Universität Konstanz

Centre for the Advanced Study of Collective Behaviour

An Overview

I. What is Collective Behaviour and our mission at CASCB?

The behaviour of collectives can be striking and captivating. But what are the mechanisms that lead to the seemingly coordinated movements of flocking birds, the division of labour in social insects, or the emergence of fashions and fads in humans? Capitalising on comprehensive multidisciplinary expertise, institutional build-up, and a unique infrastructure, the University of Konstanz and the Max Planck Institute for Ornithology (MPIO) joined forces to create the Centre for the Advanced Study of Collective Behaviour (CASCB). The CASCB´s mission is to increase our understanding of collective phenomena through theoretically informed yet highly quantitative approaches in a vibrant and globally attractive hotspot for research.

Data-oriented research on collective behaviour requires the study of dynamic, multi-scale and interdependent feedback processes: individual behaviour influences higher-order collective properties (through multilayer networks of interaction), which then influence the behaviour of other individuals, which in turn affects collective properties, and so on.

Simultaneously, it must account for heterogeneity in the actions, traits, and states of individuals as well as changing conditions in their physical and social environments. By bringing together expertise in biology, social psychology, behavioural economics, physics, and computer science, we will develop experimental approaches that will take these complexities into account in order to create a coherent understanding of collectives. Not only do our synergies provide fresh inspiration to the study of collective behaviour, they also enrich the contributing disciplines at the same time. Cutting-edge imaging and tracking technology – including the space-borne ICARUS system, and a new research building with unique facilities – will enable detailed observation in the wild as well as controlled experiments in virtual environments. Together, this allows us to address fundamental questions regarding a wide range of species, from insects to humans, and over multiple scales, from neural mechanisms via individual perception and preferences to collective outcomes in groups or entire societies.

Developing an understanding of and, in some cases, governing collective behaviour is essential for progress in many natural, social, and technological domains. The insights and paradigms generated by our quantitative studies will have implications that range from the fundamental through to the practical. Controlling pest insect swarms, curbing disease transmission, sensing speculative bubbles, incentivising cooperation, and the decentralised control of robot swarms and drones are but a few examples. The captivating dynamic and visual nature of collective behaviour will furthermore give us a distinctive opportunity to engage students and the public in the science behind the complex patterns that interacting individuals create.

II. Objectives of the CASCB as a Cluster of Excellence

1) **To establish a vibrant, interdisciplinary, and world-leading research centre** with the common goal of developing a deep and coherent understanding of the principles that underlie collective behaviour in a range of organisms, including humans, and across scales of organisation.

2) **To create a dynamic and supportive open-house environment**, with regular seminars, workshops, methodological courses, retreats, and visiting programmes, that fosters effective interdisciplinary exchange and exploits the considerable potential for synergies within our centre.

3) **To enable multi-scale analysis and modelling of collective behaviour**, from sensing and neural coding of information, to social interactions within and between groups, to population-level processes.

4) **To reveal the dynamical feedbacks between social network structure and social transmission**, such as the contagion of behaviour/information and/or physiological states (e.g. stress, emotion), taking into account the processes that give rise to, and result from, inter-individual differences.

5) **To reveal the processes that give rise to collective intelligence, and to collective stupidity.** We will seek to understand the conditions under which collective behaviour results in effective higher- order sensing, information processing, and decision-making, as well as those where collective decisions can go (sometimes catastrophically) wrong.

6) **To develop a deeper understanding of the origins of social complexity**, including the role of innovation, social learning, and the behavioural foundations of 'culture' in animal and human populations.

7) **To develop new algorithms for data processing, analysis, and visualisation** that are able to process and prioritise huge and heterogeneous data sets under rigid time constraints, thus enabling massive real-time experiments, e.g. in virtual environments.

8) **To create, employ, and make freely available a new generation of quantitative tools for the study of behaviour** that will have an immediate and lasting impact to a wide range of disciplines including neuroscience, psychology, psychiatry, complex systems, and the behavioural sciences.

9) **To apply concepts of collectives to real-world applications** such as developing policy, conducting interventions, minimising the spread of misinformation or negative physiological states (like stress), and the conservation of group-living species.

10) **To use our new space-based animal tracking system ICARUS to obtain unparalleled data on collectives**, their movements, physiology, and the social and physical environment in the wild; and to employ this global animal collective as an intelligent, networked sensing system for life on the planet.

III. Research Programme

a. Research objectives, research approach, positioning within the research area

Collective behaviour produces some of the most captivating patterns found on Earth: Billions of locusts, extending over hundreds of kilometres, devour vegetation as they move onwards; schools of fish convulse like some animate fluid while under attack from predators; and our own societies are characterised by cities, with buildings and streets full of colour and sound, alive with activity. The characteristic feature of all of these systems is that it is *social interactions* among the individual organisms, be they locusts, fish or humans, that give rise to patterns and structure at higher levels of organisation, from the formation of vast, mobile groups, to the emergence of societies with division of labour, to social norms, opinions, and price dynamics. In all cases, these large-scale "higher-order" properties of the collectives feed back to influence individuals behaviour, which in turn can influence the behaviour of the collective, and so on. Collective behaviour therefore focuses on the study of individuals in the context of how they influence and are influenced by others, taking into account the causes and consequences of inter-individual differences, such as in physiology, motivation, experience, and goals. It especially concerns itself with the individual and higher-order properties that can emerge as we move beyond dyadic (pairwise) interactions to consider the complexities that arise in the dynamic networks of communication that characterise both human and non-human animal systems (that, for simplicity, we henceforth describe as 'human' or 'animal' systems, respectively).

Social interactions, environmental conditions, and inter-individual differences all impact how social organisms make decisions regarding almost every aspect of life, including when or where to move, what to eat, and with whom to associate or mate. Developing a quantitative understanding of and, in some cases, influencing collective behaviour is essential for progress in many natural, social, and technological domains. For instance, the swarm-forming locusts described above contribute to major humanitarian crises and are estimated to impact the livelihood of one in ten people on the planet [6], yet the ability to predict when and where locusts will swarm remains elusive. Bird and bat species are known to be reservoirs of emerging pathogens, yet we often lack basic knowledge regarding where these species migrate. Half of all fish species, accounting for a quarter of all vertebrates, live in groups for at least part of their lives, yet we are only just beginning to reveal how sensory information is employed in their coordinated movements. Humans show many forms of collective behaviour as they create groups for collective action, use division of labour, enact and enforce social norms, and build institutions. Social learning among organisms, including humans, has been shown to profoundly impact the spread of behaviours through social networks and is often considered fundamental to the emergence of local 'cultures' in populations and societies. Yet, while social learning and culture are considered critical facilitators in our colonisation of almost all terrestrial environments, we still lack understanding of its influence on key ecological processes in other social animals.

