science of intelligence

Science of Intelligence

Cluster Report 2024

We examine and build intelligent behavior in order to understand it

Funded by DFG

Dear Reader,

Oliver Brock – SCIoI Spokesperson

About five years ago, more than 130 researchers from twelve disciplines of intelligence research set out on a journey with the goal to understand intelligence. This book tells the story of that journey up to the present day. We were motivated by the idea that, if the individual disciplines so far had not been successful at explaining intelligence, maybe we could make better progress by joining forces. And so we did, in the context of the Research Cluster of Excellence "Science of Intelligence," funded by the German Research Foundation (DFG).

The notion of intelligence for us encompasses all the awe-inspiring things that animals, including humans, are capable of: their surprising survival skills, the ingenuity in solving new problems seemingly with ease, and the adaptability to changing environmental conditions. The artificial intelligences created thus far, even though marvelously impressive and economically successful, do not come close in many regards to what evolution has led to in the realm of biological species. But we believe that a better understanding of biological intelligence will also allow us to create better artificial intelligences.

In this volume, you will find the many accomplishments of our journey, from the realms of biological and artificial intelligence, but also the many new questions we encountered. We hope that our stories are compelling and that they communicate our scientific progress. We hope that you will find it worthwhile to continue our journey, collectively, across the many scientific communities.

We examine and build intelligent behavior in order to understand it

All of our efforts are framed and guided by our desire to do intelligence research in an ethically sound manner. We are aware of the risks associated with any technology and we are doing our best to ensure that everything we do helps us make progress responsibly.

Now I would like to invite you to embark on your own journey through this book. Find your path from story to story, explore and assess the wealth of information, let the compelling figures and illustrations trigger your imagination. And while you do that, maybe you'll be impressed with all the things intelligence allows us to accomplish.

Enjoy!

Oliver Brock
SCIoI Spokesperson

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"What are the principles of intelligence, shared by all forms of intelligence, no matter whether artificial or biological, whether robot, computer program, human, or animal? And how can we apply these principles to creating intelligent technology? Answering these questions – in an ethically responsible way – is the central scientific objective of the Cluster of Excellence Science of Intelligence (SCIoI)."

The interactive fish projection at the Humboldt Lab exhibition *Nach der Natur*

Who We Are

Understanding intelligence is one of the great scientific challenges of our time. Yet, in spite of extensive research efforts spanning many scientific disciplines, our understanding of intelligence remains fragmented and incomplete. Until now, the involved disciplines have remained segregated, each producing its own theories and empirical findings about aspects of intelligence.

However, these theories and results are often disconnected and sometimes inconsistent. SCIoI marks a turning point: It attains cohesion among those disciplines and is a unified scientific endeavor towards an understanding of intelligence.

To reveal the principles of intelligence is a long-term goal. Therefore, the cluster is devoted to the training of the next generation of intelligence researchers, who will be "natives" in our Science of Intelligence and will ensure a deep and lasting integration of the disciplines.

Intelligence research is fundamental science but it has and will continue to have an immediate impact on industry and society. Hence, it is our responsibility to continuously assess the societal and scientific implications of our work and to ensure that research at SCIoI progresses in a socially responsible and ethically sound manner.

Cluster Timeline

2019

Hello, World!

SCIoI receives funding from the German Research Foundation (DFG) to conduct seven years of intelligence research.

2020

The Pandemic doesn't stop SCIoI Research

Covid-19 strikes, but research goes on at our cluster. Lab development progresses.

Feb 2021

More Funds from the Berlin University Alliance (BUA)

SCIoI and fellow Cluster of Excellence Matters of Activity receive funds from the BUA to set up an "Experimental Lab for Science Communication." The three-year project "CollActive Materials" is born with the aim of bringing citizens together, so they can imagine futures with intelligent materials.

Mar 2021

GSEP Fellowships Assigned

Through the Global Scientific Exchange Program (GSEP), SCIoI grants six fully funded, three-month fellowships to Master's-level students who will visit the cluster from across Africa in the summer.

Jun 2021

SCIoI Featured at Humboldt Forum exhibition

The Humboldt Forum museum inaugurates Nach der Natur, an exhibition that shows the fragility of nature through objects, videos, and simulations from all seven of Berlin's Clusters of Excellence.

Nov 2021

Labs Open!

The SCIoI labs are ready for scientists to move in: These include the Čapek Lab, the Asimov Lab, the Visual Capture Lab, the Media Lab, and the EEG (electroencephalography) Lab (see p. 104).

