• Understand how delay lines and coincidence detection can be used to produce responses tuned to inputs with specific time differences.
• Explain how the auditory system of the Barn Owl can detect inter-aural time differences and use this information to determine the azimuthal angle of a sound.
• Describe how the rat olfactory system solves the problem of detecting weak odours masked by the presence of strong odours.

*Using spike timing and delays (1 hr)*

• Discuss the problems of the standard models using firing-rates and synaptic weights have encoding both absolute and relative sizes of stimuli.
• Describe the alternative model of using spike timing with respect to an oscillatory potential and delay lines to encode information.
• Discuss the biological plausibility and functional advantages and disadvantages of this model.

*Filtering and normalization in sensory systems (1 hr)*

• Describe the concept of linear receptive fields in multiple sensory modalities.
• Describe the concept of divisive normalization in multiple sensory modalities.
• Describe the advantages and disadvantages of thinking about sensory processing in computational terms.

*Theories of the cerebellum (1 hr)*

• **Cerebellar circuitry**: Parallel and climbing fibre inputs to Purkinje cells. Influence on movement via cerebellar nuclei.
• **Marr’s theory and motor learning**: Purkinje cells receive cerebral teaching signals for movements via climbing fibres; contexts via parallel fibres. Parallel fibre synapses on P-cells modifiable when climbing fibre fires. Memory capacity of P-cells.
• **Albus** LTD at parallel fibre synapses on P-cells, basket cells and stellate cells.
• **Gilbert** Group of P-cells as the memorizing unit. Variable frequencies learned by P-cells (as opposed to binary outputs of Marr and Albus). How muscular actions are coordinated. Potential second teaching input to P-cells via the noradrenergic input.
• **D’Angelo and De Zeeuw** Granular layer plasticity: potential role in cerebellar learning.
• **Rhythmic activity in the cerebellum**: possible role in “binding” of complex contexts and in temporal sequencing of movements.
• **Experimental testing of the theories**: LTD in cerebellum. Output of P-cells during learning of movements. On-beam synchrony in parallel fibres of cerebellum.

*Neural bases of sensory decision making (1 hr)*

• Describe the experiment of Shadlen and Newsome (2001) and how it sheds light on sensory decision making such as the direction of motion of a visual stimulus.
• Understand how the neural responses in the lateral intraparietal area (LIP) appear to be weighing the evidence behind a decision about sensory stimuli.

**Essay subject matter:**