The broad spectrum of sociality evident in nature, from groups of relatively anonymous individuals that exhibit flexible membership, to stable societies with complex and individualised relationships, provides us with great opportunities to explore the processes that shape collective behaviour. Investigating these systems across taxa and from different disciplinary perspectives will make it possible to identify the commonalities and differences among collective phenomena. To do so, however, we must transcend disciplinary approaches and combine theoretical and empirical perspectives to gain a deeper understanding of general principles of collective behaviour.

1. Research objectives

We aspire to become the leading institution for research on collective behaviour. In the long term we will therefore be open to projects addressing research questions from the whole spectrum of collective behaviours across taxa and environments. To accumulate transferable knowledge, special emphasis will be placed on the establishment and showcasing of techniques and methodology. While a number of themes will guide us through the first funding period and beyond, our research is underpinned by the following fundamental objectives:

- We will seek to isolate principles that extend beyond the specificities of our systems, and to **create a conceptual framework for considering information integration, learning, and decision-making in animal and human collectives**. Such a framework will consist of a body of methods, tools and algorithms, as well as an interdisciplinary culture in which ambitious projects will be carried out.
- We aim to **lay the foundations of an overarching conceptual understanding of collectives**. Biology and human sciences describe collective behaviour using different terminology, utilising different methods, and have developed different research cultures. We will employ quantitative descriptions and precise measurement through new technology to overcome these divisions. While both the framework and such generalised, quantitative descriptions will not automatically lead to a new overarching theory of collective behaviour, it will be a big step in this direction. We will reveal the conditions under which groups achieve robustness and adaptability, the internal structures that promote effective collective decision-making, and the conditions under which collectives fail.
- We will harness our understanding of collectives to **apply these concepts to real-world applications**. This includes the design of effective interaction structures to achieve collective intelligence, and (in some cases) to direct and influence collectives, such as by modifying communication structures, incentives, or even institutions. In the case of animals, understanding the principles of their social organisation will help us to develop policy and interventions that will aid the conservation of group-living species. In addition, mankind can benefit from collectives by developing the science and technology required to employ animal collectives as a global sensor network to assess the changing health of our planet.

2. Research approach

Collective behaviour is an evocative term. Since the early days of group psychology and mass phenomena [22, 44, 21] it has been defined [29] and re-defined [5, 3] for humans and other animals [48]. In the sociological and psychological research traditions, the term has long been applied to episodic phenomena in which structural strain results in a change of the components of social action [38], whereas research on animal collective behaviour [8] has focused on processes of self-organisation whereby group structures, movements and behaviour result from relatively local social interactions. Research on social contagion focuses on transmission (spreading) processes [34], while collective intelligence focuses on the pooling of information to make better decisions [23]. Central to the study of collective behaviour, across systems and scales of organisation, are social feedbacks: individuals both influence, and are influenced by, one another. Whereas this can result in interesting properties even among two individuals, new dynamical relationships and complex feedbacks often arise as group size grows.

In the biological sciences, much progress has been made by considering how simple interactions can give rise to group structure and collective motion. Classic models of mobile groups (such as herds, flocks and schools) consider individuals as “self-propelled particles” that (inspired by collective processes in physical systems) interact with near-neighbours through “social forces”, such as short-range repulsion and a longer-range tendency to be attracted towards and/or to align direction of travel with near-neighbours [33, 46, 8, 7]. Despite the importance of these models in establishing this research field, we must move beyond this perspective if we are to progress in our understanding of collectives. Organisms are not self-propelled particles; they are decision-making entities, and while spatial relations do inform interactions between individuals, they do so indirectly through individuals’ detection of sensory cues and signals. Furthermore, although averaging pairwise interactions makes sense in classical physical systems, it often makes little sense when considering interactions among animals, since it inevitably results in information being damped out. Thus, existing models cannot account for selective amplification of stimuli, or the explicitly directed nature of interactions (individual A may be more strongly influenced by individual B than vice versa) and thus fail to appropriately describe the corresponding dynamics of social transmission in real animal groups.

As in animal groups, human societies display collective properties that are beyond the mere superposition of interactions. Individuals are entangled in multiple kinds of interactions with others, such as observation, communication, or physical contact. The link between the “micro-level” of individuals and the “macro-level” of the collective is thus formed by dynamic, multi-layer networks of interaction, and it is futile to try and address emergent collective behaviours in any natural system without considering structural causes and effects. Structural characteristics and other outcomes may be associated with differences not only between but also within individuals due to, for instance, their membership in multiple social circles or current stress level.

An integrative approach

We are at a time of unique opportunity to advance the study of collective behaviour. There are especially prescient opportunities to utilise and develop new technologies that will facilitate the integration of behavioural, physiological, neural and ecological studies of collective phenomena, and to do so in a wide range of experimental systems. It is vital, therefore, that we bring together researchers from diverse disciplines to work closely to address common questions across species boundaries. In our centre, we will establish collaborations between scholars from biology, computer science, psychology, economics, physics and sociology. These fields differ in their focal research questions, in the methods they use, and in their state of knowledge. On the one hand, experiments with humans tend to be easy to set up because individuals (often) learn quickly and can easily be exposed to relatively abstract settings (such as tasks presented on computer screens). On the other hand, research with humans has stronger ethical constraints, such as privacy issues, that place restrictions on large-scale observational studies. Moreover, other aspects of human behaviour are much more challenging to investigate, such as natural social interactions in which gestures, body language, gaze, and vocal communication may all play a role. Such studies have considerable parallels with the aims of behavioural experiments on animals, where in many cases we desire similar types of data, and where it is important to approximate naturalistic environments and to study organisms in their wild habitats. Common technological and conceptual objectives of such studies in our centre will bring human and animal researchers even closer together.

