5th Australian Workshop on Computational Neuroscience

University of Western Sydney, Campbelltown Campus
13-14 December 2011

Hosted by
MARCS Auditory Laboratories and the Bioelectronics and Neuroscience Research Group, UWS

Program, Information & Abstracts
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WELCOME (AWCN)

The Australian Workshop on Computational Neuroscience first and foremost aims to bring together researchers in the computational neuroscience discipline in Australia to enhance collaboration and the exchange of ideas. Given the success of last year’s workshop at the Queensland Brain Institute, and the number of registrations for this year’s workshop, it is our hope that this can become an annual meeting at which computational neuroscience researchers can exchange ideas, socialize, and become familiar with some of the ongoing work in the groups. It is a workshop where we can present some of our preliminary results and work in progress, as well as make our fellow researchers aware of some of the work we have recently published.

While being predominantly an Australian workshop, we welcome and value the participation from our international visitors and in particular of our keynote speakers: Klaus Stiefel, Charles Anderson, and Ralph Etienne-Cummings.

This year’s workshop at UWS is the final event in an 8 day long research fest (RESCOM 2011, Researching Communication at UWS: Brain, Behaviour and Computation) that celebrates the launch of our new MARCS Research Institute at UWS. The institute will research Brain and Behaviour, encompassing the disciplines of behavioural science, cognitive science, music, experimental phonetics and linguistics, medicine and neurophysiology, computational neuroscience, computer science, electrical and neuromorphic engineering. Needless to say, we are very excited by the opportunities this multi-disciplinary collaboration offers, and delighted by the support of the University of Western Sydney for our research.

I hope you will have many interesting discussions and encounter plenty of interesting ideas over the next two days.

André van Schaik, Leader, Bioelectronics and Neuroscience, December, 2011
WELCOME (RESCOM)

ResCom 2011 (Researching Communication at UWS: Brain, Behaviour and Computation) is a UWS Research Festival all about Communication and Inter-Disciplinary Collaboration – it is designed to encourage communication and collaboration between UWS researchers from a range of disciplines especially those incorporated in the new MARCS Institute. There are seven components of ResCom:

**Summer Schools** (Dec 5-6): 12 x 3 hour tutorials led by world leaders in a range of disciplines to encourage interdisciplinary understanding and research.

**Higher Degree Research Student Posters** (Dec 5): To encourage understanding and breadth of knowledge in UWS doctoral candidates.

**Speed Papers and Keynotes** (Dec 7): Short (4 min) papers by UWS academics plus 2 multidisciplinary Keynotes to foster cross-disciplinary understanding and research.

**UWS Vice-Chancellor Launch of the new MARCS Institute** (Dec 7): Including short spotlights on the 5 research programs of the new MARCS Institute – Learning & Development (Denis Burnham); Dynamics of Perception & Performance (Kate Stevens); Multimodal Integration (Chris Davis); Bioelectronics & Neuroscience (André van Schaik); and Human-Machine Interaction & Virtual Environments (Simeon Simoff).

**Thinking Systems Workshop** (Dec 8-9): An interdisciplinary workshop on intelligent machines, robots, human-computer interaction, and the science-arts nexus including papers from personnel on the three Australian Research Council Thinking Systems projects – the UWS-based Thinking Head project; the University of Queensland based Thinking Systems – Navigation project; and the UNSW-based Thinking Hand project.

**Sensory Neuroscience Symposium** (Dec 12): Invited speakers from around Australia presenting their latest work on tactile sensation and proprioception, visual and auditory neuroscience, the vestibular system and the chemical senses.

**Australian Workshop on Computational Neuroscience** (Dec 13-14): A workshop bringing together leading researchers in Australia and internationally to discuss the latest developments in information processing properties of biological nervous systems using a combination of mathematical, computational and experimental techniques.

By means of these seven components we aim to augment significantly the collaborative base of research at UWS, both internally and externally:

- The **first three** of these are designed to engender collaboration by increasing cross-disciplinary understanding internally at UWS.
- The **last three** are designed to engender collaboration by maintaining and augmenting focus on external partners in three specific areas of research.
- In the pivotal centre is the launch of the new MARCS Institute, an umbrella for facilitating and supporting research in Brain, Behaviour and Computational Science, encompassing the disciplines of behavioural science, computer science, cognitive science, music, experimental phonetics and linguistics, medicine and neuroscience, and engineering.
We are on the cusp of an exciting new era in collaborative research at UWS, the formation of the 10 new super-schools will facilitate cross-disciplinary interaction and the 5 new UWS institutes are charged with the task of facilitating and integrating research across areas. MARCS Labs has its basis in cross-disciplinary endeavours and we relish the opportunity for the New MARCS to continue and extend this role of promoting and augmenting cross-disciplinary interchange and collaboration.

There are a number of people who have worked very hard to make ResCom possible. The Organising Committee, with representatives from MARCS, Psychology, Linguistics, BENS, Computing and Mathematics at UWS and also from RMIT, took care of most of the top-down stuff. But the real hard work, both top-down and bottom-up, was done by Sonya O’Shanna, Darlene Williams and Kym Buckley, with able assistance from Gail Charlton and Karen McConachie. Thank you all.

We present to you ResCom 2011, as a significant first step in this new era of collaborative research at UWS. ResCom will provide researchers from different disciplines with the opportunity to present their research to a multidisciplinary audience, and sit side-by-side and hear about new areas and ideas from others. I trust that you will find it a stimulating and enriching experience and one that leads to increased research activity. Go forth and collaborate!

Denis Burnham, Director, MARCS Institute, December 2011
AWCN ORGANISING COMMITTEE

André van Schaik
Sonya O’Shanna
Kym Buckley

University of Western Sydney
University of Western Sydney
University of Western Sydney
REGISTRATION & VENUE INFORMATION

Workshop Venue
The 5th Australian Workshop on Computational Neuroscience will be held at the University of Western Sydney’s Campbelltown Campus. The campus is located on the corner of Narellan Road and Gilchrist Drive, Macarthur (enter via Narellan Road).

Within the Campbelltown campus, the workshop will be held in Building 30 (School of Medicine), located at the eastern end of the campus.

The Campbelltown campus is well serviced by public transport, including trains and buses. Detailed information on getting to the campus is provided on the UWS website: http://www.uws.edu.au/campuses_structure/cas/campuses/campbelltown.

The nearest station is Macarthur station which is at the end of the East Hills/Airport line. The School of Medicine is one of the first buildings you will see when you enter the UWS campus from the station.

If you plan to drive and park on the campus, please be warned that parking fees apply. Daily parking vouchers can be purchased from the ticket machines located in the carparks for parking in yellow bays only.

Registration Desk
The registration desk is the place for enquiries related to registration, accommodation, or any information that you require about the workshop, the campus, or the local area.

