

Proposal

for a

Princeton - Humboldt-Universität Centre for Reality Mining of Animal-Human Systems

Lead Principal Investigators (PI)

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&

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Abstract

Reality mining involves the collection and analysis of machine-sensed data regarding animal and animal-human social behaviour. It constitutes a highly innovative and largely overlooked research direction in the study of wildlife-human interactions. Currently we largely lack the means to understand how and why animals move in the way they do in the wild, how they make decisions as individuals and as part of collectives. Moreover, there is a lack of understanding how humans search, find and exploit free-ranging animals and how the exploited animals in turn respond to non-lethal anthropogenic disturbances. Deriving insights into the real-time behaviour of both animals and humans in the wild and how they interact with the environment promises many urgently needed answers to socio-economically important areas such as improved welfare in husbandry, disease transmission and sustainable management of wild fish stocks. To advance this field of study, we propose to establish an interdisciplinary “Princeton-Humboldt-Universität Centre for Reality-Mining in Animal-Human Systems”. This Centre connects ten leading PIs and their research groups, integrating cutting-edge technology, computational tools, and state-of-the-art theory for

understanding individual and collective behavioural patterns in animal and animal-human social systems. We propose an integrated solution that exploits a diverse, yet complementary, set of skills and expertise in behavioural and theoretical ecology, engineering, theoretical physics and complexity science. We will base our joint work on already-available high resolution data sets on aquatic and terrestrial systems. The proposed collaboration that is to be seeded by the present grant will allow us to integrate our complimentary expertise to develop a productive Research Centre. In the first year of seed funding, we will foster mutual exchange visits to harmonize ideas and develop first research products (software, publications). We also propose to host an international summer school for the dissemination of our expertise to a new generation of graduate students who will benefit from already available data sets. Initial work within the present grant shall culminate in the development of follow-up grants to be submitted at the end of the seed funding period to produce a durable outcome. Given the novelty of our research idea and the scientific quality of the consortium we anticipate that our team could have a lasting impact on both science and society.

Objectives

Our objectives are (1) to develop a highly visible network of excellence among scholars in Princeton and Humboldt-Universität zu Berlin in the field of “reality mining” of animal-human systems, (2) to produce highly innovative and well published research on the collective behaviour, personality and movement ecology of animals and the interactions of humans and animals, (3) to integrate traditionally separated disciplines, such as behavioural ecology, physics, fisheries science, computer science and engineering, to develop novel methodological tools and apply them to emerging ‘big data’ sets on animal behaviour and animal-human interactions in the wild, and (4) to develop excellence in graduate education, for example within a summer school of high international attractiveness, to teach graduate students in the area of reality mining of animal-human systems. The proposal will take advantage of already available high resolution positional data that were generated independently of each other in laboratory and natural settings by the ten PIs forming the present consortium. The seed initiative aims at developing into a virtual Princeton-Humboldt-Universität Centre of Excellence for Reality Mining of Animal-Human Systems. We aim at generating further funds to extend our collaboration beyond the first year of funding.

State of the art and intellectual motivation

‘Reality mining’ is defined as the collection and analysis of machine-sensed data regarding social behaviour of humans [1] and animals [2]; it enables researchers to investigate the social dynamics of almost entire populations, in extraordinary detail and with exceptional spatio-temporal resolution [1-6]. However, owing to the lack of high resolution tracking technology for many wild living animals, there is no research tradition in the non-human behavioral sciences that compares with initiatives in human behavioural research [2]. Despite some advances in specific contexts of animal ecology using movement proxies and indirect measurements [2], this area of animal research lacks a reliable body of data on which theories can be built and tested. In fact a large number of efficient foraging search and animal movement theories have been proposed in the past few years, but none have been conclusively gauged against empirical evidence, motivating substantial controversy [e.g., 7-8]. There are also important applied knowledge gaps as relates to how animals and humans interact when they encounter each other, e.g., in the context of hunting or fishing, or disease transmission. This hampers progress towards sustainable natural resource use.

Recently, two PIs of the present proposal from Humboldt-Universität have proposed a research agenda on reality mining of animal social systems [2], which we extend here to cover exploitative animal-human interactions, such as those in fisheries or hunting. Thanks to the refinement of a range of miniature tracking technologies, in addition to acoustic and visual imaging,

we are now able to employ powerful reality-mining approaches in our studies of animal social behaviour and the social-ecology of human-animals systems by recording, and subsequently analysing, positional datasets of unprecedented size and quality. This development is shifting the focus from the challenges of data generation to issues concerning data management, analysis and theory, in turn demanding collaboration among empirical field biologists and theoretical ecologists, complexity scientists and computer scientists. This proposal constitutes an attempt to foster such collaboration and to place the consortium of ten scholars at Princeton and Humboldt-Universität in the core of the Centre to further develop a new reality mining approach in animal-human studies.