While many collective mechanisms have been identified and studied for human collectives (e.g. conformity; norm compliance and enforcement; and markets as mechanisms for information aggregation and differentiation), much less is known about animal collectives. For example, we lack basic knowledge regarding the sensory basis of social interactions in many animal species, and tracking known individuals in large collectives remains extremely challenging. Nevertheless, as will be highlighted in our Research Areas, all fields investigating collective behaviour share common general questions about the nature, causes, and consequences of social feedback mechanisms across scales of organisation. Our approach will be to study and quantitatively measure collective behaviour by considering the actions, traits, and states of individuals, the structures they form and in which they interact, as well as the environmental conditions they are subjected to and create. By doing so we intend to lay the foundations of an overarching conceptual understanding and theory of collectives.

From a *theoretical perspective*, we aim to understand the perceptual, emotional, and cognitive processes and mechanisms that govern individual behaviour in social and physical contexts. We will describe these processes and mechanisms on a behavioural, physiological, and/or neural level. While it is clear that individuals are embedded in manifold physical and social environments, biology and social sciences have typically focused on individual behaviour against a backdrop of social environments. We will investigate behaviour across scales to reveal how individual behaviours and interactions among individuals translate into, and are influenced by, collective behaviour, taking into account processes such as information transmission, preference aggregation, coordination, and cooperation.

Methodologically, studying the interplay between individuals, collectives, and environments requires fine-grained experimental observations and manipulations (e.g. of different types of social information and options for social interaction, and/or the positions, perceptions, and states of many individuals). The design of empirical studies will allow comparison of observed behaviour with computational models and theoretical benchmarks. In terms of technology, breathtaking advances in computer vision, global positioning systems, virtual/augmented reality and machine/deep learning allow us to employ new quantitative approaches in the study of behaviour, and offer unprecedented access to the data streams required to make major advances in the study of collectives. We will position ourselves to maximally harness such existing and emerging technologies. In doing so, we will create a highly dynamic research environment where the depth of the questions we can address, and thus the knowledge we will obtain, will accelerate alongside that of technological change throughout the lifetime of the centre, and beyond.

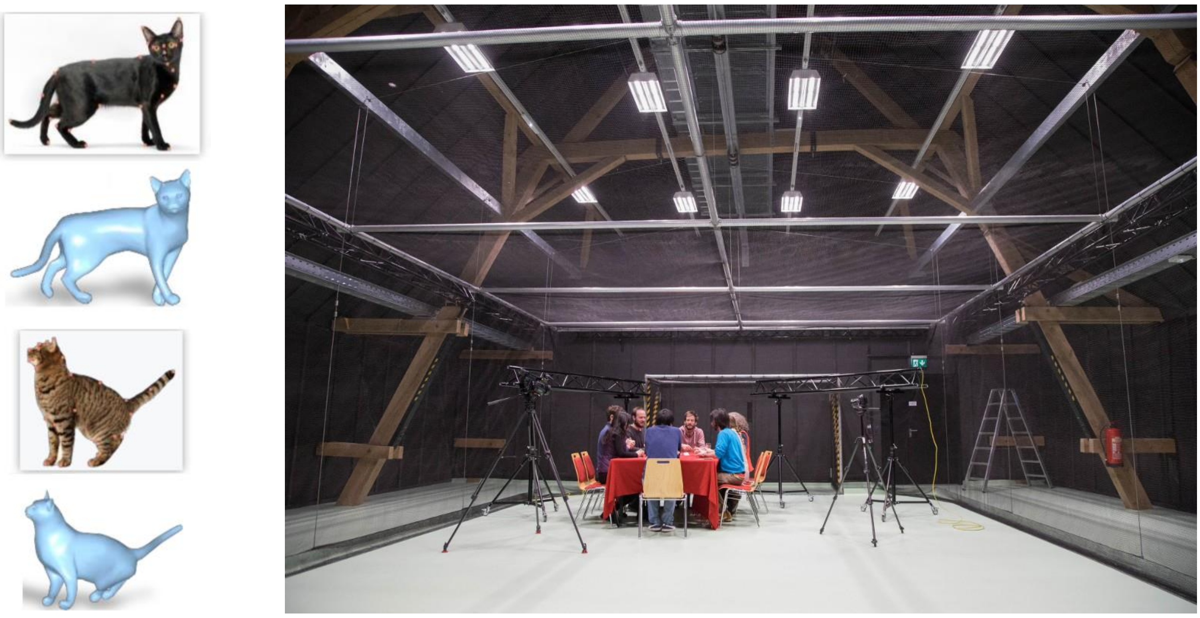
3. Research methodology

Pursuing our centre's research objectives requires that a number of new, quantitative tools and methodologies for measurement, analysis and modelling of collective behaviour be established. This requires innovations in a wide range of computational approaches, including automated tracking of movements and body postures in both humans and animals; unsupervised methods to identify behavioural and physiological states; computational reconstruction of the sensory input; techniques to map sensory input to behavioural output; and new approaches to data management, visualisation and analysis.

Recent advances in computer vision, largely driven by cost-effective and ubiquitous massively- parallel computational hardware (such as programmable graphics processing units) and corre- sponding transformation in the capabilities of deeply structured artificial neural networks (deep learning), now make it possible to achieve 3D reconstruction of complex structures, including the bodies of humans [30,24] and animals [18] (Figure 2).

Such technology sets the scene for the precise estimation of body postural/pose changes of organisms, providing crucial data that is required to quantify behavioural repertoires of individuals, including within collectives. The means by which such data can be obtained include stereo cameras, depth-sensing cameras and also marker-based (e.g. [11])) and marker-less [12, 28] motion capture systems (see [26] for a review).

For many organisms, including insects, fish and birds, such new approaches will provide vital information about how animals acquire information from their physical and social environment. These data can be combined with biological information about the eyes of each organism, such as motion-processing elements, or photoreceptor density and distribution (allowing us to estimate the acute centre(s) of their visual field; some species of birds have two foveae [49]).



(a) (b)

Figure 1: a) Accurate body posture (pose) from images can be obtained for animals as well as humans (image modified from [18]); b) The existing Imaging Barn (MPIO) allows us to perform unprecedented studies on animals and humans.

These approaches will allow us, for the first time, to study the dynamics of highly naturalistic interactions, such as when animals or people meet, eat, or make decisions together. A further technology that we will develop is Virtual Reality (VR) and Augmented Reality (AR), including fully immersive VR for freely moving animals [41]. This allows individuals to be embedded in a photorealistic synthetic world in which they can move and interact with virtual organisms, or inspect, and move around, virtual obstacles, as they do in the real world. To achieve this, we exploit the anamorphic illusion to create a virtual world in full 3D with depth cues. The above-mentioned systems and sensors impose tough constraints on run-time and task-based performance of data analysis. Our experiments on collectives will require real-time analysis to track individuals in the group and, in turn, fast rendering of reactive digital environments. Additionally, data must be analysed to detect and predict (exceptional) events that require very fast actions. To cope with the required low-latency and vast amounts of data, we will devise so-called "anytime" methods to prioritise and filter these data in dynamic and intelligent ways.

