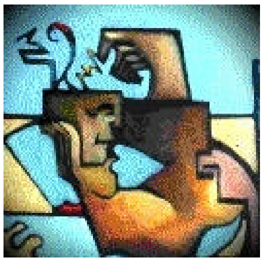
EUROPEAN SCIENCE FOUNDATION



Summer Institute in Neuroscience

NETWORK ON

Computational Neuroscience and Neuroinformatics

Final Symposium

Establishing Synapses to the Future

Belgais, Portugal, August 30-September 1, 2002

Report

Framework

The ESF Network on Computational Neuroscience was established by the European Science Foundation to promote the education of young scientists, and to facilitate the interaction and collaboration of senior scientists, in the emerging field of Computational Neuroscience and Neuroinformatics. These goals were successfully pursued through a series of three symposia, which took place in Trieste in the summers of 1999, 2000, and 2001, in conjunction with the EU Advanced Course in Computational Neuroscience. While the course provided 4 weeks of intensive training for a group of 32 students (selected from over 150 applications each year, and mainly from Europe), the symposia, taking place over an extended weekend, brought to Trieste an additional group of scientists, including many young ones but already well into their domains of expertise, for a concentrated discussion of a specific subject within the field. The interaction between course students (and faculty) and symposium participants added significant value to both the course and the symposia, and stimulated the development of close scientific relations between established and emerging scientists, particularly in Europe.

A reunion meeting

It thus seemed useful and appropriate to conclude the operation of the ESF network by holding a final meeting of all young people who, over the years, attended the EU course and the symposia. This final symposium was held again in conjunction with the 2002 EU Advanced Course, which from this year moved to Portugal, but in a separate location from the course, for a concentrated `reunion' weekend. The symposium was held in Belgais. The Belgais Center is a large farm in the countryside, away from civilization (near Castelo Branco, north-east of Lisbon and a bit less than two hours from Obidos, the course site), and close to some nice scenery for hikes and relaxation, that favoured scientific interactions. It has a large barn-turned-auditorium, which hosted the scientific sessions. It was possible to arrange for meals at the center, and some participants stayed at the center while the rest lodged in Castelo Branco (a 45 minutes drive). A bus carried course participants from Obidos on Friday afternoon, and took them back there on Sunday night. Another bus carried other participants from Lisbon airport and Lisbon downtown on Friday afternoon, and took them back there on Monday morning. The symposium thus provided a forum for all these young neuroscientists to present their research, allowing both for the strengthening of scientific links and collaborations and for an assessment of how the enterprise of promoting a new community of computational neuroscientists is progressing in Europe.

Participants

Talks were presented by

Rita Almeida, rita.almeida@neuro.ki.se Student in the 2000 EU course
28 years, Portuguese
Neuroscience Department
Retzius väg 8
Karolinska Institute
17177 Stockholm
Sweden
tel: + 46 8 728 7459
fax: + 46 8 309045
e-mail: rita.almeida@neuro.ki.se

Miguel Castelo-Branco, mcbranco@imagem.ibili.uc.pt Newly established independent researcher
35 yrs, Portuguese
IBILI
Center for Vision Sciences and Ophtalmology
Faculty of Medicine
Azinhaga de Santa Comba
3000-354 Coimbra
Portugal
tel 351 239 480286
fax 351 239 480280
email: mcbranco@imagem.ibili.uc.pt

Jörg Conradt, conradt@rubens.usc.edu Student in the 2001 EU course
27yrs, German
Institute of Neuroinformatics
University of Zurich and ETHZ
Winthherthurerstr 190
Zurich 8057
tel: +41 1 635 3023
fax: +41 1 635 3053
email: conradt@ini.phys.ethz.ch
web: www.ini.unizh.ch/~conradt

Philipp Häfliger, hafliger@ifi.uio.no Student in the 1996 EU course

32yrs, Swiss
Institute of Informatics
University of Oslo
Gaustadalléen 23
P.O.Box 1080 Blindern
Oslo 0316 Norway
tel: +47 22 84 01 18
fax: +47 22 85 24 01
email: hafliger@ifi.uio.no
web: www.ifi.uio.no/~hafliger

Antonia Hamilton, a.hamilton@ion.ucl.ac.uk Student in the 2001 EU course
25yrs, British
Institute of Neurology,
University College London
Queen Square, London, WC1N 3BG
Tel +44 20 7679 1138
e-mail: a.hamilton@ion.ucl.ac.uk
web: www.hera.ucl.ac.uk

Naoki Kogo, Naoki.Kogo@esat.kuleuven.ac.be Postdoc now joining the EU scientific community
44yrs, Japanese
ESAT/PSI
Katholieke Universiteit Leuven
Kasteelpark Arenberg 10,
Heverlee, B-3001
Belgium
tel: ++32 16 321894
fax: ++32 16 321723
email: naoki.kogo@esat.kuleuven.ac.be

Matt Lengyel, lmate@rmki.kfki.hu Student in the 2001 EU course
27yrs, Hungarian
Dept. Biophysics, KFKI Research Institute for Particle and Nuclear Physics
Hungarian Academy of Sciences
29-33 Konkoly-Thege M. ut
Budapest H-1121, Hungary
tel: +36-1-392-2222/3257
fax: +36-1-395-9151
email: lmate@rmki.kfki.hu
web: http://www.rmki.kfki.hu/biofiz/cneuro

Eirini Mavritsaki, e.mavritsaki@sheffield.ac.uk Student in the 2001 EU course
27yrs, Greece
Department of Psychology
University of Sheffield
302 Western Bank
Sheffield
S10 2TP
U.K.
tel +44 114 2226516
fax +44 114 2766515
e.mail : e.mavritsaki@sheffield.ac.uk

