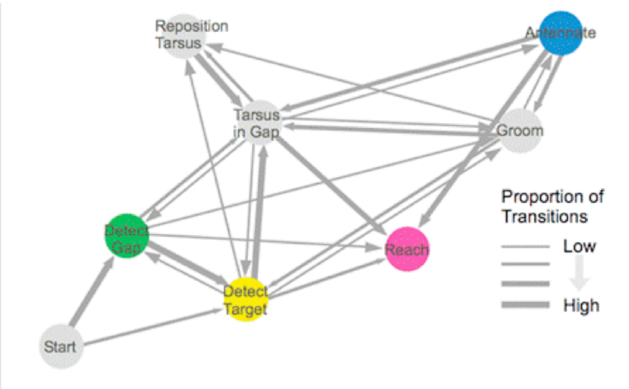
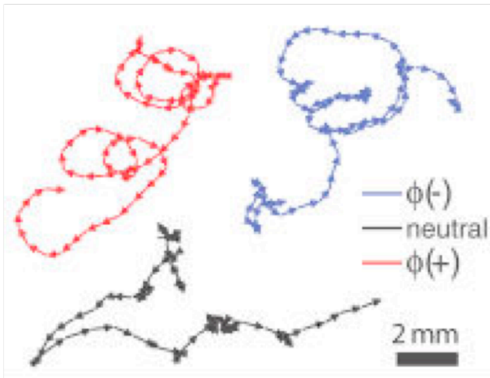
Quantitative Models of Natural Behaviour

Workshop 11 at CNS 2009 (Berlin, Germany) - 22-23rd July 2009
Organizers: **Aldo Faisal** (Cambridge) & **Greg Stephens** (Princeton)
Location: **Hilton Berlin**

Workshop website: http://www.cnsorg.org/meetings/archives/CNS2009.shtml
Further information: http://qmob.org





While we record the precision of an action potential with microsecond accuracy and characterize the impact of single amino acids on protein function, we often describe the behavior of a whole organism by eye. We seek to address this imbalance and sharpen our fundamental understanding of neural computation by organizing a 2-day workshop composed of an interdisciplinary set of speakers, both computational and experimental, engaged in quantitative behavioral analysis of a variety of systems from simple organisms via Drosophila and mice to humans.
The need for the quantitative study of behaviour in genetic organisms is becoming increasingly pressing, as we can readily capture approximately exhaustive set of intrinsic behavioral coordinates as well as neural recording and genetic manipulations. A major challenge in analyzing behavior is to discover an underlying simplicity, which reflects the underlying mechanisms that generate it. Moreover such an analysis should preserve natural variability and not average out as it often contains meaningful information about the generating mechanisms.

This workshop is intended to address two main questions:
1. How should we build models that quantify natural behavior, such that behavioral variability is reflected in a full, yet tractable manner?

2. How can we use these models to relate underlying behavioral mechanisms to neural and genetic data?

We believe that advanced statistical and probabilistic methods can be used to analyse the unconstrained natural behaviour including relevant variability. This approach offers a principled route to extract relevant features of behavioural performance and compare individual animals in a more objective manner than using highly constrained behavioural experiments. Moreover these models can be generative in nature providing us with an objective measure to distinguish between observed behaviours.

Workshop program

<u>Day 1 (22nd July)</u>

18:30 Greg Stephens (Princeton)

19:15 Aldo Faisal (Cambridge) (stand-in talk)

19:45 Stephen Shepherd (Princeton)

20:30 Wrap-up discussion evening

20:45 Dinner (Restaurant Malatesta)

<u>Day 2 (23rd July)</u>

9:30 Barry Dickson (Vienna)

10:15 Alex Gomez (Barcelona)

11:00 Coffee break

11:15 Nina Vogt (Columbia)

12:00 Holger Krapp (Imperial)

12:45 Wrap-up discussion morning

13:00 Lunch break

14:00 Zachary Mainen (Champalimaud/Instituto Gulbenkian de Ciencia)

14:45 Leslie Osborne (UCSF)