The *volume and heterogeneity of our data will be immense*. We will develop tools to integrate the analytic capabilities of computers (e.g. machine learning) with the perceptual and cognitive capabilities of researchers. By supporting hypothesis development and testing, machine learning will be a powerful tool for helping us manage the complex data generated by our research, and for elucidating causality in relationships.

In *humans*, we will investigate both natural social networks as well as more controlled set-ups of groups within the laboratory environment. Our analyses will include the observation of face-to-face interactions in terms of their underlying processes (such as verbal and non-verbal communication) and outcomes (such as who knows what, and from whom). These will be complemented by setting up computer-based experiments that allow us to control important aspects of social interaction (e.g. availability of communication, information conditions, and feedback) and social learning. In addition to establishing novel laboratory experiments, we will set up an infrastructure to conduct online experiments with large groups of people simultaneously. Not only will this allow us to access larger samples, and a larger variety of people, it will also provide the opportunity to fully control and manipulate all aspects of network structure. We will further leverage our interdisciplinary expertise in human and animal behaviour to create protocols that are comparable across species, for instance by establishing game-theoretically equivalent incentives or identifying transferable physiological treatments.

Our *theoretical approaches* will be developed alongside and in close synergy with experimental work. We will employ both numerical (computational) and analytical (mathematical) modelling approaches to explore the principles that underlie collective behaviour across systems and scales. This includes behavioural models at the individual level (e.g. psychological process models as [16], preference models as [31], or [13]; game theoretic models that analyse the strategic situation; and dynamic models of large collectives of interacting individuals). The complex reciprocal interactions and resulting feedbacks in collectives give rise to dynamical and complex networks of interaction, and many collectives exhibit strongly non-linear responses, with properties like hysteresis and sudden transitions in collective state being important features. It is essential, therefore, to employ models (and model-fitting) to understand the causes and consequences of collective behaviour. We will develop theory both to understand specific systems (such models will be informed by our detailed experimental analyses) and to seek general principles of organisation among systems that may initially appear to be disparate. For example, the theory of collective decision-making in mobile animal groups has shown that the same principles operate across vastly different systems, from fish [7] to wild primates [42], and even human groups [9]. In many cases we will employ probabilistic models of networks of interacting elements, taking into account how individuals balance personal information obtained from their own experiences, with social information obtained from observing the behaviour of others, as well as models that capture the spatio-temporal dynamics present in many collective systems. We will take into explicit account the complex networks of communication present in many collectives. We will complement stochastic dynamical modelling with tools from information theory, statistical physics, and machine learning to make notions of information flow concrete. Such approaches will greatly improve our ability to develop and refine hypotheses, and to seek the principles that transcend system specifics.

We often know, or even experimentally manipulate, the incentives of individuals, i.e. their cost and benefits. In social interactions, these incentives also depend on the behaviour of other individuals, which creates strategic incentives. This allows us to use game-theoretic approaches to analyse these situations. Game theory will serve three purposes. First, as the theory for the analysis of strategic situations, it provides useful benchmarks for empirical analysis, and allows for testing of behavioural assumptions, for example about individuals' preferences. Second, it provides interesting strategic situations that can be implemented in experiments by exposing individuals to the incentives (costs and rewards) as defined in these games. For example, how successful individuals are in coordination or dis-coordination games can be examined. Third, it can be used to investigate the evolution of behaviours, in particular the evolutionary stability of behaviour [39].

IV. Structure of the research programme

1. Research areas

Our research areas reflect the overarching research objectives of the centre (see 3.1). We aim to study the individual in the collective (Area A), and how this behaviour aggregates in the collective (Area B), using theory-based empirical studies that exploit high-tech computational methods (Area C).

Area A: Social Influence and Transmission

Social transmission among individuals is essential for the coordination of collective behaviour across scales of organisation from animal groups [43] to social [17] and economic [36] systems. In this area we will focus on the individual within the collective, investigating how they acquire information regarding their social and physical environment; how behaviour, information, and physiological states can be socially transmitted among individuals; and the impact this has on social organisation. When considering transmission, we need to consider the mechanism of social transmission. This can be passive, such as when individuals respond to cues. *Cues*, such as the sudden turn by an individual being copied by neighbours, or a person's response to changing stock prices, are inadvertent sources of information. That is, cues have not evolved specifically to convey information, but they may nevertheless do so. *Signals*, on the other hand, are active sources of information, such as alarm calls in birds, or verbal communication among humans. Signals are sent with the specific purpose of conveying information (although both animals and humans may be misinformed, or even deliberately mislead [45]). These sources of social information tend to be integrated with personally-acquired information, and organisms subsequently make a decision as to how (or whether) to respond.

Transmission describes how physiological states, behavioural changes, and/or information spread in a collective (we separate information from behavioural changes since the latter may, in some cases, be an arbitrary response that does not reduce uncertainty, and thus does not convey information [15]). Although transmission is a direct consequence of passive or active influence, it requires an additional understanding of the pathways of communication, and consequently typically the group structure. We will extend the analysis of information flow and behaviour within collectives to consider two key properties: behavioural innovation (the means by which new behaviours or solutions to problems arise in populations) and the spread of behaviour and innovations via processes of social learning. Rare innovation events can profoundly impact populations, and can even result in cumulative innovations (innovations that build upon each other). We will bring together studies of social learning and collective behaviour to employ highly quantitative methods.

Area B: Collective Intelligence and Decision-Making

Area B extends the concepts introduced in Area A, and while maintaining the themes of social influence and transmission processes, it will bring the *reciprocal social feedbacks* among individuals into focus, whereby individuals both influence others, and are in turn influenced by them. Area B will not only consider the mechanism, but also the consequences of collective action, as well as the aggregation of behaviour, preferences, and information that produce collective decisions. It will explore centralised and decentralised decision-making, and will connect proximate understanding of how mechanisms of social influence and information relate to the outcomes (and, in the case of animals, the fitness consequences) of collective decisions, as well as how they feed back to influence individuals, and so on. For the analysis of strategic situations, which always

result if the individual cost and benefit depend on the actions of other individuals, we will apply game-theoretic methods, which are particularly useful in situations where conflicting interests are present in collectives.