Dec 2021

All over the News with the "Mexican wave"

SCIoI researchers travel to Mexico to investigate sulphur mollies, fish that create collective waves to scare predators away. The news grabs the attention of *The New York Times*.

Aug 2022

Berlin Summit on Robotics

SCIoI sponsors and hosts the Berlin Summit on Robotics 2022.

May 2023

Podcast Launched

A team of SCIoI researchers launches "Punching Cards, the podcast about all things intelligent," featuring stories, anecdotes, and interviews about intelligence research (p. 80).

June 2023

Integration Hackathons

SCIoI researchers set up regular meetings, the "integration hackathons," where they discuss how to best integrate disciplines.

Jul 2023

New Membership

SCIoI becomes a member of the Big Data Value Association (BDVA).

Aug 2023

The SCIoI Summer School

SCIoI hosts its first summer school in collaboration with the International Society for Adaptive Behavior (ISAB).

Sep 2023

Master's Track

The SCIoI Master's track is launched.

Sep 2023

The SCIoI Fair

Politicians, scientists, and the public visit the SCIoI Fair, an interactive event about Science of Intelligence and intelligence research.

2024 and beyond

Looking to the Future

As we approach our sixth birthday, we are as eager as ever to continue our research and to add new elements and disciplines to integrate an evolutionary perspective. We want to further expand our valuable collaborations and continue our journey in the discovery of intelligence.

Objectives of SCIoI

1. Identifying the principles of intelligence

Understanding intelligence remains one of the most important, largely unsolved scientific problems of our time. Intelligence defines us as a species and plays an important role in our daily lives. Technological realizations of intelligence aim to fundamentally change the way we live. SCIoI wants to identify and understand the principles that underlie intelligence.

2. Closing the gap between biological and artificial intelligence

There are fundamental differences between biological and artificial intelligence.
By synthesizing technological artifacts of increasing intelligence, we want to systematically close this gap, producing technology that is intelligent.

3. Uniting the disciplines of intelligence research into a Science of Intelligence

Disciplinary fragmentation is a major obstacle to progress in intelligence research. We want to overcome this fragmentation by uniting the disciplines in a single research project. Through an integrated, interdisciplinary team effort, we aim to lay the foundations for a unified Science of Intelligence.

4. Developing engineering paradigms for intelligent systems

The dominant paradigm in engineering assumes the decomposability of problems. We believe that this assumption does not hold for intelligent agents: functional components of intelligence engage in rich and complex interactions and cannot be decomposed. To account for this, we aim to develop novel engineering approaches for building intelligent machines.

5. Building an international community of intelligence researchers

We want to create a global community of intelligence researchers, propagating our integrative scientific approach.
For this reason, we have established alliances with many different prestigious international institutions (p.113).

6. Training the next generation of interdisciplinary intelligence researchers

For centuries, science has progressed within disciplinary boundaries. These boundaries severely impede solving many of today's pressing scientific challenges, the study of intelligence being one of them. We have developed novel curricula and training programs to prepare early-career scientists to solve interdisciplinary scientific challenges.

7. Providing long-term career perspectives for young intelligence researchers

Max Planck's principle states that "a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because […] a new generation grows up that is familiar with it" (Planck, 1950). We create long-term career perspectives for a new generation of scientists, rooted in a unified Science of Intelligence.

8. Uniting the disciplines of intelligence research in one laboratory

The physical proximity of collaborators and the interdisciplinarity of collaborations positively correlates with the impact of research. SCIoI unites principal investigators from many disciplines in a single laboratory, creating a permanent structure to support impactful research.

9. Transferring research results into industry

Intelligence research is fundamental science but it also has an immediate benefit to industry as it responds to pressing economic needs.
We engage in mutually beneficial collaborations with companies to transfer insights on intelligence into applications.

10. Assessing the societal and scientific implications of SCIoI

A synthetic understanding of intelligence can have a profound impact on society and science.
We want to ensure that research within SCIoI progresses in a socially responsible and ethically sound manner. We will continuously validate and improve our proposed scientific approach.

Visions

Our Principal Investigators share their thoughts and visions for our cluster.

Jens Krause
Behavioral Biology

"Collaboration is key at SCIoI. By sharing knowledge across fields, we're not just solving puzzles; we're paving the way for groundbreaking discoveries in intelligence research."

