Sperm Chemotaxis

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Many cells and microorganisms have evolved a motility apparatus to explore their surroundings. For guidance, biological microswimmers rely on physical and chemical cues that are transduced by cellular pathways into directed movement – a process called taxis. Only few biological microswimmers have been studied as detailed as sperm from sea urchins. Sperm and eggs are released into the seawater. To enhance the chances of fertilization, eggs release chemical factors – called chemoattractants - that establish a chemical gradient and, thereby, guide sperm. Sea urchin sperm represent a unique model system for understanding cell navigation at every level: from molecules to cell behaviours. I will outline the chemotactic signaling pathway of sperm from the sea urchin Arbacia punctulata and how signalling controls navigation in a chemical gradient, and discuss recent insights into sperm chemotaxis in three dimensions.

Mathematical Aspects of Embodied Intelligence

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I will present recent results on the design of embodied systems with concise control architectures, formalising the notion of "cheap design" within the field of embodied intelligence. This notion highlights the fact that high behavioural complexity, seen from the external observer perspective, does not necessarily imply high control complexity. This complexity gap is a result of two different frames of reference, which is closely related to Uexküll's Umwelt concept. If time allows, I will present a measure-theoretic formalisation of this concept and discuss its implications.

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Ciliated surfaces and transport networks

Bodenschatz, Eberhard
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Self-organized, near-critical behavior in aggregation of social amoeba

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During starvation, the social amoeba Dictyostelium discoideum aggregates artfully via pattern formation into a multicellular slug and finally spores. The aggregation process is mediated by the secretion and sensing of cyclic adenosine monophosphate (cAMP), leading to the synchronized movement of cells across huge distances (~100 cell lengths). The whole process is a remarkable example of collective behavior, spontaneously emerging from single-cell chemotaxis. Despite this phenomenon being broadly studied, a precise characterization of the transition from single cells to multicellularity is still missing. Here, we use fluorescence imaging data of thousands of cells, concepts from phase transitions in physical systems, and multiscale modeling to describe the self-organization at the onset of aggregation. Due to physical and chemical constraints, such rules may be universal, and hence explain collective cell behavior in other biological systems.

The role of short-term synaptic plasticity for locomotion

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We are investigating the role of short-term synaptic plasticity (STSP) for motor control. STSP is a (primarily presynaptic) transient plasticity involving typically a short term (10-100 ms) potentiation of the synaptic efficiency, with is followed by a longer (100-1000 ms) reduction of the effective synaptic strength (due to vesical depletion). The timescale of STSP are important both for cognitive and motor processes.

We use a physics simulation environment (LPZrobots) to simulate robots controlled by very simple neural networks. We show, that a range of non-trivial self-organized behaviors are generated within the sensori-motor feedback loop by the short-term
synaptic plasticity. Motion patterns involve straight and circular meandering together with explorative behavior in chaotic walks. We are argue that STSP may be quite generally an important component for biological motor locations.

Twist and Turn: Phototaxis of the Dominant Marine Pico-Eukaryote Micromonas pusilla

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Phytoplankton are the producers in marine environments, and form a critical foundations that global ecosystems rely heavily upon. One of the most globally prominent of these is Micromonas pusilla – an uniflagellated photosynthetic single-celled eukaryotic microorganism found in oceanic and coastal environments.

Previous research with M. pusilla focussed on two areas, for which M. pusilla is now a model system. Firstly in understanding the dynamics of a host-virus system in which M. pusilla plays host to the Micromonas pusilla virus (1), and secondly for studies into the structure and behaviour of the eukaryotic flagella(1). Despite research on the dynamics of the flagellum, there is very little that is known about the motility of M. pusilla, such as its ability to undergo directed motion (known as “taxis”) in particular in

response to external light stimuli ("phototaxis"). This motion can be positive or negative – towards or away from the external stimulus respectively.

Previous work with M. pusilla has reported anecdotally that M. pusilla is strongly phototactic (3), but the mechanism by which M. pusilla can achieve directed motion with only a single flagellum has not been discussed – indeed, no experimental evidence has been provided to support the claim of phototaxis of M. pusilla. The general motility of M. pusilla is also lacking in description, which is surprising given the global prominence and ecological importance of this eukaryotic microorganism.

This study reports the presence of both positive and negative phototactic responses of M. pusilla over a range of intensities and wavelengths. The motility of is then characterised near a solid boundary to be that of run-and-stop motion, with comparisons between two heavily studied prokaryotes Escherichia coli and Rhodobacter sphaeroides made. Finally, the phototactic motion of M. pusilla is compared and contrasted with the chemotactic motion and mechanism of E. coli (4), and a suggested mechanism for the phototactic motion of M. pusilla is described.