Nhamoinesu Mtetwa, nmt@cs.stir.ac.uk Student in the 2000 EU course
33 yrs, Zimbabwean
University of Stirling
Department of Computing Science and Mathematics
Stirling
FK9 4LA
SCOTLAND
Tel. 44 (0)1786 467457
Fax: +44 (0)1786 464551
email: nmt@cs.stir.ac.uk

Angel Nevado, anevado@delta.ft.uam.es Student in the 2001 EU course
29yrs, Spanish
Henry Welcome Building for Neuroecology
University of Newcastle upon Tyne
NE2 4HH
Newcastle upon Tyne
UK
tel: +44 191 222 5938
fax: +44 191 222 5622
email: angel.nevado@ncl.ac.uk
web: http://www.ncl.ac.uk/biol/

Tom Nielsen, t.nielsen@ucl.ac.uk Student in the 2001 EU course
25yrs, British/Danish
Department of Physiology
University College London
Gower St
London WC1E 6BT
tel: +44 207 679 3214

email: t.nielsen@ucl.ac.uk

Christo Panchev christo.panchev@sunderland.ac.uk Participant in the 2001 ESF symposium
Bulgarian
office 229, The Informatics Centre
School of Computing and Technologies
University of Sunderland
Sunderland SR6 0DD
United Kingdom
tel: +44 191 515 3680
fax: +44 191 515 2781
email: christo.panchev@sunderland.ac.uk
web: www.his.sunderland.ac.uk/christo

Arnd Roth, roth@sun0.mpimf-heidelberg.mpg.de Student in the 1996 EU course
31 yrs, German
Abteilung Zellphysiologie
Max-Planck-Institut für Medizinische Forschung
Jahnstr. 29
69120 Heidelberg
Germany
tel: +49 6221 486 467
fax: +49 6221 486 459
email: roth@mpimf-heidelberg.mpg.de
web: http://sunny.mpimf-heidelberg.mpg.de/people/roth/ArndRoth.html

Yasser Roudi, yasser@sissa.it PhD student now joining the EU sci. community
Iranian
Programme in Neuroscience
SISSA,via Beirut 2-4,I-34014
Trieste, Italy
Twl:+39 40 3787531
Fax:+39 40 3787528
e-mail: yasser@sissa.it
webpage: www.sissa.it/~yasser

Ausra Saudargiene, ausra@cn.stir.ac.uk Participant in the 2001 ESF symposium
31 yrs, Lithuanian
Department of Psychology
University of Stirling
Stirling FK9 4LA
Scotland

UK
tel. +44 1786 463177
email: ausra@cn.stir.ac.uk

Lars Schwabe schwabe@cs.tu-berlin.de German student in the 2000 EU course and currently tutor

Cristina Simoes, cristina@neuro.hut.fi Student in the 2001 EU

30yrs, Portuguese
Brain Research Unit
Low Temperature Laboratory
Helsinki University of Technology
Otakaari, 3A
FIN-02015 HUT
Finland
tel: +358 9 451 5319
fax: +358 9 451 2969
email: cristina@neuro.hut.fi
web: boojum.hut.fi

Volker Steuber volker@bbf.uia.ac.be Student in the 1997 EU course and currently tutor

35yrs, German
Laboratory of Theoretical Neurobiology
University of Antwerp - UIA
Universiteitsplein 1
Antwerp B2610
tel: +32 3 8202612
fax: +32 3 8202669
email: volker@bbf.uia.ac.be
web: www.bbf.uia.ac.be

Jan-Jan van der Vyver, janjan@ini.phys.ethz.ch Student in the 2000 EU course

27yrs, South African
Institute of Neuroinformatics
University of Zurich and ETHZ
Winthertherurerstr 190
Zurich, CH-8057
tel: +41 1 635 3066
fax: +41 1 635 3053
email: janjan@ini.phys.unizh.ch
web: www.ini.unizh.ch/~janjan

Steve Womble, steve@sissa.it Participant in the 2001 ESF symposium

32 British
Cognitive Neuroscience Sector
International School for Advanced Studies (ISAS/SISSA)
Trieste Italy
and
Informatics Department
University of Sunderland
Sunderland UK
email steve@sissa.it or steve.womble@sunderland.ac.uk

Discussions were stimulated by

Francesco Battaglia fpbatta@email.arizona.edu IEU course tutor
32yrs, Italian
ARL, Div. of Neural Systems, Memory, and Aging
University of Arizona
Rm. 384 Life Sciences North Bldg
Tucson, AZ 85719 U.S.A.
tel: +1 520 626 2312
fax: +1 520 626 2618
email: fpbatta@email.arizona.edu
web: www.nsma.arizona.edu

Dave Beeman dbeeman@dogstar.colorado.edu EU course computer faculty
63 yrs, American (USA)
Dept. of Electrical and Computer Engineering
425 UCB
University of Colorado, Boulder, CO 80309 USA
Phone:(303) 492-2852
Fax: (303) 492-2758
email: dbeeman@dogstar.colorado.edu
web: http://dogstar.colorado.edu/dbeeman/dbeeman.html

Erik De Schutter erik@bbf.uia.ac.be EU course faculty and former director
42yrs, Belgian
Born-Bunge Foundation
University of Antwerp
Universiteitsplein 1
B2610 Antwerp
tel: +32-3-8202616
fax: +32-3-8202669

e-mail: erik@bbf.uia.ac.be
web: www.bbf.uia.ac.be/

Rodney Douglas rjd@ini.phys.ethz.ch ESF network chair
Prof Rodney Douglas
54yrs, South African
Institute of Neuroinformatics
University of Zurich and ETHZ
WinthertHurerstr 190
Zurich 8059
tel: +41 1 635 3052
fax: +41 1 635 3025
email: rjd@ini.phys.unizh.ch
web: www.ini.unizh.ch