"A good example of that is the development of the Robofish (see p. 56). As fish biologists we had many ideas on how the collective behavior of fish schools might work. However, it was only when engineers in collaboration with us built a fish robot that could be integrated into a real fish school that we were able to put some of our ideas to the test. We discovered among other things that fish can anticipate the behavior of their conspecifics."

Rebecca Lazarides
Educational Science

"AI can transform education. By studying learning processes, we can develop systems that adapt to individual needs, making learning more accessible for all."

"We aim to develop perspectives on adaptive learning by bringing together research in computer vision, robotics, IT, and educational psychology. This lets us expand current knowledge on the motivational-affective foundations of adaptive learning processes. SCIoI's collaborative environment helps us better understand how artificially intelligent agents and humans can learn together. This advances the field and addresses societal challenges, such as the need to tailor communication to each learner's individual needs."

Henning Sprekeler
Computational Neuroscience

"Biology is undergoing a revolution towards larger and larger datasets. To make sense of this data deluge, we need the interdisciplinary and collaborative spirit we live in the cluster."

"This is true for almost all branches of biology, but behavioral biology is a nice example. In the past, researchers had to watch long hours of video and annotate what the animals were doing. Today, we find ourselves using tools from robotics to control the experiment, artificial intelligence to analyse videos on high-performance computers, and statistical models from physics to understand the behavior. These are exciting times!"

Joerg Raisch
Control

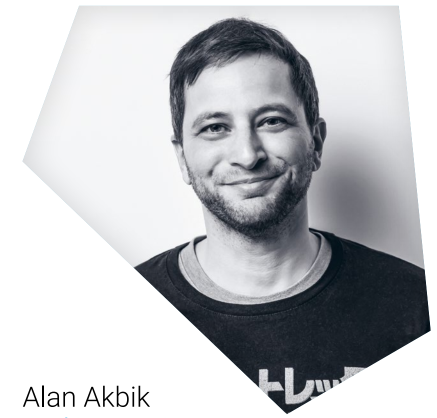
"How do we address complexity in engineering decision and control problems? The study of biological intelligence is crucial to answer this question."

"Finding methods to handle complexity in control engineering problems is a major and largely unsolved challenge. Biological systems, on the other hand, seem to be extremely efficient in coping with many degrees of freedom when facing decisions, and come up with solutions under severe time and processing constraints. We believe that studying biological intelligence within the interdisciplinary framework of SCIoI will reveal principles that can be transferred to synthesize control for complex engineering applications."

Christa Thöne-Reineke
Behavioral Biology

"Our exploration into the ethics of AI is not just philosophical. It's about creating a framework that ensures the responsible development and deployment of intelligent systems."

"Creating technological artifacts that mimic human intelligence raises ethical questions. In recent years, artificial intelligence (AI) has become more and more prevalent in our lives, and concerns around its ethics have grown. At SCIoI, we are integrating ethical considerations into all projects through a comprehensive ethics review process and a program to raise awareness of associated issues. By incorporating an ethical design from each project's inception we want to ensure compliance with ethical standards."