The registration desk is located in the foyer of Building 30 and will open at 9am each morning. Please proceed to the registration desk on your first morning to collect your name tag.
Refreshments

Morning tea, afternoon tea and lunch are provided for all registrants over the course of the workshop. Unless otherwise stated in the program, all meals and refreshments will be served in the foyer of Building 30. If you notified the workshop organisers of any special dietary requirements then be assured that we have done our best to accommodate this – please ask for Michael Hauser-Raspe at the registration desk if you need assistance.
## DETAILED PROGRAM – TUESDAY

**BUILDING 30 Foyer, UWS Campbelltown Campus**

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
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<tbody>
<tr>
<td>9.00–9.30am</td>
<td>Registration and Coffee on Arrival</td>
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<tr>
<td>9.30–9.45am</td>
<td>Welcome Address</td>
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<tr>
<td></td>
<td>Professor André van Schaik</td>
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<td>BENS, University of Western Sydney</td>
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<tr>
<td>9.45–10.30am</td>
<td>Keynote Address</td>
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<td></td>
<td>Dr Klaus Stiefel</td>
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<td>BENS, University of Western Sydney</td>
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<td><em>An inverse approach for elucidating dendritic function</em></td>
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<td>10.30–11.00am</td>
<td>Hamish Meffin; NICTA</td>
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<td><em>Sinusoidal stimulation of retinal bipolar cells: A modeling study</em></td>
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<td>11.00–11.30am</td>
<td>Morning Tea</td>
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<td>11.30–12.00am</td>
<td>Paul McCarthy; University of Otago, NZ</td>
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<td><em>Characterisation of Alzheimer’s disease using graph theoretical analysis of fMRI data</em></td>
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<td>12.00–12.30pm</td>
<td>Geoffrey Goodhill; QBI, University of Queensland</td>
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<td><em>A model for how calcium and cAMP levels determine whether axons are attracted or repelled by molecular gradients</em></td>
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<td>12.30–1.00pm</td>
<td>Levin Kuhlmann; University of Melbourne</td>
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<td><em>Mechanisms of seizure propagation in 2-dimensional centre-surround recurrent networks</em></td>
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<tr>
<td>1.00–1.45pm</td>
<td>Lunch</td>
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<td>1.45–2.30pm</td>
<td>Keynote Address</td>
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<td>Professor Charles Anderson</td>
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<td>Washington University School of Medicine, USA</td>
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<td><em>Neural Engineering</em></td>
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<td>2.30–3.00pm</td>
<td>Nicolangelo Iannella; University of Adelaide</td>
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<td><em>Nanoscale Neurocybernetics: Where the memristor meets NEURON</em></td>
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<tr>
<td>3.00–3.30pm</td>
<td>Afternoon Tea</td>
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<tr>
<td>3.30–4.00pm</td>
<td>Peter Robinson; University of Sydney</td>
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<td><em>Spike, rate, field, and hybrid methods for treating neuronal dynamics and interactions</em></td>
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<tr>
<td>4.00–4.30pm</td>
<td>Priscilla Greenwood; University of British Columbia, Canada</td>
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<td><em>Identification and continuity of the distributions of burst-length and inter-spike-intervals in the stochastic Morris–Lecar neuron</em></td>
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<tr>
<td>4.30–5.00pm</td>
<td>James Roberts; Queensland Institute of Medical Research</td>
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<td><em>Random walk analysis of fixational eye movements during viewing of natural video scenes</em></td>
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<tr>
<td>5.00–7.00pm</td>
<td>Poster Session</td>
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## DETAILED PROGRAM – WEDNESDAY

### BUILDING 30 FOYER, UWS CAMPBELLTOWN CAMPUS

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
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<tbody>
<tr>
<td>9.00–9.15am</td>
<td><strong>COFFEE ON ARRIVAL</strong></td>
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### BUILDING 30 LECTURE THEATRE

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker(s)</th>
<th>Topic</th>
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<tbody>
<tr>
<td>9.15–10.00am</td>
<td>KEYNOTE ADDRESS&lt;br&gt;Professor Ralph Etienne-Cummings&lt;br&gt;John Hopkins University, USA</td>
<td><em>Attention to Proto-Objects: Grouping-Based Saliency</em></td>
</tr>
<tr>
<td>10.00–10.30am</td>
<td>Mark McDonnell; University of South Australia</td>
<td><em>Stochastic resonance and other benefits of randomness in neural systems: Bridging theory and experiment</em></td>
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<tr>
<td>10.30–11.00am</td>
<td><strong>MORNING TEA</strong></td>
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<tr>
<td>11.00–11.30am</td>
<td>Robert Kerr; University of Melbourne</td>
<td><em>The frequency of oscillatory inputs is encoded in the connection strengths of networks of spiking neurons by STDP</em></td>
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<tr>
<td>11.30–12.00am</td>
<td>Somwrita Sarkar; University of Sydney</td>
<td><em>Hubs, information processing and overlapping modularity in the cortex</em></td>
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<tr>
<td>12.00–12.30pm</td>
<td>Andrew Turpin; University of Melbourne</td>
<td><em>Axon pathfinding in the retina need not rely on a chemical gradient</em></td>
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<tr>
<td>12.30–1.30pm</td>
<td><strong>LUNCH</strong></td>
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<tr>
<td>1.30–2.00pm</td>
<td>Nastaran Hesam Shariati; University of Sydney</td>
<td><em>A model for fundamental functional properties in primary visual cortex</em></td>
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<tr>
<td>2.00–2.30pm</td>
<td>Kevin Aquino; University of Sydney</td>
<td><em>Spatiotemporal hemodynamics: from theory to experiment</em></td>
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<tr>
<td>2.30–3.00pm</td>
<td>André van Schaik; University of Western Sydney</td>
<td><em>Bayesian inference in spiking neural networks</em></td>
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<tr>
<td>3.00–3.10pm</td>
<td><strong>CLOSING REMARKS</strong></td>
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Dr. Klaus M. Stiefel

Bioelectronics and Neuroscience Research Group, University of Western Sydney, Penrith
k.stiefel@uws.edu.au

An inverse approach for elucidating dendritic function

We outline an inverse approach for investigating dendritic function-structure relationships by optimizing dendritic trees for a-priori chosen computational functions. The inverse approach can be applied in two different ways. First, we can use it as a ‘hypothesis pump’ in which we optimize dendrites for a function of general interest. The optimization yields an artificial dendrite that is subsequently compared to real neurons. This comparison potentially allows us to propose hypotheses about the function of real neurons. In this way, we investigated dendrites that optimally perform input-order detection.

Second, we can use it as a ‘function confirmation’ by optimizing dendrites for functions hypothesized to be performed by classes of neurons. If the optimized, artificial, dendrites resemble the dendrites of real neurons the artificial dendrites corroborate the hypothesized function of the real neuron. Moreover, properties of the artificial dendrites can lead to predictions about yet unmeasured properties. In this way, we investigated wide-field motion integration performed by the VS cells of the fly visual system. In outlining the inverse approach and two applications, we also elaborate on the nature of dendritic function. We furthermore discuss the role of optimality in assigning functions to dendrites and point out interesting future directions.
**Professor Charles H. Anderson**

*Dept of Anatomy and Neuroscience (retired), Washington University School of Medicine*
*cha@wustl.edu*

**Neural Engineering**

My book with Chris Eliasmith, "Neural Engineering" MIT Press 2003, describes a framework for understanding and modeling how large scale neural circuits represent and dynamically transform analog quantities. This framework was developed over 10 years with the aid of many students and colleagues. It provides a direct link between *Neural* systems and systems *Engineering* principles such as signal processing, control theory and statistical inference. The key starting point is formalizing the biologist's concept of population coding, where many noisy, nonlinear neurons represent a lower dimensional space of system variables/signals.