Instead of using traditional data-collection techniques, such as standardised re-sighting of a comparatively small sample of individually identifiable animals once per month, week or day, a reality-mining approach employs cutting-edge, animal-borne technologies that can be applied possibly to entire local populations. This enables the automated charting of individuals' daily activities and social associations with a temporal resolution of hours, minutes or even seconds in 2D or even 3D dimensions [3,9,10]. Such near-continuous and simultaneous sampling of social encounters for all individuals in a group or population then provides the basis for fitting and testing comprehensive descriptive and predictive models of a range of dynamic processes in free-ranging animals to understand disease transmission, predator-prey interactions, patch choice, information flow within and between populations, formation of social hierarchies, the structure of population-intrinsic social networks, cooperation between individuals, and responses to sporadic ecological events (e.g., sudden changes in food availability or icing of lakes) [reviewed in 2]. This means that reality mining can contribute to efforts of modelling ecological phenomena from the bottom-up, with an assessment of the individual fitness consequences (survival, reproduction) of different behavioural strategies. The latter then joins ecology and evolution, resulting in the potential of for the first time directly modelling behaviour-mediated eco-evolutionary feedback.

Humans and animals form complex adaptive social-ecological systems. In this context, many wild animals are exploited by humans by various means. Besides advancement in basic research as elaborated above, the reality mining approach also promises to help understanding how the interactions and animals and humans is structured and what emergent patterns (e.g., space use by fishers) to expect. For example, animals may react to human presence with fear responses that reduce encounters with hunters and fishers, in turn leading to behaviour-mediated indirect interactions among predators and prey and emergent, potentially unexpected food web effects. There is also an increasing realization that the behavioural reactions of animals to human management interventions (e.g., stocking of fish, habitat enhancement in lakes, refuge building) is a decisive, yet often-overlooked factor affecting the success or failure of such interventions [11]. The suite of ecological and social processes inherent in coupled social-ecological systems interact and feedback on one another through behavioral processes, which determine emergent outcomes such as catchability, hunting success and localized overharvesting [12]. A key academic objective of global importance in the field of sustainability science is now to establish the scientific principles by which management of social-ecological systems can be achieved. No study exists that has simultaneously tracked animals and harvest-oriented humans (hunters, fishers) at fine spatial-temporal scales. This prevents us from fully testing highly contested and controversial theories on optimal search patterns of foragers in the wild (e.g. Lévy flights, fractional diffusion, intermittent dispersal, intrinsic vs. externally driven scale-free movements) [13-14]. The reality mining approach thus provides a very promising potential of improving our understanding of how fish and wildlife interact with consumptive natural resource users, promising highly relevant insights for conservation, management and sustainability of wild animal populations.

Project operation and work plan

Some empirical biologists of the present proposal have compiled rich empirical data sets on both aquatic (Princeton and Humboldt-Universität) and terrestrial (Princeton) organisms in terms of animals' movements, behavior, and physiology (see below). Moreover, some data sets on fisher

behavior and how they exploit wild-living fish populations are available. All of these high resolution data sets wait to be systematically analysed in depth. To do so requires close cooperation of world-leading theoreticians and computational research groups at Princeton and Humboldt-Universität because they have already devised some of the key mathematical, numerical and statistical modelling approaches that are required for analysis and interpretation of “Big Data”. The large volumes of data that have already been collected and the exceptional qualities of the theoretical and computational groups of the present proposal will allow us to make rapid progress right from the start. This is particularly beneficial to the strong educational component of the proposal as students that will participate in the proposed centre can be exposed immediately to a large foundation of data without having to investigate a substantial fraction of their time to data acquisition.

Our proposal is about the exploitation of synergies at a critical time where reality mining of animal-human systems is about to kick start internationally [2], initially through an exchange of faculty and graduate students, and a summer school, with the ultimate aim to not only provide knowledge transfer but also training of a new generation of graduate students in the field. Co-funding of the initiative in terms of personnel (postdocs and PhD students) is achieved by ongoing grants administered at both Princeton and cooperating institutes of Humboldt-Universität zu Berlin, specifically the Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB) (see Table 1 and Figure 1 for the range of people that are involved in in various functions).

