# research statement

Birds have been under selection pressure to optimize flight performance for a long time. Along with the anatomical adaptations to flight, brain function must also have adapted to this feat. For example, during high velocity flight a bird needs to rapidly grasp the three-dimensional structure of the environment in order to avoid collisions. I found evidence that zebra finches direct their gaze to optimize depth perception from visual motion information ("motion parallax"; Eckmeier et al., 2008) and that the visual motion resolution in zebra finches was high (Eckmeier and Bischof, 2008). A recent study from another group suggests that birds resolve visual motion much better than any other vertebrate. Together the evidence suggests that motion vision plays a fundamental role in the control of flight maneuvers. **I want to study, how visual motion controls flight maneuvers in birds, and to uncover how the unique structure of the avian brain solves general problems of flight control.** I already combined behavioral tracking with electrophysiology to test how the visual system responds to naturalistic visual motion stimuli in zebra finches (Eckmeier et al. 2008, 2013). I will expand on this approach applying motion tracking, neural activity recording, and systems analysis methods that I learned as a postdoctoral fellow. I will study the kinematics of flight maneuvers with respect to the visual environment, and the connections and function of visual motion processing brain areas. I hope my work will contribute to the development of a fundamental understanding of sensory processing and avian evolution, and will find application in flying machines.

## Project Abstract

**I want to study how visual motion guides rapid, yet accurate flight maneuvers** in birds. When negotiating obstacles in free flight, the brain integrates the distance to objects in the flight path, and the bird's self-motion. During fast flight, distances to and between objects, as well as self-motion can be most reliably perceived from visual motion cues. My goals are **(1)** to **understand the visual motion components that guide obstacle avoidance maneuvers**, **(2) to model the algorithms for motion processing in the avian visual system**, and **(3) to reveal the implementation of these functions in the brain**. I will initially focus on nucleus rotundus in the tectofugal visual system. This area is known to represent relative motion between object and background. My work on the representation of complex stimuli in this area (Eckmeier et al. 2013) informed us that the categorization of motion responsive neurons from earlier studies may be too simple. But still we know very little about the local microcircuit in this area that gives rise to these representations.

**In a five-year time frame, my lab would aim to**

1. reveal the circuits connecting motion selective neurons in nucleus rotundus.
2. model the population code for visual motion in nucleus rotundus
3. reconstruct and model visual motion patterns that control the execution of obstacle negotiation maneuvers in freely flying zebra finches

## Research Background and Initial Projects

Fundamental questions in neuroscience address behavior, neuronal processing, and brain architecture. Avian visual flight control is a promising model to study these in a naturalistic, neuroethological approach. As a phylogenetic group, birds are defined by their adaptations to visually guided flight, which was optimized over an evolutionary long time span. The avian visual system thus suits specifically the demands of flight, which makes birds the best vertebrate group to study visually guided flight control. One striking specialty of the avian brain is its architecture. The avian brain regions assumed to be homologous to mammalian cortical areas are organized in nuclei rather than layers, but retain similar complex neuronal connections, and achieve similar cognitive performance. Studying the avian brain thus promises to reveal fundamental information processing principles through comparison with other vertebrate brain architectures.

My goals will be to understand how birds can safely maneuver through difficult terrain, how the sensory information is represented and transformed within and between neuronal populations, and how this is achieved on neuronal circuit level. The novelties to my approach in this field are the **reconstruction and analysis of natural behavior-guiding sensory experience**, the **decoding of population codes** of sensory representation, and the **combination of *in vivo* electrophysiology with anatomical/histochemical cell type characterization**. My laboratory will explore these approaches by adapting state-of-the-art techniques that I learned in my postdoctoral phase. We will develop an unique view on avian neural processing that will not only complement existing efforts, but advance the general understanding in the field of neuroscience.

For small animals flying at high velocities, visual motion is the most reliable information source for self-motion perception, and the perception of distances in difficult terrain. Distance cues from visual motion stem from *motion parallax*. During locomotion, the images of close objects move faster across the retina than those of distant objects. The relative motion of such images in a visual scene creates the experience of depth. Self-motion perception, on the other hand, relies on the global image slip on the retina (*optic flow*). Optic flow patterns are distinct for translational and rotational gaze movements. When moving along a curved trajectory, these two modes combine to produce complex visual flow patterns. Optic flow further allows for the estimation of velocity, and direction of self-motion.

Perception of self-motion on the one hand, and of the three-dimensional structure of the environment on the other, demands different visual processing mechanisms. The neuronal pathway that analyzes optic flow for the estimation of self-motion, the accessory optic system, is well understood. It provides the major instructive signal for gaze stabilization reflexes, and probably maneuver control as well, through connections in the cerebellum. Where depth perception from motion parallax is processed in the avian brain is unclear. But the tectofugal visual system stands out as a possible neural substrate. Several brain areas of this pathway show a representation of object motion relative to background motion. Such representations are essential for the analysis of motion parallax. My first research target, the nucleus rotundus, is one of these areas.

While there is a general understanding of avian brain systems, only little is known about the local circuits within the visual motion processing areas. Specific cell types are almost exclusively described by spike train characteristics and stimulus responses. Immunohistochemical studies show brain-wide distributions of cell markers, but usually do not discuss cell types. Similarly rare are descriptions of cell type morphologies, let alone connectivity studies. Connecting electrophysiological properties with cell types and knowledge about their interactions is necessary to understand how a neuronal population represents information.