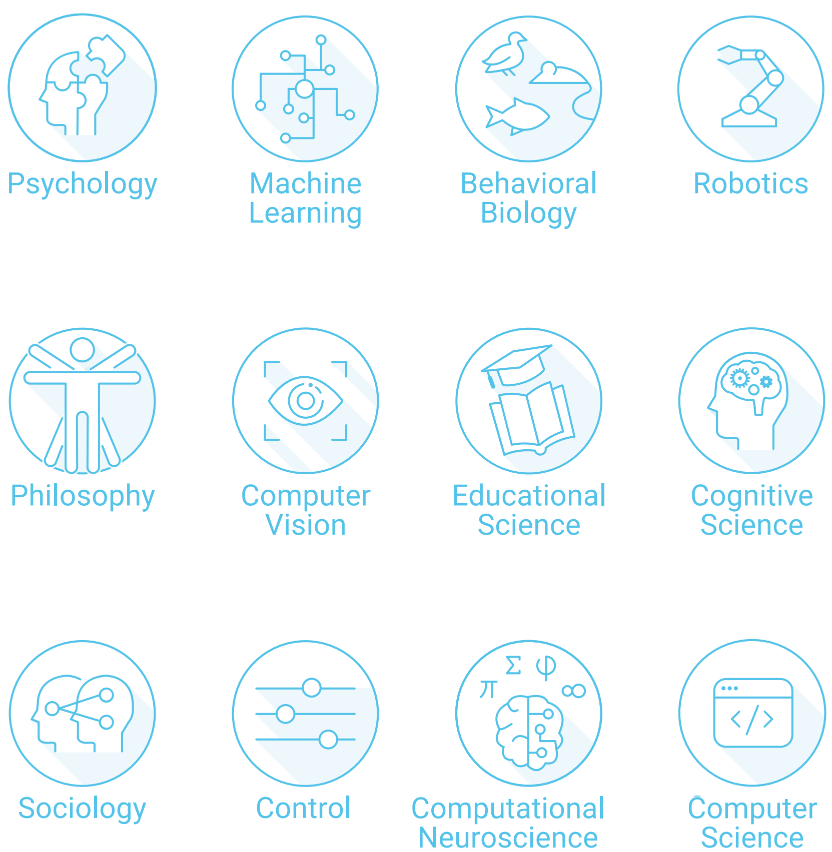
Alan Akbik
Machine Learning

"SCIoI goes far beyond current AI research by jointly investigating both biological and artificial intelligence, giving us a unique perspective on intelligence research."

"For instance, it allows us to compare biological learning/problem-solving behavior against AI models in complex experimental scenarios. By designing these scenarios with experts across disciplines, we gain a more principled understanding of intelligent behavior and the conceptual limitations of current AI models. This in turn enables us to formulate novel machine learning methods, for instance in the fields of continuous and noise-robust learning."

Our Disciplines

Understanding intelligence is an interdisciplinary endeavor. Our researchers observe and analyze intelligence from the points of view of their different disciplines. Here is an overview of what these are.



Interdisciplinary collaboration at SCIoI

Research

Intelligence research is an interdisciplinary effort made up of many different components, and our research projects represent these components

Research Structure

Our goal is to uncover the principles of intelligence in nature and to translate this knowledge into principles that will help us design and create intelligent artificial systems. In order to do this in an efficient manner, we look at our projects from different perspectives.

1. Research units

One way to organize our scientific work is by research unit, where each of our four units is based on a different research question.

We observe intelligent behaviors in nature and attempt to synthesize them (Unit 1). From these studies, we extract general principles of intelligence (Unit 2), which we further develop within technical systems in a next step (Unit 3). This research strategy is accompanied by ongoing evaluation of ethical and philosophical parameters of intelligence research (Unit 4).

2. The synthetic-analytic loop

Intelligent behavior shouldn't be observed only in terms of its various functions and components, but also as something complex that can only be studied as a whole.

Therefore, we combine analytical (mostly non-technical) disciplines with synthetic (technical) methods, while both fields are in continuous evaluation with each other. In other words, we examine intelligent behavior in nature (analytic side) in order to gather principles that will help us build efficient robots (synthetic side), which in turn will give us a better understanding of natural processes, in a continuous synthetic-analytic loop.

3. The example behaviors

In addition to the four research units, research at SCIoI can also be organized into three subunits, each pertaining to a specific type of intelligence, and characterized by a corresponding intelligent behavior. These example behaviors (pictured right) are chosen to capture fundamental aspects of individual intelligence, social intelligence, and collective intelligence.

Individual intelligence is attributed to a single agent (i.e., a person, an animal, or a robot) behaving in their environment (e.g., solving queries and opening locks to get out of an escape room).

Social intelligence is shown when several agents that exhibit individual intelligence interact with each other (e.g., collaboratively solving a puzzle), possibly also learning new things through social interaction.

Collective intelligence is shown by a group of agents, but in contrast to social intelligence, the resulting behavior cannot be attributed to any of the individuals but only to their collective (e.g., a swarm of fish escaping a predator, or a flock of sheep following the shepherd).

Behavior 1 Individual intelligence: escaping from an escape room


Behavior 2 Social intelligence: learning in social interaction

4. Project families

For the purposes of science communication, we came up with a fourth, more thematic, type of subdivision, which groups the research projects into thirteen project families, such as "ethics," "lockbox projects," "collective cognition," and so on. This gives readers a further and in some cases more immediate perspective on how thematically similar projects are connected. For this Cluster Report, we have chosen to present our research by project family.