Key Words: Micromonas Pusilla, Run-and-Stop Motion, Phototaxis.

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Towards real-world evolution of robot navigation

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Systems neurobiology of the Platynereis larva

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Precise neuronal synaptic connectivity and its modulation by chemical signaling are ultimately responsible for the circuit dynamics controlling effector activity during behavior. We currently have little information on the complete synaptic connectivity (connectome) of entire neuronal circuits and how these are modulated. The establishment of new, small, relatively simple model organisms could greatly benefit neuroscience by allowing whole-body connectomics and by expanding the range of nervous system phenomena that can be studied. We work on the larval stages of the marine annelid Platynereis dumerilii that has recently emerged as a powerful experimental system for the study of neural circuits and neuromodulation in a whole-body context. We use connectomics, neurogenetics, activity imaging, and behavioral experiments to understand how circuits influence behavior and physiology in the planktonic larvae of Platynereis. By studying different larval stages, we can also gain insights into how circuit maturation influences larval behavior during development.

Cross-streamline migration of chemically active Janus particles in flow (experiment)

Katuri, Jaideep
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Spatial learning as proxy for cognitive flexibility

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Spatial learning is a critically dependent on the hippocampus and many functional details have already been elucidated. This has lead to the occasional misconception that the hippocampus were "just for place". But while spatial learning might represent an old and premordial function of the hippocampus, it seems that other functions have highjacked the principles realized for navigation. This idea is not new but what is changing is the view on how spatial and other types of learning are linked. How much do spatial learning tasks reveal about general aspects of learning and memory. To which degree is spatial learning only the most visible or accessible facet of hippocampal function?
From research on adult hippocampal neurogenesis and the question, how the newborn neurons contribute to hippocampal function we developed more general hypotheses about how the plasticity provided by these new cells shapes the hippocampus and contributes to higher cognition.

Navigation of colonies of choanoflagellates

Kirkegaard, Julius
(University of Cambridge, DAMTP, Cambridge , United Kingdom)

As the closest unicellular relatives of animals, choanoflagellates serve as useful model organisms for understanding the evolution of animal multicellularity. Mimicking multicellular organisms, the choanoflagellate \textit{Salpingoeca rosetta} can form colonies, in which the constituents' flagella beats are uncorrelated. In this talk I will discuss what consequences this has for their navigation, focusing on their random walk behaviour and chemotaxis.

Statistical Physics and Anomalous Dynamics of Foraging

Klages, Rainer
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A question that attracted a lot of attention in the past two decades is whether biologically relevant search strategies can be identified by statistical data analysis and mathematical modeling. A famous paradigm in this field is the Levy hypothesis. It states that under certain mathematical conditions Levy dynamics, which defines a key concept in the theory of anomalous stochastic processes, leads to an optimal search strategy for foraging organisms. This hypothesis is discussed very controversially in the current literature. I will review examples and counterexamples of experimental data and their analyses confirming and refuting it. Motivated by this debate is own work about biophysical modeling of bumblebee flights under predation thread based on experimental data analysis, which I briefly outline.

Sperm navigation in chemoattractant landscapes

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Sperm are guided to the egg by chemical cues in a process termed chemotaxis. To evaluate local chemoattractant concentrations, sperm detect single attractant molecules, while moving along helical paths. This chemical input signal is then translated by an intracellular signaling system into modulations of the flagellar beat, which steers the cell up-gradient.
This sperm chemotaxis exemplifies a gradient-sensing strategy that is fundamentally different from that employed by most bacteria (biased random walks) or immune cells (spatial comparison).

Recent experiments showed that sperm cells can switch between two distinct steering modes in a situation-specific manner. While swimming up-gradient, cells employ a mode of conservative steering, characterized by slow bending of helical swimming paths towards the concentration gradient of chemoattractant. If a cell accidentally swims down-gradient, it responds with a vigorous 'off-response', characterized by fast helix bending. We argue that this dynamic switching represents a strategy of balancing risks of steering in a wrong direction by amplifying noise in sensory input. Using a theoretical description of sperm chemotaxis with decision making, we demonstrate that decision making confers a competitive advantage to find the egg, if physiological levels of sensing noise are taken into account.

Bees can follow routes with an ant brain: reimplementation and screening of a neural network model for view matching

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Sensorimotor integration directing Drosophila chemotaxis

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Behavioral strategies employed for chemotaxis have been studied across phyla, but the neural computations underlying odor-guided orientation responses remain poorly understood. Combining electrophysiology, optogenetics, quantitative behavioral experiments and computational modeling, we study how dynamical olfactory signals experienced during unconstrained behavior in odor gradients are processed by first-order sensory neurons of the Drosophila larva, and how this information is converted into orienting behavior.