We will investigate the relationship between group size, inter-individual differences, group structure (including internal modular and hierarchical structures) and the speed and accuracy of collective decisions. In addition, we will move beyond the 'group' to consider interacting collectives within the context of the complex, multi-layered, and dynamical social networks that characterise many populations. Finally, we will seek to exploit our scientific knowledge for real-world human applications, including institutional design (for instance by informing environmental or public health policies, wildlife protection, or autonomous system design) and using the vast collective of instrumented animals on our planet to obtain vital information about processes like anthropogenic disturbances, climate change, and even to help forecast future events. In doing so, we will obtain unique data regarding collective behaviour on a global scale.

Area C: Computational Methods for Measuring and Analysing Behaviour

Our ambitious plans for data collection synergise with important and interesting computational challenges, from tracking and behavioural analysis, to building reactive and interactive virtual environments, and the management, visualisation, and analysis of vast and heterogeneous datasets. We will develop progressive methods for data processing and analysis that will allow us to filter and process data within given time constraints and to enable visual analytics. New modelling methods will be investigated to describe complex collectives and their interaction. In addition, we will develop a Collective Computation Unit (CCU) that will provide essential computational and technical support to researchers, including imaging, machine learning, storage, and support in data analysis and visualisation. The CCU will also connect our researchers with relevant experts from our Computer and Information Science department and from outside the university.

V. Research Questions

1. Research Area A: Social Influence and Transmission

Research objectives and questions: In this area, we focus on the role of social influence on the individual within the collective, paying particular attention to the mechanism of transmission of behaviours, physiological states, and information among individuals ('spreading' processes). Regardless of the study system, we aim to conduct experiments in which we can measure, and in some cases manipulate directly, the pathways of communication/influence in collectives, taking into account inter-individual differences, such as differences in individuals' prior experience, expectations, preferences, and internal states (such as motivation or stress). As outlined below, there is a lot of value in considering these collective behaviours across diverse systems, from insects to humans.

Research Question 1: What is the relation between individual cognition and social complexity?
Research Question 2: How does physiological state spread in collectives?
Research Question 3: How does information/behaviour spread in collectives?
Research Question 4: How can we develop/improve the observation, analysis, and modelling of transmission processes occurring in complex social networks?
Research Question 5: What are the behavioural foundations of animal and human culture?

1. **What is the relation between individual cognition and social complexity?** By taking an approach that scales levels of biological organisation, we will address a series of questions that seek to establish the degree to which relatively small brains, such as in insects and fish, can facilitate social complexity.

- Do apparently complex cognitive processes result from relatively simple 'rules of thumb'/approxi- mations, or are small social brains more sophisticated than we presently think?
- How do individuals reconcile personally- and socially-acquired information, and how are these represented/structured in circuits in the brain?
- Non-human animals are known to exhibit cognitive bias (where inferences about other animals are affected by irrelevant information and physiological states), but are they also subject to other 'human-like' psychological fallacies such as confirmation bias?
- How can we harness our understanding of how individual cognition relates to the emergence of social complexity to inform man-made technologies, such as to guide the implementation of 'complex' social strategies in technological applications, including swarm robotics?

2. **How does physiological state spread in collectives?** Collective behaviour has pre-dominantly focused on the spread of behaviours, skills, opinions, or information within groups and populations. However, there exists enormous potential to also consider the social contagion of physiological states, such as stress or emotion. We have all experienced a tangible 'tension', or a good or bad 'vibe', when in collective situations. Yet there is little empirical work addressing the

scientific basis of such processes, or their consequences.

- What are the feedbacks between physiological state(s), social network structure, and the spread of information/skills/behaviours across networks?
- How can these feedback processes be manipulated (e.g. via modifying network structure and/or influencing individuals with specific network positions) to prevent negative physiological states (like stress) from spreading – and are such modifications feasible/ethical in real-world social networks?
- How quickly, and over what scale, can physiological states percolate through real-world (complex and dynamic) social networks?
- Can we achieve real-time assessment of physiological states (as well as autonomic states) in both the laboratory and under natural conditions – and if so, how can this (in combination with the above questions) be employed to improve the quality of animal and human lives?

3. How does information/behaviour spread in collectives? While a lot of work has been conducted on the spread of information and behaviour, much remains unknown. In non-human animals, for example, it has proved extremely hard to quantify transmission of information. Unlike for humans, it can often be very unclear what (if anything) is being transmitted in social networks. Where properties like changes of behaviour are seen to percolate through groups, it is still often ambiguous as to whether this conveys information (to do so, it must meaningfully reduce uncertainty). In human research, there is a growing body of literature on opinion dynamics and social contagion covering diverse topics such as political beliefs, risk perceptions, and health behaviours. Besides investigating how information and behaviours spread, this research is also concerned with impact and development of heterogeneity and collective outcomes such as polarisation. The biggest remaining challenge is the trade-off between assessing actually relevant behaviours and beliefs in real-world settings on the one hand, and a precise observation or even experimental manipulation of the underlying mechanisms and network structures on the other. We plan to overcome this challenge by re-assessing real behaviours and beliefs in natural social networks and by expanding upon existing experimental studies in which transmission dynamics and network structure can be manipulated in a controlled fashion.

- How does information degrade, become amplified, and/or become distorted during transmission?
- "Computation" and "information processing" are often used colloquially when discussing biological networks – how can we develop a well-grounded information-theoretic formalism that will make these notions concrete?
- How do individuals differ in their susceptibility to social influence and what affects it?
- How do individual perceptual and cognitive biases impact transmission (e.g. the amplification of mis-information)?
- Does the mechanism of transmission within groups also account for that between groups? Do other processes, such as within-group affiliations/group-identity, influence transmission, and if so how?
- Do non-responders act to passively, or actively, inhibit the spread of information and/or behaviour in collectives?

- In neurobiology it is known that neurones, or neural circuits, can reduce problems associated with correlated information by amplifying temporally close, but spatially distributed input: do organisms also act in the same way to de-correlate social information (as is suggested by some studies on humans [45]). If so, how is this encoded at different levels of social complexity?