15:30 Aldo Faisal (Cambridge)

16:15 Coffee and tea break

16:45 Andrea Cavagna (Rome I)

17:30 Dirk Brockmann (Northwestern)

18:15 Netta Cohen (Leeds)

19:00 Summary & Discussion (Aldo and Greg)

20:30 Farewell drinks

Dirk Brockmann (Northwestern)

Money Circulation, Trackable Items, Scaling laws and Universal Human Mobility Patterns

Travel in our globalised world has reached a complexity and volume of unprecedented degree. More than 60 million people travel billions of kilometres on more than 2 million international flights each week. Human mobility is responsible for the geographical spread of emergent human infectious diseases and plays a key role in human mediated bioinvasion. Understanding human mobility patterns on multiple scales is thus of fundamental importance. Pervasive user generated data represents a novel and promising source of information and promising opportunities for the indirect yet precise assessment of human mobility. I will report on the recent discovery of scaling laws in global human mobility based on the analysis of the geographic circulation of over 10 million dollar bills registered at the popular bill tracking website www.wheresgeorge.com. I will present recent results obtained from a complex network analysis of the data, present unviseral properties of multiscale human mobility networks and show that they can be used to identify geographically coherent communities that only vaguely resemble those provided by geopolitical ones and that provide an operational segmentation of maps into a hierarchical set of regions and boundaries. I will briefly talk about European transportation networks, geocaching and trackable items.

Andrea Cavagna (Roma I)

Group-spanning correlations enhance collective response in bird flocks

From bird flocks to fish schools, animal groups often seem to react toenvironmental perturbations as if of one mind. The nature of the information transfer mechanism granting such striking coherence is still unclear. Here, by measuring the individual velocities in large flocks of starlings, we find that birds are spatially correlated over scales as large as the entire flock. Group-spanning correlation extends maximally the effective perception range of the individuals, thus making all animals within the group effectively connected to each other, in spite of the short-range nature of the actual interaction. Long-range correlation is the key to undamped information transfer across the group and it suggests that flocks behave as self-organized critical systems, poised to respond optimally to external perturbations.

Netta Cohen (Leeds)

C. elegans forward locomotion: From experiments to models and back

The nematode worm C. elegans is as an excellent model system for studying the respective roles of neural control and external factors in shaping behavior, With only 302 neurons in a hard-wired neural circuit, the worm's apparent anatomical simplicity belies its behavioral complexity. Indeed, C. elegans exhibits a rich repertoire of complex behaviors, the majority of which are mediated by its adaptive undulatory locomotion. Understanding the neural control of the locomotion system is therefore an important step towards an integrated model of the entire animal. In this talk, I will discuss how pinning down the role of physics in shaping the locomotion can help constrain models of neural control and elucidate the underlying neural control mechanisms. Previous studies of the C. elegans locomotion - both experimental and modeling - have focused by and large on the worm's crawling on agar gels. Here, we would like to understand how the single neural circuit that controls forward locomotion in the worm's ventral cord is able to generate kinematically distinct patterns of locomotion in different physical environments: specifically, the worm's crawling on dense gel-like media, and its swimming in liquids. As a first step, we record the locomotion of worms in different physical environments (water, agar like gels, and intermediate environments) to characterize the swim-crawl transition. We use three metrics - undulation frequency, body wavelength and body amplitude - to quantify the locomotion patterns and to directly relate them to relevant properties of the physical environment. This then allows us to present a unified description of C. elegans locomotion across this range of environments as a single behavior that is smoothly modulated with the visco-elasticity of the environment (Berri et al., 2009). We validate our experimental conclusions with a computational neuromechanical model that explicitly incorporates the ventral cord neural control, muscles, body properties and the physics of the environment. Model simulations give good quantitative agreement between the locomotion patterns of the model and experimental results in a variety of environments. Finally, we discuss specific predictions and implications of our results for understanding both the physical properties of the worm and its neuromuscular control.