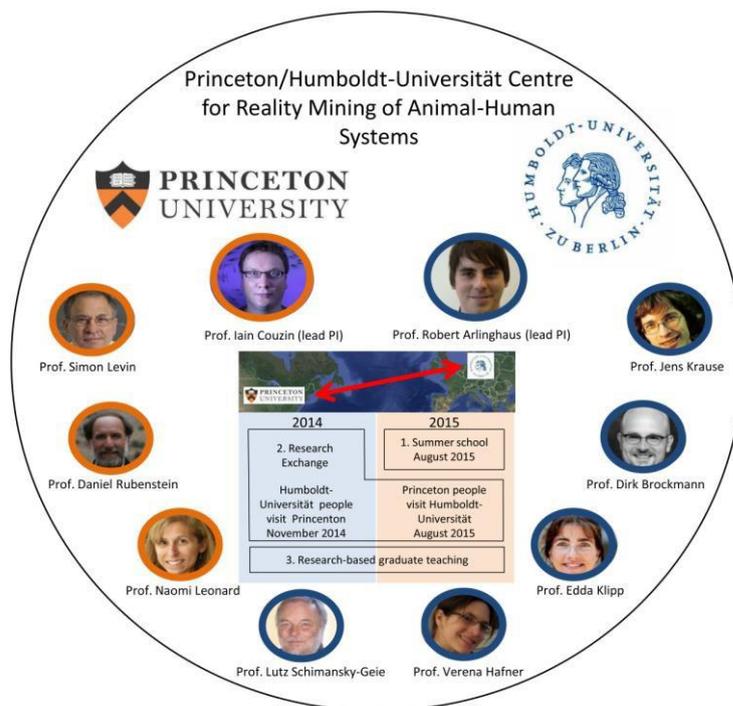


Fig. 1. Overview about PIs and planned initiatives in the seed funding project.

To meet our objectives, we have formed an interdisciplinary consortium of leading empirical and theoretical research groups (Table, 1, Figure 1) crossing several departments, institutes and disciplines (behavioural ecology, theoretical ecology, evolutionary biology, theoretical and computational physics, engineering, complex systems, computer science) at both Princeton University and Humboldt-Universität

zu Berlin. We have matched competencies at both organizations. The speaker of the consortium is Prof. Dr. Robert Arlinghaus for Humboldt-Universität and Prof. Dr. Iain Couzin for Princeton University. Selected PIs of our consortium have previously collaborated with each other (Prof. Dr. Jens Krause and Prof. Dr. Lutz Schimansky-Geier at Humboldt-Universität with Prof. Dr. Simon Levin and Profs. Dr. Iain Couzin, Naomi Leonard and Dan Rubenstein at Princeton), providing evidence of productive interactions. However, there is no ongoing joint project or any joint third party funding. The present grant is therefore a seed funding to facilitate the intensified cooperation extending the cooperation to ten research groups that share complementary competencies and interests in the reality mining of animal-human systems. We aim at the medium-size seed grant and propose to use the funds to engage in three core areas (Figure 1).

[1] Research exchange: The consortium will integrate complementary data sets (see below) existing at Princeton and Humboldt-Universität zu Berlin in the context of the emerging field of collective decision-making, animal personality and movement ecology and develop novel methods for the analysis of reality mining questions as they apply to animal systems and human-animal interactions. To that end, we plan to have two longer-term mutual visits by Humboldt-Universität scholars to Princeton and visa versa. Delegations will include the PIs and selected doctoral students and postdocs for a total core group of ten people, and we tentatively plan for one week visits. We will use the first visit timed to November 2014 to Princeton to develop and consolidate research plans, which will then be distributed to all graduate students listed in Table 1. It is planned to do the exchange visit of a core group in August 2015 to Berlin to finalize the research products (e.g., software, manuscripts, chapters in PhD projects). The time between November 2014 and August 2015 will be used to do the research, which will be integrated into ongoing PhD and postdoc projects. Running of the one-year research programme will be organized over Skype and email as is typical in joint research projects. Cost for these initiatives relate to travel, accommodation and per diem allowances for in total 20 people as detailed in the proposal form.