4. How can we observe, analyse, and model transmission processes on complex social networks? Social networks can be highly complex, with weighted, directed, and time-varying social connectivity being the norm, not the exception. In addition, individuals in social networks are often connected by multiple types of connections (e.g. connections among family members or close friends are often fundamentally different from those among work colleagues). Furthermore, information may be propagated in different ways on the same, or on multiple interacting, networks. For example, different sensory modalities can have very different scales of propagation and sensing (e.g. a signal such as an alarm call in birds may be broadcast widely, whereas cues informing individuals of whether others are feeding or not may be much more local). To differentiate among processes, temporal changes in both network structure and behaviour must be observed, analysed, and modelled (e.g. [40,19]).

- Which computational tools are needed to reveal the time-varying functional pathways of social connectivity and information flow among organisms, including humans, in natural contexts?
- What mathematical formalisms (statistical mechanics, control theory, information theory, game theory, and Bayesian inference) are needed to investigate the reciprocal relation between node properties, network behaviour, and network function on a theoretical and experimental level?
- With such experimentally-derived theory, can we predict (and where ethically-appropriate, manipulate effectively) the transmission dynamics on real-world animal and human networks?
- If so, can we utilise this theoretical foundation to design network structures that have desirable properties, such as to facilitate fast, yet undistorted, spreading of information?

5. What are the behavioural foundations of animal and human culture? The spread of innovation, and the generation of cumulative innovations via social learning, represents a multi-scale transmission process that has considerable implications for our understanding of social complexity and the behavioural foundations of culture.

- Under what conditions is social learning adaptive [20,32]?
- To what extent can we consider processes like social norms and enforcement to occur in non-human species?
- What are the neural and behavioural mechanisms underlying the process of social learning and what are the differences between social learning in humans and other species [27]?
- When should we expect individual innovation as opposed to social learning [10]?
- Can the diffusion of innovations via social learning provide a mechanism for behavioural flexibility at the population level [1]?
- How has human culture evolved, and can we observe analogous cultural processes in other species?

2. Research Area B: Collective intelligence and decision-making

Research objectives and questions: In Area B (extending upon the approaches developed in Area A) we consider the consequences of collective action by focusing on the aggregation of behaviour, preferences, and information to produce collective decisions. While social influence and transmission are still central, here we place additional emphasis on the feedbacks from collective outcomes (such as the positive or negative consequences of collective decisions) to the individuals. Collective decisions impact all aspects of individuals' lives. For mobile animal groups, such decisions influence strongly where and when to move, and consequently individuals' exposure to risk, and their ability to regulate nutritional requirements. For humans, collective decision-making occurs across scales of social organisation, from within family groups, to businesses, institutions, and governments. In many cases, collective decisions made at one scale may impact those made at others, and consequently the aggregation of opinions must be considered within the context of the dynamical structure of social networks.

Research Question 1: How does the composition, size, and social/communicative structure of groups impact collective decision-making?
Research Question 2: How can groups exhibit both robustness and flexibility?
Research Question 3: How can we infer causality of influence in decision-making groups? Research Question 4: When do collectives fail and can we predict this?
Research Question 5: How can we exploit our advancements in the science of collective intelligence for real-world applications?

1. How does the composition, size, and social/communicative structure of groups impact collective decision-making? Analysis of real-world social networks will be used to develop new theories for social (and socially-inspired) sensing and decision-making networks. Building on the research performed in Area A (the active and passive processes utilised for information transfer), we will take into explicit account the probabilistic inference and decision-making capabilities of organisms, such as how they balance personal information obtained from their own experiences with social information obtained from observing the behaviour of others. Within this theme we will ask:

- How do properties such as individual expertise, biases, and individual-level self-interests affect and become affected by network structure?
- What are the consequences of the above properties on the speed and accuracy of collective decision-making?
- What disparities occur, and when, between top-down optimisation and game-theoretic solutions?
- To what extent can we inform new design principles for structuring groups or institutions to achieve more effective decision-making?
- Over the longer term, can we extend these analyses to the population-scale to consider explicitly inter-group interactions? Here, we anticipate to find important new dynamics and

interaction terms impacting processes such as polarisation of opinions/preferences and social learning.

2. How can groups exhibit both robustness and flexibility? Animal groups exhibit the seemingly opposing properties of being both robust to noise (such as to gusts of wind, or eddies), and yet sensitive to input (whereby the change of behaviour in only a few individuals responding to a predator can rapidly dictate the motion of the entire group). How this is achieved is not yet understood. These groups offer a unique opportunity to reveal and model the mathematical principles that underlie robustness and adaptability in complex systems.

- To what extent is it possible, by employing an integrative experimental and theoretical approach, using numerical and analytic methods, to develop a quantitative understanding of information transfer processes in animal collectives?
- What properties of real-world communication networks determine the dual-nature of robustness and adaptability during collective decision-making?
- How is the (often multi-scale) functional complexity of collectives related to the success/fitness of individuals?
- Being both robust and flexible is highly desirable for technological solutions to real-world problems. Can we employ our understanding of natural collectives to inform new design solutions for distributed control (e.g. for autonomous vehicles and swarm robotics)?

3. How can we infer causality of influence in decision-making groups? A major bottle-neck in the study of collective behaviour is that the pathways of communication are often not directly observable. In addition, the recursive nature of social feedbacks during processes like collective decision-making (as described above) means that even when social interactions can be detected, it is extremely difficult to infer the causality of social influence on social networks (which themselves are often dynamic, with varying strengths and directness of influence).

- How can we develop and exploit new computational tools for the algorithmic determination of hidden causal relations in time and space within collectives?
- New technologies, such as AR and immersive VR (see also Area C) offer a means of controlling causality. Is there a way for us to develop these technologies to devise a means to infer the decision-making algorithms employed by individuals within collectives?

4. When do collectives fail and can we predict this? Much research in collective decision- making has focused on the benefits. However, it is also essential to determine under which circumstances, and by what mechanisms, collectives can actually make worse decisions, leading to suboptimal individual and collective outcomes. For animal groups, it is becoming evident that collective migratory species are particularly at risk of sudden collapse due to anthropogenic influences [47].

- Why does collective failure occur, and can we predict and mitigate the risks of such failure?
- How do individual biases impact judgements and decisions in collective contexts? For instance, do biases become amplified?
- How can we employ this understanding to inform institutional design, for example, in the compo-

sition of expert committees, hierarchies of decision-making, and optimal rules for information aggregation?