Harry Erwin harry.erwin@sunderland.ac.uk 2001 ESF symposium participant
55 yrs, American
University of Sunderland
School of Computing & Technology
PO Box 299
Sunderland
SR6 0YN
United Kingdom
tel: +44 (0)191 515 3227
fax: +44 (0)191 515 2781
email: harry.erwin@sunderland.ac.uk
web: www.cet.sunderland.ac.uk/~cs0her/

Vasco Galhardo galhardo@med.up.pt EU course organizer
32yrs, Portuguese
Faculty of Medicine of Porto
University of Porto
Alameda Pr Hernani Monteiro
4200-319 Porto - Portugal
tel: +351 22 6090840
fax: +351 22 5505728
email: galhardo@med.up.pt
web: gaia.ibmc.up.pt/groups/morphoph/galhardo

Bruce Graham, bpg@cs.stir.ac.uk EU former course tutor
43 years, Australian
Department of Computing Science and Mathematics,
University of Stirling
Stirling FK9 4LA

Scotland, U.K.
tel: +44-1786-467432
fax: +44-1786-464551
email: b.graham@cs.stir.ac.uk
web: www.cs.stir.ac.uk

Boris Gutkin gutkin@iaf.cnrs-gif.fr EU course tutor
36, USA
Gatsby Computational Neuroscience Unit
University College London
Alexandra House
17 Queen Sq
London WC1N 3AC
+44-20-7679-1187
boris@gatsby.ucl.ac.uk

Rolf Koetter rk@hirn.uni-duesseldorf.de Former EU course tutor and ESF symp. Participant
40yrs, German
Vogt Brain Research Institute
Heinrich Heine University
Moorenstr 5
D-40225 Dusseldorf
tel: +49 211 8112095
fax: ditto
email: rk@hirn.uni-duesseldorf.de
web: www.hirnforschung.net

Eurjeong Lee e.lee@nih.knaw.nl Now joining the EU scientific community
30yrs, Korean(South)
PFC workgroup,
Netherlands Institute for Brain Research,
Meibergdreef 33, 1105 AZ
Amsterdam, the Netherlands
tel. +31 20 566 5498
fax. +31 20 696 1006
email : e.lee@nih.knaw.nl
web: http://www.nih.nl/programs/groups/Cognition/intro.htm

Deolinda Lima limad@med.up.pt Portuguese, chair of the Portuguese Neuroscience society

Luis Mendonca ee96074@fe.up.pt Portuguese student in the 2000 EU course

Klaus Obermayer oby@cs.tu-berlin.de German, EU course director
40 years, German
Fakulta"t f"ur Elektrotechnik und Informatik
Technische Universit"at Berlin
FR2-1, Franklinstrasse 28/29
Berlin 10587
tel: +49 30 314 73442
fax: +49 30 314 73121
email: oby@cs.tu-berlin.de
web: www.ni.cs.tu-berlin.de

Soon-Lim Shin, ssl21@hanmail.net Student in the 2000 EU course
32yrs, South Korean
Lab of Theoretical Neurobiology
University of Antwerp
Universiteitsplein 1
B2610
tel: +32 3 820 2610
fax: +32 3 820 2669
email: soonlim@bbf.uia.ac.be
web: www.bbf.uia.ac.be

Alessandro Treves ale@sissa.it EU course director and ESF symposium organizer
42yrs, Italian
Cognitive Neuroscience sector
SISSA (Intern. Sch. for Adv. Studies)
via Beirut 4
34014 Trieste, Italy
tel: +39 040 3787 426
fax: +39 040 3787 528
email: ale@sissa.it
web: www.sissa.it/~ale/

Hui Wang, hwang@esf.org ESF representative to the symposium

Florentin Woergoetter worgott@cn.stir.ac.uk 2001 ESF symposium participant
42 yrs, Austrian
Dept. of Psychology
University of Stirling
Stirling FK9 4LA

tel.: +44 1786 466369
fax: +44 1786 467641
email: worgott@cn.stir.ac.uk
web: www.cn.stir.ac.uk

And by **30 EU course students** (see separate list at the end)

Scientific programme

Saturday August 31, morning	**Opening** by Rodney J Douglas **Introduction** by Hui Wang **Session I** Arnd Roth Ausra Saudargiene Antonia Hamilton Tom Nielsen	The mission of the ESF network How ESF operates **Biophysics-based computations** Predicting the function of neurons from their morphology Biophysical re-evaluation of a linear model for temporal sequence learning Muscle noise in motor control Glutamate diffusion and spillover at a cerebellar synapse
Saturday August 31, afternoon	**Session II** Yasser Roudi Matt Lengyel Lars Schwabe Christo Panchev Volker Steuber Steve Womble **Concert** by Maria João Pires	**Neural network computations** Mixture states in realistic associative memories Feed-forward networks of the hippocampus: one architecture - two dynamical modes Successive refinement coding in the visual system? Self-organization and association in networks of spiking neurons with active dendrites Pattern recognition in the cerebellar cortex A model of complex temporal sequence processing using neocortical hardware Schubert Piano Sonata D960
Sunday September 1, morning	**Session III** Rita Almeida Angel Nevado Eirini Mavritsaki Cristina Simoes **Address** by Deolinda Lima	**Imaging and computation** Modeling the link between functional imaging and neuronal activity: synaptic metabolic demand and spike rates Estimation of the encoded information in the brain with functional imaging Modelling the NMR response during classical conditioning Phase-locked activity between human SI and SII cortex Welcome from Portuguese Neuroscience

	Workshop by M. J. Pires	Body control and awareness
Sunday September 1, afternoon	Miguel Castelo-Branco **Session IV** Nhamoinesu Mtetwa Philipp Häfliger Jörg Conradt Naoki Kogo Jan-Jan van der Vyver	Neural correlates of global motion perception, as revealed by fMRI **Using neural computation in applications** Stochastic resonance and limited precision in a network of LIFs Examples of spike processing electronic systems Detecting landmarks for robot navigation in natural environments Reconstruction of subjective surfaces from occlusion cues: a feedback model An interface between autonomous robots and humans

Abstracts

Biophysics-based computations

Predicting the function of neurons from their morphology

Arnd Roth

Abteilung Zellphysiologie, Max-Planck-Institut für Medizinische Forschung, Jahnstr. 29, 69120 Heidelberg, Germany

How does dendritic morphology shape the functional architecture of different types of neurons? Using compartmental models of reconstructed neurons endowed with the same distribution of active conductances we isolate morphology as the only variable. We show that the spread of subthreshold synaptic potentials, the forward- and backpropagation of action potentials in dendrites as well as the interaction of somatic and dendritic action potential initiation sites is tuned by subtle details of the dendritic branching pattern.