[2] Summer school for graduates and postdocs: The second visit from Princeton scholars to Berlin in August 2015 will be extended by one week during which we plan to host an international summer school on the reality mining of animal-human systems. The summer school will be advertised after November 2014 to attract 20 graduate students or post docs to focus on data collection, methods (e.g., robotics) and analysis and computational tools for high resolution data set. Access to the summer school will be prioritized to internal candidates, but we will reserve 8 slots for international attendees. Funding to attend the summer school is not part of the budget, only operating costs and travel costs for invited speakers will be claimed. It is hoped that the university can provide meeting facilities as in-kind support. The summer school will be designed so that PIs of the Princeton-Humboldt-Universität initiative will serve as lecturers and teachers to train the international graduate students in cutting edge methods of analysis and presentation of high resolution data sets.

[3] Research-based graduate teaching: PIs at Humboldt-Universität are engaged in a range of master-level programs. We will use the first visit in Princeton in November 2014 to identify a range of projects that are amendable for interdisciplinary study projects or for master theses. We will popularize the topics in ongoing teaching modules (e.g., in the module “Experimental fish behaviour” or “Integrative Fisheries Management” in the winter semester 2014/2015 at Humboldt-Universität zu Berlin and within the Humboldt master programs in Biology and Physics) to recruit students. These students will then be jointly supervised by Princeton and Humboldt scholars to help graduate students enjoy working on cutting edge questions in world-wide leading groups, while at the same time fulfilling curriculum demands. Successful students will present their work at the above mentioned summer school in August 2015.

Available data sets and proposed analysis strategy

We propose to focus our initiatives on the following questions, data sources and analysis strategies, each contributing to papers and chapters of the involved postdocs and PhD students (Table 1) as well as serving the teaching purpose in the international summer school.

Aquatic organisms

Personality, social structure and predator-prey interactions of lentic fish in the wild: Since 2009, the Arlinghaus lab at Humboldt-Universität runs a 3-D underwater tracking system in a natural lake in the Biosphere Schorfheide-Chorin. The telemetry system spans the entire lake and allows the tracking of up to 120,000 fish on the same frequency (ultrasound at 200 kHz).

Table 1: Current list of PIs and associated Post-Docs and PhDs. Only selected people (about 10 of each partner) will take part in the physical exchange, but all will work in smaller subteams in one way or another on reality mining topics.

Professor	Affiliation	Expertise	Post-Docs and Phds
Humbolt-Universität zu Berlin			
Robert Arlinghaus (lead PI)	Faculty of Agriculture and Horticulture, Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB)	Fisheries, fish behavioral ecology, human behavior	1: PhD Christopher Monk (Btype) 2: Postdoc Shin Nakayama (HU Fellow) 3: Postdoc Josep Alos (Marie Curie Fellow)
Dirk Brockmann	Institute for Theoretical Biology, Robert Koch Institute (RKI)	Complex Systems, Anomalous Transport, Lévy Flights, Network Science	1: PhD Olga Baranov (RKI PhD Fellow) 2: Postdoc Shen Li (RKI)
Verena Hafner	Computer Sciences	Cognitive Robotics	1: PhD Damien Drix (DFG) 2: PhD Sasa Bodiroza (EU) 3: PhD Oswald Berthold (DFG) 4: PhD Christian Blum (DFG) 5: Postdoc Guido Schillaci (EU)
Edda Klipp	Institute of Biology	Theoretical Biophysics	1: PhD Wolfgang Giese 2: PhD Max Schelker 3: PhD Katja Tummler 4: PhD Friedemann Uschner 5: Postdoc Thomas Spiesser 6: Postdoc Clemens Kühn 7: Postdoc Max Flöttmann
Jens Krause	Faculty of Agriculture and IGB	Collective decision-making	1: Senior Scientist Max Wolf (IGB) 2: Postdoc Ralf Kurvers (BType) 3: Postdoc David Bierbach (BType)
Lutz Schimansky-Geier	Institute of Physics	Stochastic Processes	1: PhD Paul Radtke 2: PhD Bernard Sonnenschein 3: Postdoc Artur Straube
Princeton University			
Iain Couzin (lead PI)	Department of Ecology and Evolutionary Biology	Collective Animal Behaviour	1: PhD Jaan Altosaar 2: PhD Andrew Berdahl (with Simon Levin) 3: PhD Matt Grobis 4: PhD Olivia Guayasamin 5: PhD Albert Kao 6: PhD Simon Leblanc (with Simon Levin) 7: PhD Ariana Strandburg-Peshkin 8: PhD Colin Twomey 9: Postdoc Sean Fogarty 10: Postdoc Andrew Hein (with Levin/Leonard) 11: Postdoc Haishan Wu
Naomi Leonard	Mechanical and Aerospace Engineering	Control and Dynamical Systems, Robotics	1: PhD Katherine Fitch 2: PhD Paul Reverdy 3: PhD Will Scott 4: PhD Tian Shen 5: Postdoc Vaibhav Srivastava
Simon Levin	Department of Ecology and Evolutionary Biology	Theoretical Ecology	1: PhD Eleanor Brush 2: PhD Charlotte Chang 3: PhD Lisa McManus 4: PhD Andrew Tilman 5: PhD Emma Fuller 6: Postdoc James Waters (with Couzin) 7: Postdoc Juan Bonachela 8: Postdoc Frants Jensen (with Couzin/Rubenstein)
Daniel Rubenstein	Department of Ecology and Evolutionary Biology	Animal Behavior, Zoology	1: PhD Ipek Kulachi 2: PhD Jennifer Schieltz 3: PhD Qing Cao 4: Postdoc Wilfred Odadi