The Neural Engineering methods show how to characterize neural systems in terms of dynamics and computations defined over system variables, without having to focus on individual neuron responses. Nevertheless, these methods allow for the construction of large-scale, detailed models at the level of single neurons. In short, these methods have resulted in a powerful framework that has been applied to sensory, motor, and decision making neurobiological circuits, a brief description of the latter will be provided. Recently, Eliasmith has written a book, "How to Build a Brain", Oxford University Press (in press) that proposes how these methods can underwrite a full cognitive architecture in networks of spiking neurons.
Professor Ralph Etienne-Cummings

Department of Electrical and Computer Engineering, The Johns Hopkins University
Sponsored by the IEEE Circuits and Systems Society
retienne@jhu.edu

Attention to Proto-Objects: Grouping-Based Saliency

A visual saliency map is useful in any visual sensory system (be it artificial or biological) in that it helps deal with information overload by directing the application of computational resources to interesting parts of the image. Itti et al. [1] developed a saliency map which utilizes differences in features across an image to find interesting (salient) locations. The model was able to predict human eye fixations for images featuring pop out and predict human eye fixations better than chance in more complex scenes [1]. However, Gestalt psychologists argue that humans perceive the whole before they analyze individual features. A recent study [2], showing that objects predict eye-fixations better than features, supports this. Our work has been influenced by these findings, as we build the next generation visual saliency algorithm which finds salient objects rather than features. First, the visual scene is deconstructed into intensity, color-opponency and motion channels. The saliency algorithm then uses the principles of border ownership neurons discovered by Zhou et al [3] and grouping neurons, proposed by Craft et al [4], to extract objects from each channel at different scales. A normalization is then applied so that unique objects are awarded the highest saliency and common objects the lowest saliency. The ability of this biologically plausible algorithm to predict human eye fixations has been shown to exceed the current state of the art biologically inspired and mathematically derived models. Our model is also ideal for hardware implementation for real-time execution.

Sinusoidal stimulation of retinal bipolar cells: A Modeling Study

Tatiana Kameneva¹, Hamish Meffin¹,², David B. Grayden¹,³ and Anthony N. Burkitt¹,²,³

¹ NeuroEngineering Laboratory, Dept. of Electrical & Electronic Engineering, University of Melbourne
² NICTA
³ Bionics Institute

Presenter: hmeffin@yahoo.com

Retinal bipolar cells (RBCs) are neurons that relay information from photoreceptors and horizontal cells to amacrine and ganglion cells. In patients who have degenerative eye diseases, a substantial fraction of RBCs survive photoreceptor loss. Electrical stimulation of the retina, including RBCs, can result in the restoration of rudimentary vision. To investigate responses of RBCs to electrical stimulation, we developed models of two groups of RBCs: a group with low-voltage activated (LVA) Ca²⁺ current (group G+) and a group without the current (group G−). Using experimental data from the literature, the constrained models of the groups were used to explore responses of RBCs to sinusoidal stimulation of varying frequency. We sought to account for electrophysiological differences between the groups G+ and G− on the basis of differences in the magnitudes of the maximal conductance of LVA Ca²⁺ current, gT. Sinusoidal stimulation of amplitude 0.04pA at 2, 10, 25, 100Hz frequencies were applied to both groups and responses were compared. For gT≥0.01S/cm², the model reproduced experimental results for the group G+; for gT≤10−5S/cm², the model reproduced experimental results for the group G−. The membrane potential in the group G+ reached higher depolarization levels at lower frequencies (2-10Hz) than the membrane potential at the highest frequency (100Hz). There were no differences in maximal depolarization with varying frequencies in the group G−. Since a higher level of the membrane potential corresponds to higher probability of information transfer from bipolar cells, using sinusoidal stimulation at lower frequencies has higher probability of activating RBCs in the group G+.
Characterisation of Alzheimer's disease using graph theoretical analysis of fMRI data

Paul McCarthy¹, Lubica Benuskova¹, Liz Franz²

¹ Department of Computer Science, University of Otago, Dunedin, New Zealand,
² Department of Psychology, University of Otago, Dunedin, New Zealand

Presenter: pauld.mccarthy@gmail.com

Graph theory is a novel approach in the analysis of functional connectivity in brain imaging data. We have performed graph theoretical analysis of a publicly available fMRI data set, in an attempt to find differences between healthy subjects, and subjects with Alzheimer's disease. We apply our techniques to group-averaged fMRI data, and also give a preliminary statistical comparison of individual subject data across groups. Our hope is that this work will lead to a better understanding of the damaging effects of dementia, and will potentially give rise to new and quantitative methods of diagnosis.
A model for how calcium and cAMP levels determine whether axons are attracted or repelled by molecular gradients

Elizabeth M Forbes\textsuperscript{1}, Andrew W Thompson\textsuperscript{1}, and Geoffrey J Goodhill\textsuperscript{1,2}

\textsuperscript{1} Queensland Brain Institute, The University of Queensland, St Lucia, 
\textsuperscript{2} School of Mathematics and Physics, The University of Queensland, St Lucia

Presenter: g.goodhill@uq.edu.au

Wiring the brain during development requires growth cones at the tips of growing axons to make a complex set of guidance decisions. Growth cones are often guided by molecular gradients, but the same gradient can be interpreted as attractive or repulsive depending on the internal state of the growth cone. In particular it has been shown previously that levels of calcium and cAMP in the growth cone can strongly influence this decision. Here we addressed this issue quantitatively using a computational model of the relevant signal transduction pathways in the growth cone. This was adapted from a previous model addressing the switch between LTP and LTD in synaptic plasticity, but crucially we considered how the output of this network would be different on the two sides of the growth cone due to the external gradient. The model both reproduced a large array of known experimental results, and made a number of novel and sometimes surprising predictions. We tested these predictions and confirmed that the new data also fitted with the model. Together these results provide the first quantitative explanation for a large and often puzzling set of phenomena in the biology of axon guidance, and may also help in the optimization of therapies to aid the regeneration of axons after injury.
Mechanisms of seizure propagation in 2-dimensional centre-surround recurrent networks

David C. Hall\textsuperscript{1,2}, Levin Kuhlmann\textsuperscript{2,3}

\textsuperscript{1}Victoria Research Labs, National ICT Australia,
\textsuperscript{2}Department of Electrical and Electronic Engineering, The University of Melbourne,
\textsuperscript{3}Department of Optometry and Vision Sciences, The University of Melbourne

Presenter: levink@unimelb.edu.au

Understanding how seizures spread throughout the brain is an important problem in the treatment of epilepsy, especially for implantable devices that aim to avert focal seizures before they spread to, and overwhelm, the rest of the brain. This paper presents an analysis of the speed of propagation of seizure-like activity in 2-dimensional recurrent integrate-and-fire networks containing excitatory and inhibitory populations and having a difference of Gaussians connectivity structure, akin to that observed in cerebral cortex. In the same network, alternative mechanisms are explored in order to explain the range of seizure-like activity propagation speeds (0.1-100 mm/s) observed in two animal-slice-based models of epilepsy: (1) low extracellular [Mg\textsuperscript{2+}], which creates excess excitation and (2) introduction of GABA antagonists, which reduce inhibition. Moreover, two alternative connection topologies are considered: excitation broader than inhibition, and inhibition broader than excitation. It was found that the empirically observed range of propagation velocities can be obtained for both connection topologies. For the case of the GABA antagonist model, consistent with other studies, it was found that there is a threshold degree of inhibition below which waves begin to propagate. In addition, any degree of inhibition can introduce disorder into the 2-dimensional wave patterns. For the case of the low extracellular [Mg\textsuperscript{2+}] model, it was found that depression of inhibitory synapses provides a potential candidate for explaining the emergence of slowly propagating waves. This work provides a localised network understanding of the propagation of seizures in 2-dimensional centre-surround networks that can be tested empirically.
Nanoscale Neurocybernetics: Where the memristor meets NEURON

O. Kavehei, N. Iannella, S. Al-Sawari, and D. Abbott

Centre for Biomedical Engineering, School of Electrical and Electronic Engineering, The University of Adelaide