Biophysical re-evaluation of a linear model for temporal sequence learning

Ausra Saudargiene

Department of Psychology, University of Stirling, Stirling FK9 4LA, Scotland, UK

The goal of this work is to relate the ISO-learning (Isotropic Sequence Order) rule to the biophysical effects of spike-timing dependent plasticity (STDP) at a single neuron. The ISO learning algorithm (Porr and Wörgötter, 2001) is a linear, rate-coded, drive-reinforcement learning rule for temporal sequence learning. It learns the temporal correlation between the conditioned and unconditioned inputs and shifts the output response forward in time, so that it will occur earlier. The resulting weight change depends on the relative timing between the onsets of the conditioned and unconditioned inputs. To calculate the weight change the learning rule uses the product of the band-pass filtered inputs and the temporal derivative of the output. The resulting characteristic is similar to STDP in its anti-symmetrical shape, but based on rate coded inputs.

The question arose if the same learning rule could be applied in a single-compartment spiking neuron model and whether it would again lead to the same (or a similar) anti-symmetrical weight change curve.

Our model contains a NMDA synapse called the "plastic synapse" receiving pre-synaptic spikes. STDP depends on the correlation of pre- and postsynaptic events. Thus, we introduce a membrane depolarisation postsynaptic to the synapse and arising from another source (as discussed below), and consider this as the postsynaptic or "driving" event. These assumptions are based on the facts that the NMDA-receptor channel is vital in triggering STDP and that its conductance is voltage-dependent. The source of depolarisation (driving event) was modelled by one of 1) and AMPA driving synapse 2) an NMDA driving synapse or 3) a back-propagating spike event.

We calculated the weight change of the so called plastic NMDA synapse using the ISO-learning rule. The band-pass filtered input was assumed to be represented by the synaptic conductance function of

the plastic synapse. This was multiplied by the derivative of the membrane potential in order to emulate the ISO-learning rule. In the simulations we fed a spike pair to the plastic NMDA synapse and the driving synapse. In case of a back-propagating spike, we modelled it by injecting a current at the predefined time. This pulse sequence was repeated 10 times with the long intervals between the pairs of spikes to avoid the interdependences. The time difference between spikes was varied from -50 to 50 ms, and the change of the weight of the plastic synapse was plotted versus this temporal difference.
In all cases the ISO-learning rule leads to an anti-symmetrical weight change curve, which has the most realistic form when the back-propagating spike is used as a driving event. We were able to show that the shape of the STDP curve depends on both the plastic synapse's characteristics and the change of the membrane potential under it. The results indicates that ISO-learning rule leads in a generic robust way to STDP in a spiking neuron model.

The role of muscle noise in motor control

Antonia Hamilton

Sobell Dept of Motor Neuroscience and Neurophysiology, Institute of Neurology, University College London, UK

Signal-dependent noise causes variability in all voluntary movements, but it not known what factors in the motor unit pool and muscle cause this noise, or how the noise varies across muscles. By comparing voluntary force generation to force generation induced by neuromuscular electrical stimulation, I show that muscle noise is not due to peripheral factors such as the neuromuscular junction. A simulation of the muscle and motor neuron pool demonstrates that the orderly recruitment of motor neurons is a critical factor in generating signal-dependent noise. The second experiment compares the coefficient of variation of muscle noise to muscle strength for four muscle of the arm. I show that there is as muscle strength increases, muscle noise decreases in a logarithmic fashion. This result is predicted by the model of the motor unit pool, where the number of motor units in a muscle determines the level of noise in a muscle. These results are used to derive new cost functions which predict how the muscles of the arm should be used to minimise the consequences of signal-dependent noise in voluntary movement.

Release probability dependent changes in the AMPA-receptor EPSC waveform

Tom A. Nielsen

Institute of Neurology, University College London, UK

At many glutamatergic synapses in the central nervous system, the evoked synaptic conductance waveform is dependent on the release probability, such that in low extracellular calcium concentrations, the current decay accelerates. This non-linearity has typically been ascribed to spillover of released glutamate between neighbouring active zones, but it is unclear by which mechanism glutamate spillover would cause an acceleration. Using simulations of the linear diffusion of glutamate in the synaptic cleft following stochastic release at multiple release sites, we show that the acceleration is also not caused by an effect of the number of released vesicles per trial. We recorded isolated spillover currents at multiple release probabilities at the cerebellar mossy-fibre to granule cell synapse, and show that the magnitude of these currents plotted against the likely release probability fits the Hill equation with a Hill coefficient similar to that reported for AMPA receptors. It is therefore likely that the acceleration is caused by non-linear activation of postsynaptic glutamate receptors.

Neural network computations

Disappearance of spurious states in analog associative memories

Yasser Roudi

SISSA - Programme in Neuroscience, via Beirut 4, 34014 Trieste, Italy

We show that symmetric *n*-mixture states, when they exist, are almost never stable in autoassociative networks with threshold-linear units. Only with a binary coding scheme and full connectivity we could find a limited region of the load-sparsity plane in which either 2-mixtures or 3-mixtures are stable attractors of the dynamics.