5. How can we exploit our advancements in the science of collective intelligence for real-world applications? The science of collective decision-making could impact, and even transform, our society. Distributed sensing and decision-making are increasingly of interest in applications including intelligent infrastructure, the design of effective social structures for effective decision-making, the control of autonomous vehicles for exploration, and human transport. In the natural world, there are also immense possibilities if we could predict, and possibly even influence, large-scale collective behaviour (e.g. locust swarms).

- To what extent is it possible to develop a predictive understanding of swarm formation and movement in locusts over regional, or possibly even continental, scales? This will require new miniature tracking devices, formal methods for model scaling, and inclusion of detailed information about weather, topology etc.
- Can we harness processes like collective sensing – using tools like ICARUS to gain near realtime access to movement decisions of the global animal collective – to assess the changing health of our planet?
- Can we employ the collective ('sixth') sensing of animals to anticipate and forecast disasters such as impending earthquakes and volcanic eruptions?
- To what extent will animal collectives provide information on local and global atmospheric conditions that can be used for meteorological forecasts, or to indicate food shortages or feasts (such as by observing desert locust outbreaks)?

In the long run, we think that answering these questions will result in real-world applications that improve the livelihoods of people.

3. Research Area C: Computational Methods for Measuring, Analysing and Visualising Collective Behaviour

Research objectives and questions: In this area, we focus on data acquisition methodolo- gies (e.g. computer vision), progressive data processing, analysis and visualisation and modelling methods. The projects in Areas A and B require a number of different components that can be seen as an iterative data-to-knowledge process that comprises several steps: data acquisition will happen through various tracking systems that produce vast amounts of spatio-temporal data from which we will derive body postures, compute sensory input, determine neighbourhood relations, and obtain essential quantitative behavioural descriptors

The produced data will be typically large in scale, heterogeneous and involve a very broad range of time scales. Multi-dimensional data will be required to represent state descriptions of individuals, as well as the sensory information on which they base their decisions. Complex network and hierarchical data are necessary to effectively capture relations among individuals within, and between, groups, in addition to the vast spatio-temporal data required to define animal movements and body postural changes. Computer science research related to animal collectives raises a number of questions in regard to our application domains in biology, the human sciences, but also to computer science itself. Below, we outline the core research domains and scientific questions that we intend to address in Area C over the lifetime of the centre. This will be followed by specific details on a number of short-term (up to 3 years) starting projects.

Research Question 1: What are appropriate learning methods for tracking, posture, and behaviour?
Research Question 2: To what extent will “anytime” methods allow us to analyse, visualise, and guide complex real-time experiments?
Research Question 3: How does visual abstraction work for different species?
Research Question 4: Which modelling methods are needed to describe complex collectives?
Research Question 5: Can emerging technologies such as AR revolutionise research on collective behaviour?

1. What are appropriate learning methods for tracking, posture, and behaviour? The development of sensors and tracking technology is very active, making more detailed and precise measurements at a much higher speed possible. Deep learning has been proven to be efficient in tracking and also posture estimation, but more sophisticated and precise methods will need explanatory models and insights into the involved processes. A new generation of methods combining learning and explicit, explanatory models is needed to overcome the limits of pure learning-based approaches. Such combined methods will be the next step in data analysis, but it is not clear yet how these aspects can be combined. Detailed tracking data, such as posture, will help us here to explore and predict behaviour (e.g. posture over time) on different levels of abstraction.

- What are appropriate combinations of data-driven and explicit models in tracking and posture estimation?
- To what extent do such methods allow us to use generalised shape template models that adapt to new species?
- Can we derive a suitable low-level behavioural space or 'vocabulary' for each species, known as an automated ethogram, that describes classes of stereotypical motions [2, 4].

2. To what extent will "anytime" methods allow us to analyse, visualise, and guide complex real-time experiments? The data produced by our real-time experiments will be vast, and reactions (such as hindering birds to fly into the nets of the hangar) will have to be executed very fast. It is not yet clear how to cope with such amounts of data in such a short time. We will therefore develop anytime-methods for data management and processing that readily provide results with a bounded error, which decreases the more time is spent processing the data. Such components will be central in an increasing set of applications where data streams of ever increasing size have to be processed, ranging from traffic surveillance to finance data analysis.

- What changes in operating systems and programming environments are necessary for such components and where are their theoretical limits [14]?
- Which of the basic algorithms for information visualisation can be implemented in a progressive/incremental way [35]?

3. How does visual abstraction work for different species? VR experiments in the Imaging Hangar will require the creation of huge amounts of image data, since large display walls have to be filled at high frame rates.

- Although abstract visual representations can influence certain aspects of animal behaviour (e.g. reflex responses to certain visual cues [41]) we know little about which visual features are important for coordinating behaviour within collectives: at what level of visual abstraction can virtual environments still elicit natural behaviours, and can we use this knowledge accelerate our scaling up (in size and reactivity) of VR and reactive environments?
- Can such perceptual experiments help us to better understand the visual systems of our various model species?

4. Which modelling methods are needed to describe complex collectives? Currently, formal models for collectives are still quite limited with respect to the size and complexity they can describe.

Our vision, however, is to develop a comprehensive formal modelling and analysis framework for building a theory of self-organised, collective computations (inspired by, for example, the frameworks of category theory and complexity theory). Irrespective of the specific organisms involved, we aim to be able to identify the key parameters driving a certain collective behaviour. Our formal models will inspire and guide us in the design of collective algorithms with given purposes (swarm intelligence). Existing examples of such algorithms are ant colony optimisation (ACO) and particle swarm optimisation (PSO)[37], which both contributed to the field of optimisation. We expect a number of questions to arise from our experiments:

- What models of computation best describe cognitive, probabilistic decision-making individuals exposed to sensory input and social influences?
- To what extent can we identify causal effects in collectives by analysing interacting individuals?
- Will a combination of machine learning and causal inference be appropriate for modelling such scenarios?
- How and why do emergent collective properties arise as a function of connections of individuals via possibly multiple relational networks (e.g. communication, genetic relatedness, physical proximity)?
- Can analogies between biological models and computer programmes help to model collectives and form a theory of their behaviour?

5. Can emerging technologies such as AR revolutionise research on collective behaviour? In the future, new and tiny devices will allow us to manipulate visual and other senses of animals and to change their individual perception of the world. This will generate exciting research possibilities that are also challenging for computer science. Augmented Reality (AR) will be another technology we intend to employ to alter visual perception. Today, AR glasses are available for humans, but in the future, miniaturisation might allow us to apply similar techniques to animals.