The system allows high resolution insights into what wild fish of different species do 24/7 [2]. From 2009 to 2013 high resolution positional data of all major top predatory fishes existing in the lake were collected (perch, *Perca fluviatilis*, catfish, *Silurus glanis*, and pike, *Esox lucius*). The data will be used for answering research question on the existence of personality in fish, the stability of social structure and the interactions of fish and human predators.

Position, posture, sensory data and social structure in wild-living guppies and lemon sharks and other schooling fish: The Krause lab contributes data sets on small populations of individually tracked fish (guppy, *Poecilia reticulata*, and lemon shark, *Negaprion brevirostris*) that were collected in the field over multiple years. Positional data of entire schools were extracted from video recordings, each lasting 60 to 90 minutes. The main aim of the project is to understand the social dynamics of these species, which can be used to model and predict population differences and processes such as disease and information transmission. The Couzin Lab has developed software that allows the tracking of the position and body posture of all individuals within groups, as well as to reconstruct (computationally) their time-varying visual fields. This software can automatically recognize individuals and deal with a high degree of occlusion (Fig. 2). This allows the analysis of extremely high-resolution data on a range of fish species, including Golden shiners (*Notemigonus crysoleucas*) and zebrafish (*Danio rerio*) in groups of up to 1000 individuals – a technique that will be applied to the above-mentioned data sets on guppies to study leadership, collective decision-making and collective evasion of predators by fish in the laboratory.

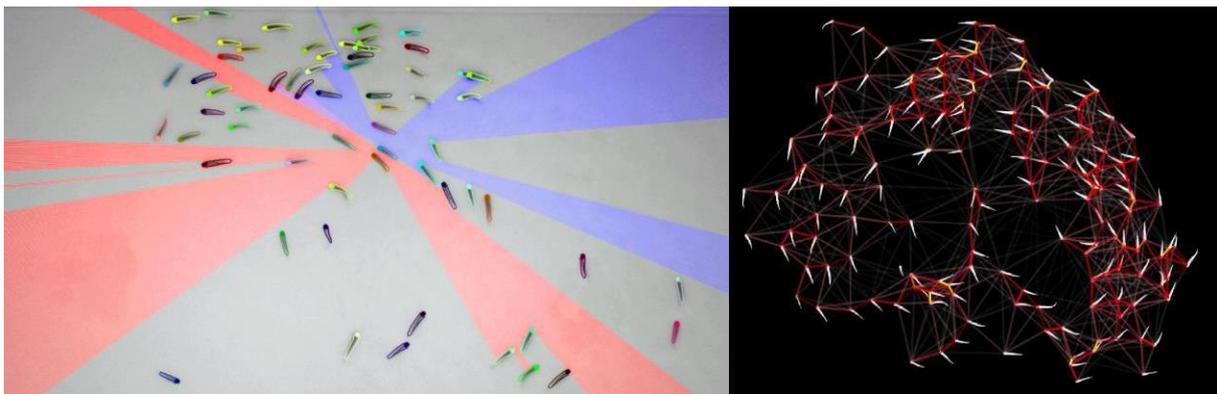


Fig. 2. Left, Visual field reconstruction for a focal individual. Ray-casting is used to determine, from each eye (for each individual) the bodies or boundaries visible. Many thousands of equally-spaced rays are cast from the eye to represent the line of sight in all directions. Each ray terminates at a surface: the body of another fish, the fish's own body, the tank wall, objects, etc. Here the rays are superimposed on a tracked video frame (red = left eye, blue = right eye). Right. A frame showing the network of social influence and susceptibility to social influence in a group of Golden shiner fish.