Feed-forward networks of the hippocampus: one architecture - two dynamical modes

Máté Lengyel

Neuroscience Sector, SISSA, Trieste, Italy; and Department of Biophysics, KFKI Research Institute for Particle and Nuclear Physics, Hungarian Academy of Sciences, Budapest, Hungary

Properly tuned receptive fields in feed-forward networks depend on topographical input (afferent cells with properly tuned receptive fields connect topographically to their postsynaptic partners with little or no convergence/divergence) or on attractor network dynamics provided by specfic intra-layer lateral connections (recurrent excitation/inhibition). For hippocampal place cells neither might be availabe. We investigated how theta oscillation can transform the dynamics of a simple feed-forward network without topographical input or recurrent connections so that tuning curves of individual cells remain sharp in spite of the considerable convergence/divergence between layers. The mechanism is also shown to be appropriate for describing fine details of place cell firing.

Successive refinement coding in the visual system?

Lars Schwabe

TU-Berlin, Dept. of Computer Science and Electrical Engeneering, Franklin Str. 28/29, 10587 Berlin, Germany

Rapid adaptation is a prominent feature of biological neuronal systems. From a functional perspective the adaptation of neuronal properties, namely the input/output relation of sensory neurons, is usually interpreted as an adaptation of the sensory system to changing environments as characterized by their stimulus statistics. Here we argue that this interpretation is only applicable as long as the adaptation processes are slower than the time-scale at which the stimulus statistics change. We present a definition of optimality of a neuronal code which still captures the idea of efficient coding, but which can also explain rapid adaptation without referring to an adaptation to different sensory environments. Finally, we apply our new idea to a simple model of an orientation hypercolumn in the primary visual cortex and predict that the interactions between orientation columns should adapt at the time-scale of a single stimulus presentation. We also simulate a network of conductance-based point neurons and show that the spike-frequency adaptation of the simulated excitatory neurons may serve as the underlying mechanism to realize the dynamic adaptation of the interactions between orientation columns predicted with the simple model.

Self-organization and association in networks of spiking neurons with active dendrites

Christo Panchev

School of Computing & Technology, University of Sunderland, UK

Presented is a model of an integrate-and-fire neuron with active dendrites and a spike-timing dependent Hebbian learning rule. The learning algorithm effectively trains the neuron when responding to several types of temporal encoding schemes: temporal code with single spikes, spike bursts and phase coding. The neuron model and learning algorithm are tested on a neural network with a self-organizing map of competitive neurons. The goal of the described work is to develop computationally efficient models rather than approximating the real neurons. The presented approach demonstrates the potential advantages of using the processing functionalities of active dendrites as a novel paradigm of computing with networks of artificial spiking neurons.

Synaptic plasticity and pattern recognition in the cerebellar cortex

Volker Steuber

Laboratory of Theoretical Neurobiology, University of Antwerp, Universiteitsplein 1, B 2610 Antwerp, Belgium

One of the most contentious issues in cerebellar research is how long-term depression (LTD) of parallel fibre (PF) synapses can implement learning in cerebellar Purkinje cells. According to classic theories of cerebellar learning, the storage of PF patterns by LTD leads to a reduced PC response, disinhibition of neurons in the cerebellar nuclei and increased output from the cerebellum. In this talk, I will present simulation results which cast some doubt on this assumption. When PF activity patterns are stored in a biologically realistic Purkinje cell model with active dendrites, the only criterion that can be used to distinguish stored and novel patterns is the length of the simple spike pause that occurs shortly after presentation of a PF pattern. Contrary to the classic view, stored PF patterns elicit shorter simple spike pauses and result in an increased Purkinje cell output. The performance of the model improves with an increased amount of extrinsic noise in the form of PF background input and is insensitive to different kinds of intrinsic noise and to temporal jitter in the PF input patterns. The results show that the use of oversimplified models can lead to erroneous results and emphasize the importance of modelling on several levels of complexity.

Plasticity in the phonological system: evidence from the tip-of-the-tongue phenomenon.

Steve Womble

University of Sunderland, UK, and SISSA, Trieste, Italy

In this study, we use a psychopharmacological paradigm to investigate the neurobiology underlying the tip-of-the-tongue (TOT) phenomenon. In particular we examine the plasticity mechanisms involved. We propose that Ca++ mediated presynaptic short term plasticity in cells located within the phonological retrieval system can account for previously reported phonological priming effects on TOT. Using caffeine as a pharmacological agent known to affect short term plasticity, we performed a psycholinguistics experiment investigating phonological priming and TOT in which participants took either 200mg of caffeine, or placebo. Our results show a clear priming effect for the caffeine group when presented with phonologically related words. However when primed with phonologically unrelated words this group showed a strong interference effect. This is consistent with our prediction of the effects of Ca++ on the neural system. Further this interference effect (resulting in a significant increase in the number of TOTs) provides strong evidence that the positive priming effect seen for the caffeine group is not due to other effects of caffeine. However we found no evidence of a priming effect in placebo conditions. Instead we found a weakly significant interference effect when participants were primed with phonologically related words. Contrary to previous published work we conclude that both a priming and a blocking effect exist and account for the latter within our model by the action of K+ channels.

Imaging and computation

Modeling the link between functional imaging and neuronal activity: synaptic metabolic demand and spike rates

Rita Almeida

Karolinska Institute, Stockholm, Sweden

Functional Magnetic Resonance Imaging (fMRI) and Positron Emission Tomography (PET) signals reflect changes in the hemodynamics, which are thought to be associated with local synaptic input to neuronal populations. However, it is the local neuronal spiking activity which is believed to be responsible for the processing of information in the brain. The aim of this work is to characterize the relationship between synaptic activity and neuronal spike rates, averaged over brain areas. A mean-field neuronal model of recurrently coupled excitatory and inhibitory neuronal populations is used. A non-linear relationship between average spiking and synaptic activities is found when:

1. the local synaptic strengths vary, 2. the external inputs vary, 3. the level of synchronization between oscillations of the average spike rates of two areas changes.
Situations where an increase in the imaging signal reflects a decrease in average spiking activity or silent neuronal populations are also described.