Presenter: nicolang@brain.riken.jp

Chua\(^1\) first extrapolated the inherent symmetry between passive two terminal circuit devices and their relationship between the four fundamental circuit variables of voltage \(v\), charge \(q\), current \(i\), and flux \(\phi\). Based on completeness, he argued the existence of a fourth elementary device based upon a relationship between charge \(q\) and flux \(\phi\). This device was called \textit{memristor} (memory resistor) and possesses the unique property of combining nonlinear resistance with non-volatile memory. Since HP's first realisation\(^2\), there has been an explosion in research about memristor and memristive nano-devices, promising opportunities for building fundamentally new computational blocks. Significantly for computational neuroscientists, active neuron models, such as Hodgkin-Huxley, can be recast into memristive devices\(^3\), making it appealing to build nanoscale implementations of neuromorphic systems. Recently, nanoscale crossbar array architectures, based upon memristors, have been shown to behave as synapses\(^4\). The mathematical expression for a memristive based synapse is equivalent to a plastic gap junction, where the timing difference between spikes, it experiences implements Spike timing-dependent plasticity (STDP). This now makes it possible to build biologically inspired adaptive nanoscale neuromorphic systems using NEURON. Memristive based simulations are typically conducted in SPICE, however, taking advantage of inherent customized solvers of NEURON\(^5\) permits such calculations to be carried out using a flexible, easy to work, and scalable environment. Significantly, it brings computational neuroscientists one step closer to hardware implementations. To the best of our knowledge, this is the first step toward introducing memristors as plastic gap junctions and the implementation of memristor equations in NEURON.

\(^4\)Choi, H; et al. (2009), "An electrically modifiable synapse array of resistive switching memory", Nanotechnology 20 (34): 345201.
Spike, rate, field, and hybrid methods for treating neuronal dynamics and interactions

Peter A. Robinson and J. W. Kim

School of Physics, University of Sydney and Brain Dynamics Center, Sydney Medical School - Western, University of Sydney

Presenter: robinson@physics.usyd.edu.au

Representing neural activity in terms of spikes or rates are complementary approaches to computing neuronal dynamics. Likewise, communication between neurons via individual pairwise links or via smoothed fields are complementary approaches to modeling information transfer. Here, spike-, rate-, and field-based approaches to neural dynamics are adapted and hybridized to provide new methods of analyzing dynamics of single neurons and large neuronal systems, and to enable faster simulations with reduced memory requirements. At the single-neuron level, the new approaches involve reformulation of dynamics in synapses, dendrites, cell bodies, and axons to enable new types of analysis, longer numerical timesteps, and demonstration that rate-based methods can predict spike times. In multineuron systems, hybrids and intermediates between spike-based and field-based coupling between neurons are used to bridge the gap between descriptions based on pairwise spike-based interactions between neurons and ones based on neural field-based interactions within and between populations. In particular, a new neuron-in-cell approach is introduced that is a hybrid between neural field theory and spiking-neuron models in analogy to particle-in-cell methods in plasma physics. This approach enables large speedups in computations while preserving spike shapes and times. The various approaches are illustrated numerically for specific cases.
Identification and continuity of the distributions of burst-length and inter-spike-intervals in the stochastic Morris-Lecar neuron

Priscilla E Greenwood¹ and Peter F Rowat²

¹ Department of Mathematics, University of British Columbia, Vancouver,
² Institute for Neural Computation, University of California, San Diego La Jolla

Presenter: pgreenw@math.la.asu.edu

Using the Morris-Lecar model neuron with a type II parameter set and potassium channel noise, we investigate the inter-spike-interval distribution as a function of applied current. The model generates spiking behavior with sequences of random numbers of spikes, separated by quiescent intervals of random length. This kind of spiking behavior is found, for instance, in stuttering inhibitory interneurons in cortex. Combining analysis of the stochastic dynamics of the model with estimation based on simulations, we show that the parameter of the exponential tail of the ISI distribution is in fact continuous over the entire range of plausible applied current, regardless of the bifurcations in the phase-portrait of the model. Further, we show that the spike sequence length, apparently studied for the first time here, has a geometric distribution whose associated parameter is continuous as a function of applied current over the entire input range. Hence this model is applicable over a much wider range of applied current than has been thought.
Random walk analysis of fixational eye movements during viewing of natural video scenes

James A. Roberts\textsuperscript{1}, Guy Wallis\textsuperscript{2}, Michael Breakspear\textsuperscript{1,3,4}

\textsuperscript{1} Queensland Institute of Medical Research,
\textsuperscript{2} School of Human Movement Studies, University of Queensland,
\textsuperscript{3} Royal Brisbane and Women’s Hospital,
\textsuperscript{4} The Black Dog Institute and School of Psychiatry, University of New South Wales

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Fixational eye movements (drift, tremor, and microsaccades) occur even when trying to keep our eyes still, and are thought to prevent image fading due to neural adaptation in the retina and beyond. Drifts and microsaccades yield apparently random gaze trajectories, widely assumed to exhibit normal diffusion, but more recently shown in forced fixation tasks to exhibit anomalous diffusion. Here, we analyze fixations recorded using a head-mounted eye tracker during free viewing of natural video scenes. These stimuli have greater ecological validity than typical static fixation targets in that viewing is unconstrained and the stimulus itself is dynamic. We find that gaze location exhibits superdiffusion for time scales up to 400 ms, reverting to diffusion or subdiffusion thereafter. The superdiffusivity does not depend on image contrast or frequency content, implying that the trajectories are not simply driven by fine-scale features of the foveal input. By treating the gaze as a random walk, we find an anisotropic step distribution that is biased toward longer and more numerous forward steps. Surrogate walks with independent steps drawn from these empirical distributions do not exhibit superdiffusion, implying that the eye movements must be correlated. We propose a biologically-plausible mechanism for these correlations as arising from a finite memory of past gaze location, such that the eye tends to avoid retracing its recent steps. The statistics of the model random walks closely match the data, and furthermore suggest a novel means of inferring the adaptation time constants of the neuronal pathways involved.
Stochastic resonance and other benefits of randomness in neural systems: Bridging theory and experiment

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Although typically assumed to degrade performance, sometimes random fluctuations, or noise, can improve information processing in nonlinear systems. While various forms of noise-enhanced processing, such as stochastic resonance, have been observed both in theoretical models of neural systems and in experimental neuroscience, the two approaches have yet to be fully reconciled [1]. We illustrate why this is the case, using examples ranging from the auditory and somatosensory systems, to cortical local field potentials. We also propose that future advances in our understanding of in-vivo benefits of random noise in neural systems will require new experiments to be developed in close conjunction with new theory that begins with concrete and precise hypotheses regarding potential computational roles of specific neural systems.

The frequency of oscillatory inputs is encoded in the connection strengths of networks of spiking neurons by STDP

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Spike-timing-dependent plasticity (STDP) is a learning rule that updates synaptic strengths based on the relative timing of pre- and post-synaptic spikes. Unlike classical, rate-based Hebbian learning, STDP can potentially encode fast temporal correlations in neuronal activity, such as oscillations, in the functional structure of networks of neurons that have axonal and dendritic propagation delays. In this study, the changes made by STDP to synaptic strengths in recurrent networks with axonal delays receiving oscillatory inputs were investigated analytically with Poisson neuron models and verified through simulations with leaky integrate-and-fire neurons. The motivation behind this was to understand how general spatiotemporal patterns can be learnt by a network of neurons with STDP present. An application of this specific model might be in explaining how the brain can perceive the pitch of complex sounds up to 300Hz, even when the fundamental frequency is missing. Both the analytical description and simulations found that connections were selectively potentiated and depressed based on their axonal delay in such a way that the delays of the strong connections in the network “resonated” with the input frequency.
Hubs, information processing and overlapping modularity in the cortex