Social dynamics of marine fishers in relation to their fish prey: Princeton and Humboldt-Universität will closely integrate their two data set to answer common research questions in relation to the social dynamics of fishers. The Arlinghaus lab has detailed spatial-data on fish and fishers distribution and movement across four years in an important recreational fishery in the Mediterranean. Detailed maps of the fish density have been developed for a high profile sedentary marine fish, the pearly razorfish (*Xyrichtys novacula*), using fishery-independent underwater-video recording. Additionally, over 60 fish have been equipped with ultrasonic transmitters and their movement has been characterized using a state-based model. The aim of the study is to identify optimal search strategies by the human predator. A similar data set is currently being compiled by the Levin lab in Princeton using commercial fisheries data in the USA. Data on fisher behaviour have been collected using GPS-based Vessel Monitoring Systems for a range of fisheries along the West coast. Agent-based models will be constructed to fit empirical data and understand social decision making and the patterns of cooperation among fishing fleets as they exploit ecologically different sedentary (sablefish, *Anoplopoma fimbria*) or more mobile fish species (Pacific hake, *Merluccius productus*).

Terrestrial organisms

Movement and predator prey interactions in terrestrial animals: Over the years the Rubenstein and Couzin labs have collected extremely sophisticated data sets on animal movement and interactions in both the laboratory, and the field, using computer vision for automated tracking, body posture and visual field reconstruction. A range of large-bodied wild-living animals (e.g. zebras, giraffes, cheetahs, leopards, and lions) have been monitored using GPS-based collars for their movement, and associations among individuals of species have been detected with visual marks across thousands of square kilometres of African savannas using sightings by scientists, camera traps, drone aircraft and even ecotourists serving as citizen scientists [15]. Individual recognition algorithms have been developed that operate in real time and feed image data as well as meta-data from satellites into an Image Based Ecological Information System data base. In cooperation with the theoretical groups at Humboldt-Universität (e.g., Brockmann lab) the main goal is to test modern foraging search theories in relation to predator prey interactions.

Animal welfare in livestock: Zebra locations, either from GPS collars or photographs run through image based recognition software and those of GPS tagged cattle will be gathered by the start of this grant to assess how environmental circumstance moves interactions between these species from mutualistic to competitive interactions. In addition, simultaneous GPS fixes from collared zebras and lions are creating a high resolution data sets that can be used to determine whether zebras ‘pull’, or ‘lions’ push lions about the landscape and for helping herders adjust grazing routes to minimize predation risk and elevate animal welfare [16].

Analysis strategy

The development of novel computational, modeling and theoretical tools to “make sense” of high resolution observational data is a rapidly emerging research area. However, despite the abundance of sophisticated theories, e.g. concerning efficient animal foraging strategies and search patterns [17], involving fractional diffusion equations [18], metapopulation models, superdiffusive Lévy flights [14], and intermittent processes [13], it has been currently difficult to test different theories and models because of the lack of high-resolution spatio-temporal data. Furthermore, recent theoretic investigations and models have concentrated either on animal movement or on social interactions and local behavior. No theoretical framework exists that investigates both, movement and interactions, in a combined framework and on multiple scales, not to mention the impact of human-animal interactions. The quality of data that has been generated by empirical fish and wildlife biologists of this proposal can be a game changer in this context.

The theoretical and computational groups of the present proposal have been at the forefront of the development of solutions to “Big Data” analysis in ecology, and we thus expect significant synergies by cofocusing our expertises under the umbrella of the proposed centre. We will start analysing the above mentioned data sets with a variety of modelling approaches that use methods from dynamical systems theory, non-equilibrium statistical physics, network theory, anomalous and fractional diffusion, non-linear stochastic processes and systems biology. We plan to develop different types of models ranging from conceptual heuristic to mechanistic agent-based computational models. Each group of each PI (Table 1) within the consortium will select the most suitable approach for his or her particular data as elaborated before. It will be unrealistic to expect all research questions will be answered by the end of this one year seed grant, but we hope to have made enough progress to have selected research products in advanced state of completion and have enough first data to write follow-up grants. Three broad classes of models our consortium plans to apply:

Heuristic (or conceptual) models help to describe broad causal relationships that are independent of particular mechanisms. We will apply such techniques to the analysis of the high-resolution positional data on the top predatory fishes in Lake Döllnsee as well as the fisher movement data along the razorfish fishery in the Mediterranean and the West coast of the USA to

classify differences in population-level spatial and temporal distributions of foragers in relation to individual movement behaviors and underlying fish resource dynamics (in the case of fisher behavior). Heuristic models also include the abundance of statistical physics-derived, descriptive models that employ fractional diffusion equations, superdiffusive Lévy flights and correlated random walk processes. Using these approaches, we plan to test whether foragers' movement patterns can be described by these processes. We will also investigate scenarios where these idealized models fail and require extensions. The precision and abundance of data offers a unique opportunity, for example, to extract important scaling exponents that play a role in fractional diffusion. Knowledge of these exponents can then be compared to predictions of a variety of theoretically predicted exponents which will allow ruling out specific models and identifying alternative candidate models.

Phenomenological models, which usually are statistical in nature, summarize observed movement patterns and will be used to establish associations between variables without necessarily having cause-and-effect relations. We will apply such approaches to determine relationships between space use of fish, fishers and terrestrial animals and environmental variables. Examples of the family of models that we will use are Fourier and wavelet analyses to detect periodicity in movement, and hidden Markov models to identify state changes (e.g., refuge seeking versus active mode). We will then relate state changes to individual-level characteristics or environmental variables.

Mechanistic models are explicit attempts to explain movement observations by an underlying model that specifies the mechanism at play. We will mainly use agent-based models to understand the mechanisms (e.g., memory, cooperation, interference, habits) that lead to the observed movement patterns. Agent based models are predominantly computational models in which individual movement behavior and interaction between mobile agents is encoded *in silico*. These types of models are particularly valuable in combination with heuristic models to test and determine potentially unexpected behavior that emerges as a consequence of the model's dynamic components. Furthermore, agent based models are flexible in design and amenable to incorporate behavioural variability in the agent set, e.g. different types of *in silico* species can be models as part of a whole systems. Finally, these types of models can be extremely important to students that will participate in the proposed research because these types of models do not require a significant experience of programming skills and overhead.

We will also aim at combination of mechanistic and phenomenological approaches. In particular, hierarchical modelling approaches using state-based modelling, which account for observed patterns generated by putative hidden processes that change in space and time [19], will be used. The versatile toolbox of hidden Markov models segments paths observed in the data by mixing mechanistic modelling of the movement process (as for example shown as biased or correlated random walks) with a statistical procedure for distinguishing and clustering the component walks [2]. Social networks and hidden Markov models can then be used in an integrated fashion to understand the mechanism behind observations. Vertebrate social network studies are still dominated by pattern recognition [2] whereas our aim is to develop dynamic models of social behaviour that start with the fission-fusion dynamics as in the case of the guppy data set [20-21].

For the highest resolution data we have, the ones on schooling fish, for which we have position, body posture and reconstructed visual fields (Fig. 2), we will develop approaches that take into explicit account the sensory information used to make movement decisions. Organisms are state-dependent, probabilistic decision-making agents, who must map complex, high-dimensional sensory input to a relatively low-dimensional behavioral output, and these data will allow us to move beyond the existing paradigm of considering individuals as abstract "self-propelled particles". We will map sensory cues to functional behavior allowing us to construct quantitative networks of social influence, and susceptibility to influence, and will employ multi-scale network analysis to determine how socially contagious behavior propagates through groups in different ecological contexts [see 22-24 for some high profile applications of the Couzin lab]. This will allow us to predict how behavioral change of an individual in a group will influence collective dynamics and will provide the basis for next-generation models of collective animal behavior.

Situation of PIs and their research in the partnership

The research groups that we have put together (Table 1) involves empirical behavioural ecologists from biological and agricultural units who will contribute high resolution data sets, engineers and computer scientists who will contribute machine learning and robotics techniques, and physicists and theoretical evolutionary ecologists who will contribute statistical and modelling techniques. We have matched competencies at both universities so that for each core competency we include one professor as PI from both Humboldt-Universität and Princeton. Each group excels in his or her particular expertise and will contribute a key ingredient to solving the puzzle of studying animal behaviour in the laboratory and in the wild at unprecedented detail.