Estimation of the information encoding in different brain areas with functional imaging techniques

Angel Nevado

Department of Psychology University of Newcastle upon Tyne. UK

We study the suitability of estimating the information conveyed by the responses of the populations of neurons in the brain by using the signal provided by imaging techniques like functional Magnetic Resonance Imaging (fMRI). The fMRI signal is likely to reflect a spatial averaging of the neuronal population activity. On the other hand, knowledge of the activity of each single neuron is needed in order to calculate the information. We explore this potential limitation by means of a simple computational model based on known tuning properties of individual neurons. We investigate the relationship between the information transmitted by the population, the signal change and the signal information as a function of the neuronal parameters. We find that the relationship is in general very different from linear. This result should be taken into account when comparing the information encoded by different brain areas with functional imaging techniques.

Modeling the NMR response during classical conditioning

Eirini Mavritsaki

Department of Psychology, University of Sheffield, UK

Although the nictitating membrane response (NMR) is important for understanding the neural bases of classical conditioning, its low-level motor control is incompletely understood. Possible mechanisms of motor-unit recruitment for the NMR were investigated by comparing the predictions of a population model with data from EMG recordings. The model was based on that described by Bartha & Thompson (1992). Each motor unit of the retractor bulbi muscle was represented by a Hill-type model, driven by a non-linear activation mechanism designed to reproduce the isometric force measurements of Lennerstrand (1974). Globe retraction and NM extension were modeled as linked second order systems. EMG data were obtained from multi-unit electrodes during NMR conditioning using a tone CS and periocular shock US.
In the first study data from the orbicularis oculi (OO) muscle was used. Putative action potentials were extracted from the EMG records by linear predictive coding, and compared with the NMR traces on CS alone trials. Results from this study suggest that the relationship between EMG spikes and NMR position can be approximated by a third-order linear filter over at least a two-fold range of frequencies. In contrast, the model is linear with respect to motoneuron firing rate over only a narrow range of frequencies (~80-110 Hz). The model therefore predicts that the increased firing during CR

development results more from the recruitment of new motor units than from higher frequency firing in units already recruited.
In the following study data from RB muscle was used. The data was obtained from multi-unit electrodes during classical conditioning using a tone CS and periocular shock/air puff US. In this work qualitative evidence suggest that the increased firing is due to recruitment.
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Phase-locking between human SI and SII cortices

Cristina Simões

Brain Research Unit, Low Temperature Laboratory, Helsinki University of Technology, Finland

Unilateral stimulation of human peripheral nerves activates the primary somatosensory cortex (SI) contralaterally and the secondary somatosensory cortices (SII) bilaterally. Phase-locking between brain regions has been proposed to either reflect joined processing or information exchange. We aimed at characterizing phase-locking between SI and SII cortices in response to electric stimuli applied once every 3 s to the right median nerve at the wrist. Ongoing neuromagnetic activity of 10 healthy volunteers was recorded with 204 planar gradiometers covering the whole scalp. After selecting a sensor maximally sensitive to the left (contralateral) SI, phase-locking between this sensor and the other 203 sensors was examined from single trial data. Statistically significant phase-locking was found around 20 Hz, 80–90 ms after the stimuli between the left SI (SIL) and the ipsilateral secondary somatosensory cortex (SIIR) in 9 subjects. Sensors with high phase-locking values over SIL and SIIR were separated by sensors with no phase-locked activity over the scalp midline, indicating that the phase-locking was not due to the sensors seeing the same source. The observed SI-SII phase-locking would not be reflected in the evoked responses because a considerable part of it was not time-locked to the stimuli. Thus our finding reveals a novel interaction in the somatosensory system.

Neural correlates of global motion perception, as revealed by fMRI

Miguel Castelo-Branco

IBILI, Faculty of Medicine, Coimbra, Portugal

The human MT complex (hMT$^+$) is known to be involved in motion perception, but it is not known how its activity is related to the computation of global motion. In particular, it is still unclear how hMT$^+$ contributes to the interplay between segmentation/integration mechanisms in emerging representations of moving surfaces.
We asked which areas of the human visual brain disambiguate whether motion signals coming from overlapping contours arise from single or multiple surfaces. This question can be examined using stimuli formed by superimposed moving gratings (plaids). These are perceived either as sliding in different directions (component motion, (CM)) or as a single coherent pattern moving in the intermediate direction (pattern motion, (PM)). With this paradigm we could assess two critical questions: First, whether MT is a substrate for perceptual decision between alternate discordant interpretations. Second, whether it represents motion in a manner consistent with the existence of a

winner-take-all model, or, in contrast, it would also allow for activity patterns consistent with the simultaneous representation of multiple surfaces.
In the present fMRI experiments we presented unambiguous plaid stimuli, that biased subjects' perception toward PM or CM, and ambiguous plaid stimuli, that induced spontaneous switches between both types of percept. During measurements, subjects (n = 10) reported their percepts by means of button presses. Data analysis included both hypothesis (multiple regression) and data-driven (cortex-based independent component analysis, cbICA) analysis of fMRI time-series.
Plaid motion was highly effective in specifically activating hMT^+. Both for unambiguous and ambiguous stimuli, activity in this area was highly correlated with the perceptual reports of the subjects. This effect was observed also in dorsal areas to which hMT^+ projects, but not in primary visual cortex. CM (two-surface perception) evoked higher activation than PM (one-surface perception). One cortical component, that included hMT+, a network of dorsal areas and the sensorimotor cortex contralateral to the hand of button-press could be reliably obtained with cbICA. The increased activation level during component motion over pattern motion is consistent with the assumption that hMT^+ represents segregated assemblies for multiple surfaces moving in different directions. Since stimulus features were kept constant during the ambiguous plaid condition, these results uncover a functional correlate of perceptual interpretation within hMT+. Our study is consistent with the presence of a directional map in MT+ and suggests that it can support not only one global representation but also multiple motion representations.