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The physical structure of the brain controls and shapes its information processing capacity. Conversely, functional dynamics (i.e. information processing and neural activity) alter brain structure. Two anatomical features that are believed to play critical roles in governing these neural dynamics are modularity and the presence of hubs. Modularity is the property that spatially contiguous neural units play functionally similar roles and are more tightly connected internally than to other regions. For example, cortical areas can be classified as visual, auditory, somatosensory or frontolimbic. Hubs are highly connected regions in the cortex that are believed to play pivotal roles in coordinating information flow in the brain, by either playing central roles in single functional clusters or connecting spatially distinct, multiple functional clusters. We show that these two major anatomical features can be linked together under a common framework. By looking at anatomical structure as a network of nodal regions and links, spectral graph-theoretic analysis shows that hubs are either (i) exceptionally well connected nodes i.e. highest degree nodes within a single module, or (ii) lie in an overlap region between structurally distinct modules and are thus part of multiple modules. Both modularity and the roles of hub regions have been previously explored using graph-theoretic analysis. In this work, we are able to relate these two distinct features under a common framework that shows their inter-relationships and their common role in shaping information processing in the brain.
Axon pathfinding in the retina need not rely on a chemical gradient

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The mechanism for the formation of the typical arcuate patterns of axon trajectories in the human retina is unclear. A common theory in the literature is that the retinal axonal growth cones follow a chemical gradient towards the optic nerve head (ONH) during development, and that the macular region around the fovea has a repellent property, steering growth cones away from the fovea. In this study, we examine a computational model of human retinal axon pathway development that does not rely on a chemical gradient to guide growth cones. Each retinal ganglion cell's axon attempts to follow exactly the same path as its nearest neighbour whose axon has already found a path to the ONH (fasiculation). The number of axons that can "stack" on top of each other is restricted in the macular region as a simple linear function of the distance from the fovea. The function is based on the cell-count data in the papillomacular bundle, which are the axons that lead directly from the fovea to the ONH, in a healthy adult eye. The predicted pathways and density of axons around the ONH from the model compare favourably with human data. Thus we conclude that there could be a mechanism guiding axons in the developing human retina that does not rely on growth cones following a chemical gradient, contrary to the dominate view in the current literature.
A model for fundamental functional properties in primary visual cortex

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A model of signal processing in the primary visual cortex is presented here. The aim is to simulate the fundamental properties of the cortical cells such as direction selectivity, orientation selectivity and spatial frequency selectivity. Further, the model aims to match the population response of these properties with those found empirically. This feed-forward model describes a single column of cat primary visual cortex and comprises a series of processing stages from retina to the primary visual cortex. Each neuron receives convergent excitatory input from the neurons in the preceding stage, where the input is weighted with a Gaussian function centred on the recipient neuron. All neurons in the model are simulated as low-pass temporal filters to produce a generator potential. For all cells other than photoreceptors and bipolar cells, this potential is rectified to obtain action potential rate. The model reproduces several fundamental properties of the primary visual cortex as well as the diversity of responses across population of cells. Direction selectivity originates from a small delay between on-centre and off-centre inputs to cortex: each cortical cell produces a large generator potential in its preferred direction and a small response in the opposite direction. Orientation selectivity of the model results from the spatial separation of on- and off- inputs. Finally, population statistics in the model reproduce those found in the laboratory.
Spatiotemporal hemodynamics: From theory to experiment

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Functional Magnetic Resonance Imaging (fMRI) experiments rely on precise characterization of the Blood Oxygen-Level Dependent (BOLD) signal. Inferences of the brain’s information processing mechanisms are frequently made with BOLD, so understanding of the physiological origin of this signal is of vital importance in systems neuroscience. To date, the link between neural activity and BOLD is poorly known, leaving typical studies to rely extensively on statistical correlations of mental task with resulting signal, which obscures the underlying mechanisms. Furthermore, these correlations don’t take into account fine-scale spatial interactions, which further restricts their ability to infer neural processing. This study provides a systematic approach to these issues via a recently developed spatiotemporal model of hemodynamics, derived from physiology. Here, the spatiotemporal hemodynamic response is calculated and shown to imply the existence of traveling waves of hemodynamic activity. We confirm the existence of these waves in fMRI through evoked responses in the primary visual cortex with high-resolution fMRI. This then means that local neuronal responses (<1 mm) can influence hemodynamics on a larger scale (~5 mm). These findings have many implications for computational neuroscience, discussed here: (i) Inferences of connectivity and dynamics from fMRI may be incorrect and/or distorted; (ii) We can use fMRI to access smaller neural scales than are commonly assumed; (iii) We can exploit resonant properties to infer spatiotemporal characteristics of neuronal activity for the first time with fMRI; (iv) we can deconvolve spatiotemporal BOLD responses to estimate spatiotemporal neuronal activity more precisely.
Bayesian inference in spiking neural networks

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The brain creates a coherent interpretation of the external world based on input from its sensory system. Yet data from the senses are unreliable and confused. How does the brain synthesise its percepts? Recent psychophysical experiments indicate that humans perform near-optimal Bayesian Inference in a wide variety of cognitive tasks, such as motion perception, decision making, or motor control. In Bayesian Inference – a powerful mathematical framework – the likelihood of a particular state of the world being true is calculated based not only on sensory input signals but also on prior knowledge about the external world that the system has already learned. The Bayesian framework has also been shown to be ideal for fusing information from different sensory modalities and is robust to errors in individual sensors. If we could understand, in an engineering sense, how the brain accomplishes this, then we could apply this knowledge to the electronic sensors we build.

Neurons in the brain use action potentials (spikes) to communicate with each other. From calculations based on the energy consumption of the brain, it has been estimated that, on average, each neuron fires only one spike per second, although individual sensory neurons can fire close to 1000 spikes per second. The question of how Bayesian Inference can be implemented using spiking neurons with such slow communication rates is intriguing. In the past five years a dozen of papers have been published showing glimpses of how this could be achieved. In this presentation, we will discuss our investigations into an implementation proposed by Sophie Denève [1,2].

A polychronous neural network uses the spatiotemporal pattern of firing to represent information [1] while in classic neural networks it is the firing rates of neurons that is used for this purpose. The term polychronisation is used to indicate that the neurons fire asynchronously; however, in this neural network spikes travel via axonal connections with specific delay values to arrive at the post-synaptic neurons simultaneously, thus in turn evoking new spikes. This time-locked relation can be used to implement a short-term memory composed of spatial-temporal patterns. There are two general ways to obtain appropriate connection delays for a polychronous network. The first method, which we refer to as delay selection, supposes that the delay values of the connections between neurons are random and fixed at the beginning. Random stimulation, together with a weight adaptation algorithm, such as Spike Timing Dependent Plasticity (STDP), is applied during development to prune and select appropriate subsets of delays by enhancing the weights of the connections with proper delays while decreasing the improper ones [2]. The second method, which we call delay shift, adapts the actual delay values of the connections between neurons during training. In biology, such adaptation may be achieved by changing the length and thickness of dendrites and axons, the extent of myelination of axons, or the density and type of ion channels [3-5]. We are not aware of any publication describing a delay shift approach for polychronous networks. We have implemented a polychronous network using delay shift in analogue VLSI.