- What will be the impact of VR and AR technology on collective behaviour? Will it be possible to control such technologies in a way so that subjects will not be distracted (using wireless technology)?
- Will this enable completely new experimental designs and a much deeper understanding of the involved cognitive processes?

Finally, and most challengingly, the computational methods described here will enable us to combine artificially-designed collectives with natural collectives: we will embed artificially-designed collectives in natural habitats of animals as a means of influencing animal swarms. The findings will tackle diverse fields beyond traditional biology, including biochemistry (molecular collectives) as well as psychology, sociology, and anthropology (human collectives). Formal models will also be one way to find a “vocabulary” for human- and animal-oriented research.

VI. The Centre for the Advanced Study of Collective Behaviour

In conclusion, it is our goal to create to a vibrant, internationally visible centre of research that plays a considerable role in the future of collective behaviour research. One of the greatest strengths of our centre, which will also be one of its greatest challenges, is to bring together people from such a wide range of disciplines and study systems, and to unite them in the pursuit of shared research goals. At the same time, however, there is an enormous opportunity here to learn from one another and to see the world in new ways. In our centre, we will not divide our researchers by discipline – rather, computer scientists, biologists, psychologists, physicists, economists, and social scientists will all work closely together in the same offices and labs. This will be made possible on the one hand by the planned VCC building, and on the other by the university's existing campus structures, which promote natural proximity between individual researchers and disciplines.

As mentioned above, we are of course more than aware of the challenges posed by bringing together a rather eclectic group of individual researchers from a range of academic disciplines. The three speakers (from the Departments of Biology, Computer Science, and Economics) will therefore be responsible for ensuring that the centre remains an interconnected, interactive, and dynamic community at all times. We are also aware of the tensions present in science with respect to multidisciplinary research and maintaining within-disciplinary visibility. Increasingly, there are excellent opportunities for publication, including major general science journals as well as interdisciplinary journals and conferences. We will provide our early career researchers with the infrastructure they need to flourish and assist them in identifying viable career paths both within academia and in the public or private sector.

We are committed to creating a dynamic and open community, which will rapidly gain global visibility and quickly evolve into a go to place for anyone working on collective behaviour. In addition, we will emphasise the importance of reproducibility in science, ensuring free and expedient access to all of our experimental data and tools. Staying true to our concept of an open-house, our centre will actively engage the broader community with our research activities and proactively share its activities with the public. Collective behaviour naturally captures the imagination of wide audiences, and we will leverage this opportunity with a dedicated outreach programme – including educational formats, exhibitions, and citizen science – that promotes transparency and the transfer of knowledge. In doing so, we aim to produce a lasting, positive impact on academia and the wider community.

As written in Section 3.1, we will experience (and develop) transformative new technologies within the lifetime of our cluster, some of which are perhaps unimaginable today. The adoption, and development, of technology has resulted in massive advances in other scientific areas, such as molecular and cellular biology, and physics. The time has come for us to transform the behavioural sciences. Dramatic innovations in computer vision, global positioning systems, genetic manipulation, physiological recording, and machine learning allow for unprecedented access to the data streams required to make major advances.

VII. Synopsis

We define collective behaviour as the study of individuals in the context of how they influence and are influenced by others, taking into account the causes and consequences of inter-individual differences, such as in physiology, motivation, experience, and goals. It also includes the study of the individual and higher-order properties that can emerge as we move beyond dyadic (pairwise) interactions to consider the complexities that arise in the dynamic networks of communication that characterize both human and animal systems.

Our centre was created to provide a globally unique environment for the quantitative analysis of behaviour with the aim to foster a culture of research, facilitated by the integration of theory, experiment, and technology that allows us to cut across both disciplinary and conceptual boundaries. No other research initiative offers an environment that is home to a similarly comprehensive collective of topically interested experts from biology and human behavioural sciences to visual computing and data science. No other place provides access to comparable facilities; and nowhere else is all of this to be found in a single, beautiful location.

Our Cluster welcomes knowledge, expertise and collaboration from all around the world and during our work we seek to implement equality and minimize inequalities wherever we see them. Our aim is to build a diverse environment where everybody feels welcomed, respected and appreciated. We are constantly striving to provide an environment free of discrimination or harassment and accept everyone without regard to race or ethnic origin, religion or belief, nationality, social class, sexual orientation, gender identity, age, physical, mental or sensory abilities and/or expression. The supporting structures of the Cluster are in place to provide support and assistance for personal growth and change at any given time. We implement collegiality, respect and interdisciplinary collaboration as an essence for outstanding research practices. Hence, we are creating the environment where scientists and supporting colleagues can pave the path for truly excellent scientific discoveries and careers.

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Appendix:

1: List of starting projects from the original cluster proposal

Area A:

A1: *Short and long-term spread and modulation of individual physiological stress states in the collective*

A2: *The dynamics of social transmission in structured contexts*

A3: *Individual and collective appetite – how is eating shaped by social influence?*

A4: *Mechanisms underlying heterogeneity in social learning between individuals and groups*

A5: *Preferences and incentives for innovation*

Area B:

B1: *Using immersive virtual reality to reveal the dynamical structure of social interactions during collective decision-making*

B2: *From the coordination of individual brains to effective collective decision-making*

B3: *Signalling and collective decision-making in moving animal groups*

B4: *Collective sensing over multiple scales during migration*

B5: *The global animal collective – an intelligent, networked sensing system for our planet*

Area C:

C1: *Automated tracking methods and interactive virtual environments*

C2: *Progressive visual analytics of collective behaviour data*

C3: *Formal modelling of collective systems*

2: List of new large projects since 2019

Large projects:

L19-01: *The role of communication structure in consensus decision making in human and animal groups*

L19-05: *Human-in-the-loop analysis of collective eating behaviour*

L20-01: *Spatial dynamics of mate-choice in blackbuck leks*

L20-02: *Collective behavior of active colloidal particles via reinforcement learning*

L20-04: *Environmental uncertainty shapes rat foraging behaviour in large scale environments*

3: List of new medium-sized projects since 2019

Medium-sized:

M20-01: *Deep learning of priors for Bayesian inverse problems in image analysis*

M20-02: *Collective transmission of physiological states and behaviour in fish*

M20-05: *A software framework for multisensory environments*

M20-06: *Active sensing and collective motion in groups*