Topographical pathways guide chemical microswimmers

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Achieving control over the directionality of active colloids is essential for their use in practical applications. Here we demonstrate a guiding method based on step-like submicrometre topographical features, engineered through a photo-lithography based process and thin film deposition. The Janus particles reliably dock on sub-micron sized steps based on their phoretic and hydrodynamic interactions and move along the edges for significantly long times, which systematically increase with fuel concentration. We also show that this effect is size dependent and evaluate the limit of the step-size necessary to achieve guiding. Using especially engineered system this principle can be used to develop autonomous devices at the micron-scale.[1]

Based on: J. Simmchen, J. Katuri, W. E. Uspal, M. N. Popescu, M. Tasinkevych & S. Sanchez. Topographical pathways guide chemical microswimmers. Nat. Comm. 7, 10598 (2016).

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Information Theory and Signal Transduction in Biological Systems

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The proposal that ideas from systems and control engineering might help understand biological organisms goes back at least to Wiener's 1943 book on Cybernetics. Although Wiener's work predates Shannon's 1948 mathematical theory of communication, it already discussed logarithmic information measures (as well as negative feedback loops and other modern concepts). Control requires state estimation, and so the frameworks of control theory and information theory were intertwined for biological systems from the start. Paradoxically, the success of Shannon's theory for engineered systems lies in its separation from the control problem for which the information is transmitted.

In this talk I will review some of the success stories in the application of information theoretic analysis to understanding biological systems, particularly sensory pathways. Quantitative application of information theory benefits from individually resolved (rather than population level) measurements of responses to signaling. The availability of cell track data showing the response (through movement) of the social amoeba Dictyostelium discoideum to chemical gradient signals provides an early example. More recently, high throughput measurement techniques have allowed the collection of large individually resolved datasets for a variety of biochemical signal transduction systems, for example tumor necrosis factor signal levels.

As a starting point for analysis of biochemical signaling channels, A. Eckford and I have solved the capacity of a two state, discrete time Markov channel model for signal transduction via binding of a ligand to a single receptor protein (Eckford and Thomas 2013 ISIT). We are able to show that in the continuous time limit with rapid unbinding of the receptor, our capacity reduces to the capacity of the Poisson channel obtained by Kabanov in 1978.

Finally I will explore the hypothesis that utility-optimal behavioral strategies are always information-optimal, and discuss a counter example (Agarwala, Chiel and Thomas 2012, J. Theor. Biol.).

Cross-streamline migration of chemically active Janus particles in flow (theory)

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For microswimmers, the interplay of swimming activity and external flow can promote robust directional motion. For instance, the direction of propulsion can align against the flow ("upstream rheotaxis") [1,2] or perpendicular to it ("cross-streamline migration") [3]. Motivated by recent experiments, we present a deterministic theoretical model of a Janus particle in shear flow near a planar wall. When the particles are inactive, they simply rotate and are carried downstream along fluid streamlines. When the particles are active, they are attracted to certain orientations that are nearly perpendicular to the direction of the flow, and they swim across flow streamlines. We show how this attraction emerges from the interplay of shear flow and near-surface swimming activity. Adding the effect of thermal noise, we obtain probability distributions for the swimmer orientation that show good agreement with the experimental observations. Our findings could be used to sort microswimmers by activity, as well as to understand how microswimmers would behave in applications involving fluid flow through tight spaces.

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Navigation in turbulent environments

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A mesoscopic field theoretical approach for active systems

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We introduce a mesocopic modeling approach for active systems. The continuum model allows to consider microscopic details as well as emerging macroscopic behavior and can be considered as a minimal continuum model to describe generic properties of active systems with isotropic agents. The model combines aspects from phase field crystal (PFC) models and Toner-Tu models. The results are validated by reproducing results obtained with corresponding agent-based microscopic models. We consider binary collisions, collective motion and vortex formation. For larger numbers of particles we analyze the coarsening process in active crystals and identify giant number fluctuation in the cluster formation process.

Neural mechanisms of ant navigation

Webb, Barbara
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Ants are highly capable navigators. They have been the focus of behavioural and ethological study for many years, and a range of algorithmic models of their behaviour have been proposed, often tested in robot implementations. Our recent work has focussed on bridging the gap to understanding the neural circuits that underly capacitities such as visual orientation, path integration, and the combination of multiple cues. In each case there is an important interplay between exploiting critical sensory cues in the natural environment, and the efficient and robust computation that supports behavioural control. Maintaining a tight loop between behavioural, modelling and robot studies has been key to progress in this field.