Real-time implementation of the primary auditory neuron activities

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A cochlear implant operates in real-time as do the ears of humans. For tuning the auditory nerve responses of the cochlear implant model, a real-time computational model of the auditory pathway is a useful tool to have as a guide. In this work we develop a real-time computational model that will be able to generate signals from various stages of the auditory pathway such as the basilar membrane vibrational velocities, inner hair cell receptor potentials and auditory nerve response rates. Results will be presented in a numerical form in a file as well as visually in a graphical format for further analysis. In case there is a need to port the algorithms to embedded processors, processing time of algorithms would also be made available for feasibility analysis.
Emergent BCM via Neuromorphic VLSI synapses with STDP

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The Bienenstock-Cooper-Munro (BCM) rule\textsuperscript{1-3} is an experimentally verified form of synaptic plasticity where the alteration of synaptic weight depends upon the rate of pre and post-synaptic firing of action potentials. Previous theoretical studies have investigated how the precise timing of random pre- and post-synaptic spike activity and spike timing-dependent plasticity (STDP) leads to changes in the efficacy of synaptic weights, assuming Poissonian spike statistics. In particular, when a particular class of STDP rule, based upon multiple spike interactions are used, the time averaged behaviour of synaptic weight changes was shown to exhibit analogous behaviour to the classical BCM rule and can inherit its functional properties. Here, we present two distinct neuromorphic VLSI circuit implementations and some of their behaviour. The first circuit implements the classical pair-based STDP\textsuperscript{4}, while the second realizes a previously described triplet-based STDP rule\textsuperscript{5}. We use these different circuits to examine whether BCM learning is an emergent property. A 0.35 µm standard CMOS process model has been used in HSpice to implement the two mentioned circuits. Simulation results demonstrate how well, the proposed triplet-based STDP circuit produces the threshold-based behaviour of the BCM. Also, the results testify to similar behaviour for the VLSI circuit for pair-based STDP in generating the BCM.

Stochastic pooling networks embedded in cortical networks of excitatory and inhibitory neurons

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Recently we defined a general network concept called a Stochastic Pooling Network [1]. This notion involves stochastic dynamical processes that take place on a widely occurring class of network structure (ranging from macroscopic social networks to neuron populations and nanoscale electronics) leading to various unexpected emergent features, such as suprathreshold stochastic resonance [2]. The key feature of stochastic pooling networks that leads to such effects is the interaction of random noise with lossy compression and redundancy. Previous work on describing populations of neurons as stochastic pooling networks has assumed very regular and simple network topologies and neuron models, e.g. [3]. Here we demonstrate that stochastic pooling networks can be observed embedded within a class of network models typically used for simulating gamma frequency oscillations in cortical local field potentials, i.e. recurrent networks of sparsely connected pyramidal neurons and interneurons that individually fire at rates much smaller than the gamma oscillations [4]. We examine various complex network features, such as a wide degree distribution, and local clustering.

Application of hierarchical temporal memory to auditory data

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Hierarchical Temporal Memory—HTM—is an innovative model of neocortical information processing, developed with the aim not only of understanding intelligence, but also of building intelligent machines [1,2]. As a hierarchical memory-based computational framework, HTM implements some of the known organisational and operational features of the neocortex, and has been shown to perform well when applied to vision and static recognition problems [1]. Particularly in object classification and pattern recognition problems, the algorithms and structure behind HTM exhibit a remarkable ability to learn, with accurate performance and robustness to noise, translations and transformations [2].

We investigate the feasibility of enhancing existing HTM approaches by adding mechanisms that enable learning and recognition of patterns and sequences in time varying signals. In particular, we pre-process speech data by using a biomimetic model of the basilar membrane and inner hair cells, and based on the models output, present the HTM with a sparse distributed representation of the data. Our study shows preliminary results towards the implementation of algorithms that will ultimately lead to an HTM model able to handle auditory data and perform time-based inference [3].

Slope-based stochastic resonance in phasic auditory brainstem neurons based on realistic models of channel noise

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Stochastic variability in conductances due to random transitions between ion channel states can non-trivially affect neural behaviour [1,2,3]. However, accurate and computationally efficient methods of simulating this noise must be developed in order to integrate it into larger scale network models based on biophysically realistic neuron models. It is therefore valuable to compare and contrast the effects of computationally efficient representations of noise with models that more closely represent the intrinsic biophysical source of noise [1,2].

Recent work with a phasic neuron model used to represent auditory brainstem neurons has shown that the presence of channel noise modelled by an injected white noise current, distinctly alters the firing properties the neuron, which exhibits a form of stochastic facilitation [3] labelled as “slope-based stochastic resonance” [4]. Here we examine slope-based stochastic resonance in the same model neuron with more realistic intrinsic channel noise, modelled by a full Markov chain description of the ion channel state configurations, with established voltage dependent transition probabilities. We also compare our results to newly developed stochastic differential equation models that approximate the full Markov chain description [1,2].

Fitting synaptic and intrinsic neural parameters in T stellate cells of the Cochlear nucleus

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T stellate cells of the cochlear nucleus provide a robust spectral representation of auditory information, and enhanced coding of temporal information. This poster presents a biophysically-realistic neural network model of the microcircuit controlling T stellate cells, with three inhibitory interneurons. Intracellular recordings of chopper units have been classified into three types (Paolini et al., 2005): chopper sustained (CS), and two transient choppers (CT1 and CT2). Our work advances current hand-tuning approaches by optimising synaptic and intrinsic neural parameters in T stellate cells with a fitting algorithm. The network was simulated in NEURON with Poisson and Hodgkin-Huxley models. The input auditory model provides the major phenomenological qualities of experimentally recorded ANFs (Zilany et al., 2009). Inputs from 20048 kHz project onto 100 frequency channels, with each channel containing three inhibitory neurons. Optimisation of each chopper unit used the CF of exemplar units: CS (3.9 kHz 40 dB SPL), CT1 (8.2 kHz, 85 dB SPL), CT2 (12.4 kHz 35 dB SPL). The intracellular traces from Paolini et al. (2005) form the basis for the optimisation routine of T stellate cell model along with the CV statistics of each chopper type. In terms of excitatory and inhibitory inputs, the subtypes can be concisely summarised by: CS Exc>>Inh, CT1 Exc>>Inh, and CT2 Exc>Inh. There was little difference in intrinsic parameters. Heterogeneous chopper subtypes in T stellate cells are primarily a result of differences in synaptic parameters. Our work also demonstrates that a complex microcircuit can be fit using combined spiking and intracellular data.

Interplay between propagation delays and single-cell oscillations in the dynamics of inhibitory networks

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Fast oscillations have been observed in several brain areas and have been proposed as a general substrate of neural computation, but they are still incompletely understood. Here, we characterise the effects of single-cell oscillations and distance-dependent transmission delays on the synchronisation properties of inhibitory networks of either Integrate-and-Fire (IF) or Generalised Integrate-and-Fire (GIF) neurons with subthreshold oscillations. As parameters are varied, these networks can exhibit asynchronous activity, sinusoidal oscillations or non-linear, fully-developed oscillations, in which network bursts are separated by time intervals of silence. Individual neurons fire irregularly, at a rate that is an order of magnitude lower than the network frequency. In the absence of transmission delays, network activity is asynchronous. When all transmission delays are equal, the network exhibits highly synchronous firing behaviour, even for weak inhibitory coupling. Further increases in coupling do not affect activity because individual neurons are already driven very close to the inhibitory reversal potential at the peak of each inhibitory cycle. When transmission delays are distributed in a range, as expected from a spatial arrangement of neurons, network activity is sensitive to changes in inhibitory coupling, with stronger coupling resulting in higher synchronisation. GIF networks synchronise more, leaving greater windows of opportunity for spiking and hence higher firing rates. The interplay between conduction delays and single-cell oscillations modulates synchrony and firing rates in interneuronal networks, suggesting a functional role for the resonant properties observed in many interneuronal types.
Determining the impedance of the retinal layers from noisy voltage measurements

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A retinal prosthesis aims to restore some visual perception to a person with vision loss due to retinal degeneration. Obtaining accurate maps of the electrical impedance throughout the retina may aid the design of more effective prostheses. Our method obtains the complex impedance of the retina by solving the continuity equation. A 2-dimensional retinal slice is modelled as having conductivity and permittivity maps that vary with frequency and position. Complex voltage measurements are computed for an applied sinusoidal voltage of 1 Hz to 100 kHz, which is within the range of typical retinal stimulation. The measurements are down-sampled to a grid and white noise is added. A moving average filter is then applied and the first and second partial derivatives of the real and imaginary components of the voltage grid are computed. The conductivity and permittivity are estimated with a Dirichlet boundary condition. The accuracy of this method is evaluated by comparison of the conductivity and permittivity maps used to generate the voltages and the impedance map calculated from the voltage grid.