Using neural computation in applications

Stochastic resonance and limited precision in a network of LIFs

Nhamoinesu Mtetwa

Computer Science, University of Stirling, Scotland, UK

We have realised SR in a network of leaky integrate-and-fire (LIF) neurons on both a floating point (FP) platform (Java) and an integer platform (FPGA). SR in digital systems has been associated with FP implementation. We have shown that SR is possible on lower resolution integer based digital hardware such as an FPGA. We present results for both a single neuron and a 2-layer network of LIF neurons.

Examples of spike processing electronic systems

Philipp Häfliger

Institute of Informatics, University of Oslo, PO Box 1080, Blindern, N-0316 Oslo, Norway

Neurophysiologists find ever more hints, that neurons transmit relevant information about a stimulus with just a few or even just one action potential. The exact timing of those spike signals seems to be meaningful. The general concept is known as 'temporal coding'. At present there is much speculation going on, on how exactly the nervous system uses spike timing to encode information. A small number of models have been proposed so far.

Our group at the Institute for Informatics at the University of Oslo is fascinated by the prospects of temporal encoding that is so different from synchronous digital encoding methods or purely analog data representation. We try to apply the concept in electronic circuits to solve concrete problems. We hope to get insight in the strength and limitations of some models in real physical implementations. Thus we can give feedback to the neuroscience community and develop novel electronic computation devices.

In this talk I will introduce our implementation of one such device that uses 'latency encoding', a concrete temporal coding scheme. The integrated circuit computes the mutual shift in a one-dimensional stereo picture. Developing this circuit it turned out that many analog operations on latency encoded signals can actually be performed by asynchronous digital logic. Also the sources of noise and the measures to improve signal to noise ratio turned out to be different from analog circuits.

Detecting Landmarks for Robot Navigation in Natural Environments

Jorg Conradt

Institute of Neuroinformatics, ETH / University Zurich, CH

The goal of this project is finding salient objects for landmark-based navigation on a mobile robot in natural environments. Once landmarks are detected, the algorithm estimates their relative positions to the robot (e.g. their x, y, and z coordinates). The only input used is a stereo video signal from two pan-tilt cameras mounted on the robot.
The principle idea of finding landmarks in the environment is based on a saliency map ([1], [2]). Feature detectors are used to decompose both original images independently and to provide stimulus for neurons in saliency maps. Neurons with many active inputs (e.g. at the corner of a bright object on dark background) increase their activity and simultaneously suppress other neurons in the map. Once the activity in the saliency map exceeds a threshold, the focus of attention will be directed to that point. In this project, the pan-tilt system will direct the camera to that point.
If both images from the stereo camera were taken under ideal conditions, the first spots found independently in both images would correspond to each other, as would the second, the third, and so on. However, mismatch will occur due to different viewing areas of both cameras, noise in the signals, varying lighting conditions, etc. To avoid the problem of mismatching points, the corresponding feature detectors in both images are coupled (left and right camera). Therefore, the same features found in both images enhance each other, whereas contradictory features suppress each other. This interaction only occurs in a limited vertical range (corresponding points must be on the same height because of horizontally mounted cameras). In the horizontal direction, however, the width of the interaction varies in a wide range and can incorporate prior knowledge about the expected depth of objects.
Additionally, an interaction between both saliency maps is introduced, such that activity at any place excites the corresponding region in the other map. Once the most salient locations in both maps exceed a threshold, the pan-tilt unit focuses on that point. Knowing the object’s positions in both images and both cameras’ pan-tilt angles, the object’s real world position can be computed. For convenience reasons, a multiplayer perceptron is used to perform the mapping from 8D-space (x, y, pan- and tilt angle from both images) to 3D-coordinates (x, y, and z) relative to the robot.

Finally, I will give a short outlook on how we imagine storing visual object properties for later retrieval from different spatial positions.

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[2] L. Itti and C. Koch (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. Vision Research, 40(10-12):1489-1506, 2000.

Reconstruction of subjective surfaces from occlusion cues: a feedback model

Naoki Kogo

Katholieke Universiteit Leuven, Belgium

In a Kanizsa figure, illusory contours as well as a subjectively brighter central area are perceived. Replacing the pacman figures to L shaped corners or crosses causes either a reduction or a complete disappearance of the subjective properties. This indicates that a detection of macroscopic properties of the figure is involved in the illusory perception. A model has to implement a function that responds to this property.

We developed a model based on a hypothesis as followings. When these figures are presented, the brain is trying to figure out the depth order of the objects in the image while the conflict between the macroscopically detected feature and the original input causes the illusion. This is realized by a feedback model based on the surface completion scheme. The model used, a "half Gaussian derivative" filter to detect junctions in the image, and "differentiated signal" of the depth measurement, by which the depth relationship between the two areas is expressed. Surfaces with a depth rank order determined by the junction properties were reconstructed by applying a diffusion equation to this signal. And, finally, the original image is modified based on the reconstructed surface map and the result is fed back into the first step to iterate the whole procedure.

This model showed responses to a wide variety of Kanizsa type figures that are consistent with psychophysical experiments. In addition, the iteration of the feedback loop kept enhancing the effect. To make the model more robust, the precise method for the feedback modification of the input image, are being developed.

An interface between autonomous robots and humans

Jan-Jan van der Vyver

Institute for Neuroinformatics, UniZH / ETHZ, CH

Being capable of judging and predicting the state of an autonomous system, and thereby its actions, my be considered the most important part of human-machine interaction. In the case of "embodied" machines this requires communicating the inner state, without disregarding the "Eigenleben". In our solution we used aesthetics as a guideline to map the internal states onto fractals. The evolution of these patterns through time facilitated prediction. The solution is in keeping with the princple of least action, and the mappings were justified using a novel complexity measure. The proposed ideas were implemented as a component of the Ada project of the Swiss national exhibition "EXPO02".