Lead PIs of the initiative are Prof. Dr. Robert Arlinghaus at Humboldt-Universität and Prof. Iain D. Couzin at Princeton University. Both are mid-career tenured professors with complementary expertise in the field of fish behaviour and fisheries management (Arlinghaus) and collective behaviour of animals (Couzin). The other PIs contribute specialized knowledge in collective decisions and behavioural ecology (Prof. Dr. Jens Krause Humboldt-University matched to Prof. Dr. Daniel Rubenstein Princeton University), theoretical physics, biomathematics, biophysics and complexity sciences (Prof. Dr. Dirk Brockmann, Prof. Dr. Lutz Schimansky-Geier, Prof. Dr. Edda Klipp Humboldt-Universität matched to Prof. Dr. Simon Levin, Prof. Dr. Iain Couzin and Prof. Dr. Naomi Leonard Princeton University) and robotics, control theory and computer sciences (Prof. Dr. Verena Hafner Humboldt-Universität matched to Prof. Dr. Naomi Leonard Princeton University). Arlinghaus, Couzin, Rubenstein and Krause will be responsible for generating and contributing high resolution data sets on animal and human behaviour in the wild, Brockmann, Schimansky-Geier, Klipp, Levin, Couzin & Leonard will be contributing novel statistical and mathematical tool kits, and Hafner and Leonard will contribute novel solution of developing robotics and control theory for experimental studies.

The group as a whole offers four outstanding qualities. First, PIs are already at the forefront of studies on collective decision making of animals as evidenced by numerous papers in the top ranked journals such as Science, Nature, Proceedings of the National Academy of Sciences of the USA and Current Biology and moreover have been at the forefront in defining the applicability of reality mining ideas to animal social systems as evidence by a review article in Trends in Ecology and Evolution [2]; however, there are limited recent joint papers bridging Humboldt-Universität und Princeton in this area, which will be fostered by the present initiative. Second, PIs are able to draw unique data from a range of cutting edge positioning systems and interactive robots. Available data include 2D and 3D imaging of human crowds and schooling fish, 3-D telemetry systems covering an entire lake in Brandenburg (Germany), terrestrial animals assessed using GPS and Unmanned Aerial Vehicle systems in Africa (see above), and interactive robotics for use in experimental settings. Third, there is already evidence of successful collaboration among some of the PIs, although the initiative planned here is entirely new as is the mix of people involved. Finally, there exists substantial complementary third-party funding for human resources and data collection (see below). The initiative will also strengthen the networks with associated research organizations, in particular the IGB.

Contribution to international aspirations of the home unit

Humboldt-Universität zu Berlin: The initiative ideally meets the mission of the Faculty of Agriculture and Horticulture (LGF) at Humboldt-Universität in which the lead PI is associated. The LGF stresses the importance of international collaboration to meet pressing environmental and agricultural challenges facing humanity. The LGF is already well connected to 30 international university partners, but there is no explicit link to the prestigious Princeton University. Some of the Humboldt PIs (Jens Krause and Lutz Schimansky-Geier) have previously collaborated and published papers with selected Princeton PIs, but the virtual Centre proposed here should provide global visibility and research output that is evidence of a more cohesive collaboration. Seven out of 9 masters programs at the LGF

at Humboldt-Universität are delivered in English rather than in the German language, which is evidence of the international orientation of the LGF. This also provides ideal conditions to integrate the Centre's PIs into ongoing teaching and student supervision, for example in the international Masters of Fishery Science & Aquaculture. The competences brought together within the proposed Centre also support the restructuring of the LGF and its integration with the Institutes of Biology and Psychology within the newly emerging Faculty of Life Sciences. One of the core themes of common interest of the new Faculty is the understanding of human decision-making as elaborated in the concept paper that the steering committee of the reorganization process has recently submitted to the Presidency of Humboldt-Universität. The more applied results expected from the Centre's activities in relation to fisheries and wildlife management will spin off towards the Integrative Research Institute (IRI) Transformation of Human-Environment Systems (THEsys).

Princeton University: Locally, the initiative is ideally suited to draw on Princeton's strengths in the area of collective behaviour and population biology since the Princeton PIs already work together. By melding theoretical, behavioural, ecological and engineering skills, the group is uniquely suited to not only understand the mechanistic rules that connect individual actions to group levels behaviour, but also its underlying environmental determinants. By introducing remote sensing technologies into the study of behaviour this team is also transforming the way behavior is studied. Given the new theoretical and data analysis tools as well as the data sets that become available by partnering with faculty, postdocs and graduate students at Humboldt-Universität the cooperation will bring substance to our vision. The cooperation will in particular facilitate the integration of some of the best datasets on animal movement that exist today and will serve as the foundation by which we can create a lasting interdisciplinary team, necessary to address critical global questions relating to animal movement and human-animal interactions, such as anthropogenic influence on populations and biodiversity. Finally, the cooperation will substantially broaden Princeton's international reach.

References

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