Simulations have been run for a range of SNRs and measurement spacing in order to demonstrate that the method works for various numbers of voltage measurements and noise levels. For example, a 200\textmu m\times400\textmu m retinal section with sinusoidally varying conductivity and permittivity maps was considered. The signal-to-noise ratio (SNR) of the voltages was set to 20dB and a grid of spacing 5\textmu m was used. The average error of the conductivity and permittivity maps was 20.6%. In future work this will be tested in an \textit{in vitro} preparation.
Modelling study of connectivity and function of octopus cells of the mammalian Cochlear nucleus

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Octopus cells are neurons in the auditory brainstem of mammals that respond most strongly to the onset of broadband sounds. They receive many (>60) connections from auditory nerve fibers with a broad range of characteristic frequencies. Their intrinsic electrophysiology suggests that they detect co-incidence of incoming synaptic information.

Our investigation used a compartmental Hodgkin-Huxley model to reveal the relationship between the octopus cell’s morphology, electrophysiology, connectivity and ultimate function. The dendritic propagation time of the post-synaptic potential was quantified in a model that simulated $in vitro$ conditions. A realistic periphery and auditory nerve model was then used to create a model that simulated $in vivo$ conditions and test the effects of the dendritic delay on the octopus cell’s response to sound.

It was found that:
- The location of sodium channels in the axon initial segment vs. the soma was important for function.
- Octopus cells receive hundreds of synapses, rather than 60.
- The frequency span of the octopus cell’s input is narrower when it receives input from lower characteristic frequency auditory nerve fibers.
- The role of active channels in the dendrite may be to maintain timing that is independent of post synaptic potential amplitude.
- The $in vivo$ octopus cell model behaved most realistically when auditory nerve fiber synapses were connected such that the dendritic delay compensated for the traveling wave delay of the cochlea.
Eigenshape analysis of growth cone morphology

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Guidance of neuronal growth cones (GCs) by molecular gradients plays an important role in the development of the nervous system. The extracellular environment local to these GCs is an important determinant of their complex morphology, and thus analysis of GC morphology can potentially reveal information about the mechanisms underlying axonal guidance by molecular gradients. Here we utilised the model system of GC turning (pipette) assays whereby rat P2 superior cervical ganglion axons were exposed to gradients of nerve growth factor (NGF). To ascertain GC chemotactic sensitivity, we varied the pipette NGF concentration to map the GC attractive response, and of the repulsive response whereby intracellular Protein Kinase A was inhibited by KT5720. Time-lapse movies of these experiments (191 movies, 50-70 min duration, sampling rate = 1 frame/min) were analysed using a customised semi-automatic image segmentation program so as to determine the GC outlines from each movie frame. From the population of growth cone outlines (11272 movie frames), we used Principal Component Analysis (PCA) to extract the GC mode shapes (the mode shapes that reproduce the greatest variance in the shape-space occupied by the GC population). We present results of our analysis that reveals correlations between particular shape modes and the chemotactic response.
Critical fluctuations in cortical models near instability

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Computational models of cortical activity play a crucial role in explaining and inverting neuroscience data. During healthy activity, the cortex is assumed to operate within a linearly stable domain, becoming unstable and exhibiting nonlinear oscillations only during pathological states such as epilepsy. Linearly stable systems submit themselves readily to perturbation analysis, allowing the spatial and temporal spectra to be predicted in the Fourier domain via derivation of a series of transfer functions. A variety of computational models have been submitted to this analysis, including the purely cortical neural mass model of Jansen and Rit and the corticothalamic neural field model explicated by Robinson and others. Of note, that analysis predicts that fluctuations should dissipate quickly and hence show only short range spatial and temporal correlations. In this study, we explore the nature of predicted fluctuations in cortical activity in a variant of the Jansen-Rit model as it passes close to a nonlinear bifurcation. By integrating the resultant stochastic differential equations, we find that spatial and temporal correlation lengths in the system fluctuations can diverge due to the emergence of power law scaling. There is broad empirical support and a compelling theoretical argument that the cortex operates close to instability. Our findings are hence of significance to those using computational modelling to understand cortical activity.
Evoking transitions between readiness and action in a phase-coupled oscillator model of motor cortex

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Rapid changes in behaviour require rapid changes in brain states yet the brain must also remain stable in the face of noise and uncertainty. We compared two mechanisms for evoking controlled transitions between distinct spatiotemporal phase-of-firing patterns in a two-dimensional model of motor cortex. Cortex was modelled as an array of phase-coupled Kuramoto oscillators that were spatially coupled using a centre-surround connection topology. The strength of the inhibitory surround was systematically manipulated to evoke either self-organised spatial wave patterns or spatially synchronous phase patterns where waves were assumed to encode motor action and synchrony to encode motor readiness. Bistable patterns of wave and synchrony were also observed near the transition boundary. Bistability promises rapid transitions between co-existing states by direct perturbation. We thus compared the time-course of state transitions between waves and synchrony by (i) manipulating the strength of the inhibitory surround between two mono-stable regimes and (ii) perturbing the oscillator phases while the inhibitory surround was held fixed in the bistable regime. The perturbation method was found to evoke faster transitions than manipulating the coupling topology but the outcomes were less reliable. In both cases the pseudo local field potential generated by the model was reminiscent of that observed in human motor cortex during voluntary movement. We suggest that motor cortex may exploit bistability to achieve rapid motor actions but at a trade-off between speed and reliability.
Interacting wave patterns in spiking neural circuits with STDP: Spontaneous symmetry breaking and associative memory

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Recent experimental results have shown that multiple localized coherent activity patterns are widespread in the brain. These patterns are observed to propagate across the cortex as localized propagating waves with complex interactions. Despite their ubiquity in the brain, the formation mechanism of the dynamical patterns and their functional roles have remained unclear. By constructing a spatially extended spiking neural circuit, we are able to reproduce the multiple wave patterns with complex interactions. Prompted by the presence of spike timing sequences generated by propagating waves, we further add spike-timing dependent plasticity (STDP) to the model. We find that STDP can facilitate the spontaneous formation of localized propagating patterns by the physical principle of spontaneous symmetry breaking, which we characterize numerically and analytically. Furthermore, we demonstrate that STDP can be used to learn and then control the propagation paths of individual wave patterns. Finally, based on STDP modulated interacting dynamics of localized waves, we propose a new mechanism for conditional associative learning and memory, which are able to successfully link neurons dynamics with the timescale of tens of milliseconds to behavioral task involving times on the order of seconds.
Frequency entrainment in a mean-field brain model with delayed feedback