**Initial Projects:**

(1) Little is known about cell types and circuitry within avian visual brain regions, however, to understand local circuits, one needs to know how the recorded cells interact. To open this path of investigation, **I will define cell types in nucleus rotundus by their electrophysiological response, morphology and inhibitory/excitatory function**. Following *in vivo* loose patch electrophysiology and biotin cell fill, the morphology of a cell with known response patterns can be determined. Counterstaining with GAD antibody will then reveal whether the recorded neuron is inhibitory.

(2) Motion sensitive neurons in nucleus rotundus do not fall into discrete categories when presented complex motion stimuli. I hypothesize that the representation of a moving scene in nucleus rotundus depends on a population of neurons, each with a unique tuning for combinations of different motion properties, like speed or direction. I will record multiple cells simultaneously while presenting complex optic flow stimuli. The results will be complex, modulated spike trains. I will use spike-triggered averages to estimate the receptive field and tuning of each neuron. I want to apply computational modeling methods to then generate a predictive model of how this population of neurons represent visual motion.

(3) Visual motion provides the most reliable cues for distance estimation and self-motion during flight. **I hypothesize** that the birds monitor the retinal image of an opening in order to fold their wings in time before passing through the opening. **I will track the trajectories and head movements of zebra finches** as they maneuver through openings of different sizes. **A result that supports my hypothesis** would be, for example, a flight velocity dependent visual flow pattern that reliably triggers a bird to fold its wings.

## Further Outlooks

By studying how visual motion controls flight maneuvers, my goal is a computational model that will successfully navigate through an artificial scenario, like a bird. Such a model could be implemented in autonomous vehicles. This project would further generate naturalistic motion stimuli to be used to test the response of neuronal populations. By systematically targeting different areas in the tectofugal visual system during replay-experiments, or even in flying zebra finches, I will learn how information is transformed between brain areas. A computational model of these transformations would be a great step in understanding biological information processing and could inform machine vision techniques. To further study the biological implementation of these processes, the results of my studies connecting electrophysiological and anatomical properties of cell types should be extended by further histochemical characterizations and *in vitro* connectivity studies.

## Experience

My research plans are based on my doctoral studies, and were significantly updated by my experience gained as a postdoctoral fellow, while not conflicting with the research of my previous advisers.

I tracked head movements in zebra finches during my PhD project. We filmed zebra finches flying around an obstacle with high-speed cameras, and tracked the head position and beak angle in three dimensions. This tracking data revealed a gaze strategy in freely flying zebra finches that facilitates depth perception from motion parallax (Eckmeier et al., 2008). The birds held their heads in a constant orientation in allocentric space and only changed head orientation in saccadic shifts. By reducing the time during which the gaze turns, the bird experiences longer time intervals with optimal visual input for depth perception.

I combined the tracking data with a computer model of the flight arena to reconstruct the view the bird had experienced during flight. These videos were then presented during electrophysiological recordings in the zebra finch visual system (Eckmeier et al., 2013). Nucleus rotundus is a brain area in the tectofugal visual system that signals object motion relative to background motion, a prerequisite for processing motion parallax.

To test the response properties of neurons in nucleus rotundus, we chose naturalistic stimuli, instead of simplistic traditional stimuli, because the avian brain evolved to process natural, three-dimensional scenes. Response properties would thus reflect the natural distribution of visual properties in a natural scene. The results from this initial neurophysiological study showed a continuum of stimulus preferences for motion stimuli. This hints toward a complex, population based representation of visual motion.

The electrophysiological study was done in anaesthetized animals, while, obviously, only awake animals actually perform flight maneuvers. This discrepancy evoked my interest in brain state and its modulation of neuronal properties. This is how I became interested in studying neuromodulation in mice. Dr. Shea (CSHL, USA) had developed a paradigm that allowed to study effects of the brain state regulating neuromodulator noradrenaline in mice. Noradrenaline induces plasticity in the olfactory system. I established a wide-field imaging method in the lab, to show that the odor induced output of olfactory sensory neurons is changed after an episode of noradrenaline release (Eckmeier and Shea, 2014). Neuromodulation and brain state thus have an impact on the sensation of smells even presynaptic to the main olfactory bulb. We think this mechanism may play a role in arousal dependent memory formation.

The most direct way to study natural behavior and naturally computing brains, is to record from the brain in the awake and behaving animals. Because I want to understand the ethological context of the noradrenaline/arousal dependent plasticity, I investigated the temporal structure of noradrenaline release in behaving mice. I used a microwire bundle on a movable drive to record neuronal activity in locus coeruleus during courtship, paired with IR video visual behavior, and the ultrasonic vocalizations. It is known that phasic shifts in the firing patterns of noradrenaline releasing locus coeruleus, either precede a behavior or follow a stimulus. First results (presented at SfN, 2016) showed no correlation of vocalizations with LC burst activity.

During my short postdoc with Dr. Megan Carey (since August 2015) at the Champalimaud Foundation in Lisbon (Portugal), I collaborated with other lab members to improve methods for animal motion tracking (LocoMouse) and a spike train analysis appropriate for the special properties of Purkinje cell firing. In parallel I began developing a setup to study cerebellar activation during mouse locomotion. In this context I attended workshops in computational neuroscience and made myself familiar with basic machine learning (support vector machines and neural networks) and machine vision principles that will be useful for bird flight analysis.