EU course student participants

Andersen, Tobias (Danish, male)
Helsinki University of Technology, Finland
e-mail: tobias@lce.hut.fi
project: A cellular Bayesian integrator

Anishchenko, Anastasia (Belarussian, female)
Brown University Providence, USA
e-mail: anish@holley.physics.brown.edu
project: Small-World Network of Integrate-and-Fire Neurons

Arabzadeh, Ehsan (Iranian, male)
SISSA Trieste, Italy
e-mail: ehsan@sissa.it
project: A computational model for psychophysical adaptation

Babadi, Baktash (Iranian, male)
IPM Tehran, Iran
e-mail: baktash@ipm.ir
project: A feed-forward model for visual backward masking

Badoual, Mathilde (French, female)
CNRS Gif-sûr-Yvette, France
e-mail: Mathilde.Badoual@iaf.cnrs-gif.fr
project: Model for temporally asymmetric synaptic plasticity

Baker, Tanya (USAmerican, female)
University of Chicago, USA
e-mail: tibaker@midway.uchicago.edu
project: Implementing the Retinex Algorithm

Cho, Raymond (Canadian, male)
University of Pittsburgh, USA
e-mail: chory@msx.upmc.edu
project: Memory model

Cozzi, Laura (Italian, female)
University of Genova, Italy
e-mail: laura.cozzi@dibe.unige.it
project: Effects of intrinsic resonance frequencies of neurons at network level

De la Rocha, Jaime (Spanish, male)
Universidad Autonoma de Madrid, Spain
e-mail: jaime.delarocha@uam.es
project: Stimulus discrimination by population bursts in a network with short-term plasticity

Dodla, Ramana Reddy (Indian, male)
New York University, USA
e-mail: dodla@cns.nyu.edu
project: Mathematical modeling

Gollisch, Tim (German, male)
Humboldt Universitaet Berlin, Germany
e-mail: gollisch@itb.biologie.hu-berlin.de
project: Model for Grasshopper Song Detection

Goncalves, José (Portuguese, male)
Max-Planck Int. Research School for Neurosciences Goettingen, Germany
e-mail: j.goncalves@stud.uni-goettingen.de
project: How to track and model labeled membrane proteins?

Griffin, Sarah (British, female)
University College London, UK
e-mail: s.griffin@ucl.ac.uk
project: Mechanisms of binaural interactions

Gupta, Anirudh (Indian, male)
The Weizmann Institute Rehovot, Israel
e-mail: anirudh.gupta@weizmann.ac.il
project: Simulation of networks with diverse dynamic excitatory and inhibitory synapses

Hall, Catherine (British, female)
University College London, UK
e-mail: catherine.hall@ucl.ac.uk
project: Nitric oxide in the brain

Le Franc, Yann (French, male)
INSERM Bordeaux, France
e-mail: yann.lefranc@bordeaux.inserm.fr
project: Quantification of information transfer through the dorsal horn network

Longden, Kit (British, male)
University of Edinburgh, Scotland
e-mail: kit@anc.ed.ac.uk
project: CA1 pyramidal cell calcium concentration in experimental epilepsy

Marian, Ioana (Romanian, female)
University College Dublin, Ireland
e-mail: Ioana.Marian@ucd.ie
project: Self-organization of active dendrites for pattern discrimination

Oliveira, Rodrigo (Brazilian, male)
University of Sao Paulo, Brazil
e-mail: rodrigo@neuron.ffclrp.usp.br
project: Curvature Detection in Primary Visual Cortex A Possible Mechanism

Pettersen, Klas (Norwegian, male)
Agricultural University Aas, Norway
e-mail: klas.pettersen@itf.nlh.no
project: Modeling ion channels

Pipa, Gordon (German, male)
MPI for Brain Research Frankfurt, Germany
e-mail: pipa@mpih-frankfurt.mpg.de
project: Spiking behavior of a neuron in dependence of the statistic of input spike trains

Ponomarenko, Alexei (Russian, male)
Universitaet Duesseldorf, Germany
e-mail: alexei.ponomarenko@uni-duesseldorf.de
project: Theta rhythm modulation by histamine in septo-hippocampal network

Scorcioni, Ruggero (Italian, male)
Krasnow Institute Fairfax, USA
e-mail: rscorcio@gmu.edu
project: Analysis of Granule Cells of the Rat Dentate Gyrus

Solinas, Sergio (Italian, male)
University of Antwerp, Belgium
e-mail: sergio@bbf.uia.ac.be
project: Advanced model for Molecular Layer Interneurons in the Rat Cerebellar Cortex

Troncoso, Xoana (Spanish, female)
University College London, UK
e-mail: x.troncoso@ucl.ac.uk
project: Modeling the early visual system

Van Rijsbergen, Nicola (British, female)
University of Edinburgh, Scotland
e-mail: njvr@anc.ed.ac.uk
project: Action of Dopamine at perforant path synapses in CA1

Vervaeke, Koen (Belgian, male)
University of Oslo, Norway
e-mail: k.g.vervaeke@basalmed.uio.no
project: A-current function in frequency dependent spike broadening

Weiland, Claus (German, male)
Universitaet Frankfurt, Germany
e-mail: weiland@zoology.uni-frankfurt.de
project: A multi-threaded solver for nerve equations

Wojcik, Grzegorz (Polish, male)
Marie-Curie-Sklodowska University Lublin, Poland
e-mail: gmwojcik@neuron.umcs.lublin.pl
project: Computations on Spikes and LSM

Yousif, Nada (British, female)
University of Plymouth, UK
e-mail: nada.yousif@plymouth.ac.uk
project: The synchronizing power of corticothalamic feedback