Barry J. Dickson (IMP, Vienna)

Genetic and Computational Analysis of Drosophila Courtship Behaviour

The courtship behaviour of *Drosophila melanogaster* provides an ideal genetic model for invesigating how information processing in defined neural circuits generates complex animal behaviour. Despite considerable progress in the basic genetics of courtship behaviour, two major obstacles must still be overcome before genetic data can be mechanistically linked to circuit physiology and behaviour. First, we need to be able to automatically extract rigorous quantitative descriptions of normal and perturbed behaviour from courtship videos. Second, we need to identify the relevant neurons and circuits in the fly's brain and obtain independent genetic access to each of the distinct types of neuron involved. I will present ongoing research that attempts to address both of these challenges.

A. Aldo Faisal (Cambridge)

Variability and the nervous system - from molecules to behavior

Variability affects all stages of our nervous system - from perception to action - and spans many levels of biological organization – from the interaction of signalling molecules in neurons, the responses of neural circuits, to the control of our limb movements. I will present I will discuss computational strategies our brain uses to operate in the face of variability at the level of sensorimotor control and how we can extract meaningful features from the highly variable output of the nervous system, that is behaviour. We study how subjects trade-off sensory and movement uncertainty by deciding when to initiate their actions in a ball catching task with twist. We formulate this task in a probabilistic framework and show that subjects' decisions when to start moving is statistically near optimal given their individual sensory and motor uncertainties. Most importantly we can predict each individual's performance in this sensorimotor task by measuring in two independent experiments their respective sensory and motor variability.

Alex Gomez (EMBL-CRG Barcelona)

Navigation mechanisms in Drosophila larvae

Neural circuits essentially transduce sensory stimuli into behavioral responses. In this talk I will focus on the ability of Drosophila melanogaster larvae to perceive, integrate and orient according to changes relative to intensity of odorant cues. Why to study the fruit fly? Why larva? Why olfaction? Its non-trivial stereotypical behavioral repertoire and the powerful genetic toolkit available, combined with high-resolution automated tracking and statistical analysis, settle this insect as a paradigm for deciphering the neural algorithms governing compass behaviors.

Holger G. Krapp (Imperial College London)

Neural mechanisms underlying stabilization reflexes in flies

Postural reflexes and gaze stabilization are elementary prerequisites for adaptive behaviour across phyla. Understanding how these tasks are accomplished requires a quantitative assessment of both the behavioural performance and the underlying neuronal pathways. Ideally, such a systems approach should be performed in an animal model system where the behaviour and the neuronal activity at the level of individually identified circuits and cell can be monitored. Amongst other animals the fly has proven to be complex enough to address such fundamental questions but simple enough to obtain conclusive answers on how neuronal activity controls reflex behaviour. In my talk I will focus on the neuronal mechanisms involved in fly gaze stabilization and flight control. I will present experimental results obtained at different levels along the optomotor pathway ranging from the integration of local motion information to multimodal fusion, including the transformation of sensory signals into motor commands to control specific behavioural tasks. Finally, I will outline the development of new experimental techniques, which aim to investigate how flies combine sensory signals from different modalities when performing simple sensorimotor tasks. Simultaneously monitoring the neural activity and the behavioural output will also allow us to study whether flies employ efference copies (forward models) to specify their sensory information processing under closed-loop conditions.

Zachary Mainen (Champalimaud/Instituto Gulbenkian de Ciencia)
Neural Mechanisms of Olfactory-Guided Decisions in Rodents

Aldo Faisal (stand-in) (Cambridge)