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A compact mean-field brain model is applied to explore various rhythmic, electrophysiological brain activities that are often seen by diagnostic tools such as electroencephalography (EEG). The model involves thalamic neurons that are stimulated by external source and delayed feedback via corticothalamic loops, and modulated by a slow ion-channel variable. Despite its simple formula, the model illustrates various dynamical firing patterns, especially when the strength and time delay of the corticothalamic loop are controlled. In particular, it is shown that two distinct patterns, one entrained to thalamic dynamics itself and one entrained to the loop properties, appear alternatively, which may provide an understanding of dynamical origins of the slow (1-4 Hz) and fast (8-12 Hz) EEG oscillations that are dominant at sleep and wake brain states, respectively.
Neural field theory of calcium dependent plasticity

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Calcium dependent plasticity (CaDP) is a mechanism that can produce spike-timing dependent plasticity (STDP). Here, CaDP is introduced into a recent neural field theory to explore large-scale synaptic plasticity. Analytical and numerical results show that: (1) Neural properties have two stable states, one corresponding to normal brain states, and another corresponding to high-activity seizure states. (2) Paired associative stimulation (PAS) pairs an electric pulse stimulation and transcranial magnetic stimulation (TMS) to induce large-scale STDP-like plasticity. Since TMS stimulates a large cortical area and induces a long temporal depolarization tail, pairing TMS shortly before or after the pulse stimulus depresses or potentiates the synapse, respectively, and calcium dependent plasticity then produces large-scale STDP. (3) For subthreshold stimuli, our theory predicts a form of spike-rate adaptation. (4) Persistent superthreshold stimuli induce seizure, which is an attractive stable state. Thus, our neural field theory of calcium dependent plasticity enables us to address long-standing problems of stability, adaptivity, and precise spike-timing in Hebbian learning.
Homogeneous and inhomogeneous connectivity and geometry in cortical networks

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The brain is extremely complex anatomically and performs many highly specialized functions. It is thought that to implement such a diverse set of functions there must exist a set of highly specialized connections within the white matter of the cortex. Connection matrices (CMs) are often used to visualize and analyze cortical white matter connectivity data; however, the amount of specialization and the connective architecture in general is not well understood. Concepts such as modularity and hierarchy currently guide much research in this area, but the modularity and hierarchy of the cortex cannot yet be described conclusively. Moreover, anatomical studies have observed that connectivity is homogeneous across the cortex to a first approximation and such observations have been successfully applied to work in areas such as mean-field modeling. This leads to an apparent paradox, with indications of broad homogeneity conflicting with those of inhomogeneity in the form of extensive modularity and hierarchy. Are both sets of observations variations on an underlying theme and can the broad homogeneity be disentangled from inhomogeneous specialized connectivity; modular, hierarchical or otherwise? We have previously shown that simple homogeneous models based on geometry are able to reproduce networks very similar to those observed experimentally. This indicates that cortical networks are more homogeneous that previously thought, however there is still likely to be significant and important inhomogeneous connectivity. Here we investigate a method to differentiate some homogeneous and inhomogenous connections through constructing CMs in Toeplitz form.
Model predictions for the effects of light on entrainment and sleepiness of permanent night workers

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Shift work is becoming increasingly popular in developed countries with almost 20% of the population working permanent or rotating shift schedules. Long term shift work is associated with multiple health problems, which are likely to be caused by prolonged desynchronization of bodily circadian rhythms. Other consequences of shift work include loss of concentration and increase of sleepiness resulting in accidents. In this study a mathematical model of sleep-wake cycles is used to examine the effects of light on entrainment and sleepiness of night shift workers. This model accounts for the state-related transitions in the firing of wake-active monoaminergic nuclei in the brainstem and sleep-active ventrolateral preoptic nuclei of the hypothalamus under the influence of the homeostatic and circadian drives. The circadian drive is controlled by the suprachiasmatic nucleus of the hypothalamus, which is entrained by light and other environmental inputs. In good quantitative agreement with experimental data the model showed significant improvement of entrainment and sleepiness on the night shift schedules with application of bright (~10 000 lux) and moderate (~3000 lux) light during the shifts, and darkness during the day. However, such high light intensities are not often used at workplaces due to their high energy-consumption. Using the model effects of different light protocols and shift start times that have not been addressed experimentally are examined. Based on the results new light profiles and shift scheduling are suggested that are expected to (i) improve entrainment and sleepiness, (ii) be less energy consuming, and (iii) be experimentally testable.
Brain state estimation using a mean field corticothalamic model

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A physiologically based neural field model of the corticothalamic system is used to predict brain activity and EEG. Our model reproduces EEG activity during wake and sleep, and can be fitted to experimental data to extract model parameters. Comparisons to experimental data have allowed us to identify and separate key wake and sleep states in the model. By analyzing EEG data as it varies over time, we are able to track the evolution of brain states and probe the differences between states. Potential applications included refined sleep staging, monitoring drowsiness, seizure prediction and characterization of other abnormalities.
**Existence and bifurcation of canard-induced mixed mode oscillations in a pituitary lactotroph model**

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We combine bifurcation analysis with the theory of canard-induced mixed mode oscillations to investigate the dynamics of a novel form of bursting. This bursting oscillation, which arises from a model of the electrical activity of a pituitary cell, is characterized by small impulses or spikes riding on top of an elevated voltage plateau. Oscillations with these characteristics have been called ‘pseudo-plateau bursting’ and are more effective than single spikes in evoking hormone release. Unlike standard bursting, the subsystem of fast variables does not possess a stable branch of periodic spiking solutions, and in the case studied here the standard fast/slow analysis provides little information about the underlying dynamics. We demonstrate that the bursting is actually a canard-induced mixed mode oscillation, and use canard theory to characterise the dynamics of the oscillation. We also use bifurcation analysis to determine the region of parameter space where bursting occurs as well as salient properties of the burst such as the number of spikes in the burst. Thus, the full-system bifurcation analysis provides a view of the sequence of spike-adding transitions and associated bursting solutions, whilst the slow/fast analysis helps us to understand why these transitions occur. This demonstrates that the combination of these two analysis techniques can be a powerful tool for understanding the pseudo-plateau bursting oscillations that arise in electrically excitable pituitary cells.
Bistability in LTP-related gene regulatory networks

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The activity-dependent enhancement of synaptic transmission described in 1973 by Bliss and colleagues referred as long-term potentiation (LTP) has been a main focus of study in neurobiology as a cellular mechanism of learning and memory. However, the role of new protein synthesis and new gene expression in LTP persistence is yet not fully understood. Despite the fact that the field of neuroscience has been relatively slow to adopt functional genomics, recently LTP-related gene regulatory networks (GRN) have been proposed (Ryan et al. 2011). We hypothesise that the GRN responsible for LTP-maintenance functions as a complex cell switch between a pre-LTP state, before the experimental high-frequency stimulation (HFS) has been carried out, and a LTP-induced state. HFS serves as a perturbation which shifts the expression state from the former to the latter. Based on this view, we propose a computational approach in which we study the LTP-related GRN topologies in their intrinsic capacity for manifesting such a bistable behaviour. To that end, we compute dynamics based on random weight matrices using experimental data from microarrays. We characterize the LTP-related network properties and their capacity to exhibit bistability by comparing them with random networks with similar properties.
Continuity of the distributions of burst-length and inter-spike-intervals in the stochastic Morris-Lecar neuron: burst-length distribution is geometric and inter-burst interval distribution is exponential.

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The effects of noisy inputs on neurons and neural networks is of great importance to nervous system function. The major intrinsic source of noise is the random opening and closing of ion channels in the neural membrane. While the noise-free Morris-Lecar model is either quiescent or fires tonically, the stochastic model produces bursts of spikes over a wide range of applied current that far exceeds the intervals of bistability associated with the Hopf bifurcation. Using simulations and counting stochastic trajectory crossings of a Poincare section, we compute the distributions of burst-length and inter-burst-intervals and find they vary continuously with applied current I.