Analysis of decision making in an insect's gap-crossing behavior

Success or failure of particular behavioral tasks often depends on the selection of an appropriate action based upon the interpretation and accumulation of sensory information. However, it remains often unclear how sensory information is used to decide upon the appropriate action. We studied grasshoppers, which had to cross gaps of varying widths (>200 trials in 4 animals and ~5 gap widths). These insects choose to either reach or jump across gaps or refuse to cross at all. Insects displayed a stream of dozens of behaviors (e.g. parallax movements, probing the gap with antennae, grooming) executed before the final action (reach, jump, refusal) occurred. These pre-action behaviors are interwoven with each other and are highly variable from trial to trial. This has previously made it difficult to understand what behavior (and thus what sensory information) contributed to the decision making process, which is symptomatic for behavioral studies of decision making in freely behaving animals. We take a novel, computational approach to overcome this problem and analyze the behavior leading to the decision. Prediction success rate using this modethod overall trials was high (86%) after observing only the first 14 behavioral states in the sequence (sequences were as long as over 100 state transitions) – thus the decision was taken early on and much of the subsequent sensory behavior must have been only used to fine tune the action. We propose that this behavioral sequence approach is directly amenable to analysis using traditional bioinformatics techniques; for example Hidden Markov Models to estimate how sensory behavior affects internal states representing the build up towards an action decision.

Leslie Osborne (UCSF)
Insights into neural mechanisms of behavior from analysis of variation

Suppose that the variability in our movements is caused not by noise in the motor system itself, nor by fluctuations in our intentions or plans, but rather by errors in our sensory estimates of the external parameters that define the appropriate action. For tasks where precision is at a premium, performance would be optimal if no noise were added in movement planning and execution: motor output would be as accurate as possible given the quality of sensory inputs. We have use visually-guided smooth pursuit eye movements in primates as a testing ground for this notion of optimality. In response to repeated presentations of identical target motions, nearly 92% of the variance in eye trajectory can be accounted for as a consequence of errors in sensory estimates of the speed, direction and timing of target motion, plus a small background noise that is observed both during eye movements and during fixations. The magnitudes of the inferred sensory errors agree with the observed thresholds for sensory discrimination by perceptual systems, suggesting that these very different neural processes are limited by the same noise sources. Computing the signal to noise ratio of pursuit movements allows us to estimate a "behavioral threshold" akin to a threshold for reliable perceptual discrimination of a change in target motion. We find that pursuit thresholds agree quite well with perceptual thresholds throughout the sensory-driven period of movement initiation. These results suggest that pursuit can be a reliable read-out of the evolving sensory estimate of target motion. To probe computational features of visual motion estimation, we added a stochastic component to target motion and found the temporal filter that best predicts the eye movements in time. The optimal linear model could account for about 50% of pursuit variation.

Greg Stephens (Princeton)

More bits for behavior: from C elegans movement toward the principles of animal action

A major challenge in analyzing animal behavior is to discover some underlying simplicity in complex motor actions. Here we show that the space of shapes adopted by the nematode C. elegans is surprisingly low dimensional, with just four dimensions accounting for 95% of the shape variance. These "eigenworms" provide a complete, quantitative description of worm behavior, and we partially reconstruct equations of motion for the dynamics in this space. The reconstructed dynamics contain multiple attractors, revealing novel pause states and we find that the worm visits these in a rapid and almost completely deterministic response to weak thermal stimuli. Stimulus dependent correlations among the different modes suggest that one can generate more reliable behaviors by synchronizing stimuli to the state of the worm in shape space. We confirm this prediction, effectively “steering” the worm in real time.

Nina Vogt (New York University)

Development of a behavioral assay for color vision in Drosophila

The Drosophila compound eye is composed of about 800 ommatidia, each of which consists of six outer and two inner photoreceptors. Color information is detected by the inner photoreceptors R7 and R8. The two types of photoreceptors project into different neuropils in the optic lobe. The outer photoreceptors arborize in the lamina, while the projections of the inner photoreceptors bypass the lamina and directly innervate the medulla, which is thought to be the main processing center for color vision. In order to understand how color information is processed in the medulla, we are developing an assay for color vision, based on the behavior of single flying flies in a colored (blue and green) LED arena. True color vision requires that flies be able to recognize wavelengths independently of intensity. We are using an operant learning paradigm to teach flies to prefer one color over the other. During the assay, the behavior of the flies is monitored, and the data are then automatically analyzed. Once the behavioral assay is established, we will take advantage of our collection of highly specific Gal4 drivers to manipulate neuronal activity in different medulla cell types to study their function in color vision. This approach will add functional data to the anatomical map of the Drosophila medulla and will provide insight into the processing of color information in the brain.