Behavior 3 Collective intelligence: cooperative shepherding

From Parrots to Robots and Back

What cockatoos' behavior tells us about animal cognition

BY SOLVEIG STEINHARDT

Up until the 1960s, it was commonly believed that tool use is unique to human beings. This belief was first challenged by observations on chimpanzees, who proved to be able to do things like cracking nuts with stone tools and fishing for ants or termites with sticks. Some of us may have even seen documentaries about the New Caledonian crows, who are not only pros in tool use, but appear to be quite intentional in their search or creation of tools. More recently, researchers have started observing the amazing capabilities of the Goffin's cockatoo.

In general, cockatoos are well known for being particularly curious, playful, and eager to explore. They adapt well to the urban environment, and in some areas of Australia, they are referred to as "trash burglars." Despite those facts, when the researchers first started studying them, they were astonished by the white cockatoos' capabilities not only in tool use, but also in solving complex sequential mechanical problems. Their skills and abilities are particularly revealing of their intelligence and give us a good starting point to understand some aspects of intelligence at SCIoI and to apply that knowledge to the creation of better robots.

But let's start from the beginning: In 2013, cognitive biologist Alice von Auersperg from the University of Veterinary Medicine in Vienna started researching Goffin's cockatoos and their ability to solve lockboxes. A lockbox consists of a series of consecutive mechanisms that, if solved in the right order, lead to the solution of the puzzle and a reward for the cockatoo, normally a cashew nut, the cockatoos' favorite snack. Soon after she set up the experiment, Alice was joined by Alex Kacelnik, an Oxford University behavioral biologist who was interested in animal intelligence, but also curious about how natural intelligence relates to artificial intelligence. When, a couple of years later, Alex organized a meeting in Oxford about these topics, he met a Berlin roboticist, Oliver Brock, and together they started talking about the interaction between animal behavior and robotics. Their relationship developed from there, and it may not be too far-fetched to say that that was one of the sparks that later gave rise to SCIoI: Brock, Kacelnik, and von Auersperg became important founding pillars of the cluster, and when the time came, they drafted their proposal for a project on cockatoos and robots.

"The birds quickly become better at solving the lockbox after only one or two successes"

When asked what the project was about, Alex Kacelnik said, "We are trying to find out whether cockatoos can infer physical properties of the world, other than specific solutions to specific problems, and at what level of conceptualization they can learn sophisticated forms of mechanical solutions. This helps our research in two directions; while biological intelligence inspires the creation of intelligent artificial systems, these systems also give biologists new insights into natural intelligence. There's a lot of potential information in bird behavior, and we want to translate this to artificial intelligence."

The original experiments served as a great starting point for research at SCIoI. Departing from their results, Alice, Alex, and Oliver designed the SCIoI project "Intelligent kinematic problem-solving," with roboticist Manuel Baum as the core doctoral researcher. Manuel had been involved in various aspects of the previous experiment in Vienna. On the one hand, he had created a modular version of the lockbox apparatus and sent it to Vienna. There, his collaborators Theresa Rössler and Antonio Osuna-Mascaró helped with designing a new experiment with eight birds, and recording the

Above and left: cockatoos at the University of Veterinary Medicine in Vienna

A cockatoo works on solving the lockbox

"A lockbox consists of a series of consecutive mechanisms that, if solved in the right order, lead to the solution of the puzzle and to a reward for the cockatoo, usually a cashew nut"

data for later analysis. On the other hand, he had also "gotten his hands dirty" analysing the data. "We designed an ethogram to encode the birds' behaviors: we labeled events like 'bird touches wheel' or 'bird stops touching wheel.' Then we did a lot of explorative data analysis in order to create the hypotheses we would later test." said Manuel.

"After months of plotting curves and analyzing behaviors, we noticed interesting patterns. Firstly, the birds quickly become better at solving the lockbox after only one or two successes. Secondly, we identified three factors that influence the birds' behaviors: engagement (i.e., the more they solve the puzzle the more they are willing to work on it), strategy (their ability to decide which parts of the lockbox need the most attention), and sensory motor skills (the fewer actions you need, the faster you'll be.) You need to look at all three factors in order to fully understand the behaviors. But doing that in depth is a complex task, so we decided to focus more on strategy," said Manuel. "In previous experiments, we had mainly hypothesized about what the birds learn, but this latest one was a deeper dive into *how* they learn."

While the original plan was to use robots as abstract models to apply the idea of the synthetic-analytic loop (see p. 16) and learn something about the birds, in science things don't always go as planned. "The question is more challenging than we initially thought, as robots are farther away from Goffin's cockatoos than hoped," said Manuel. "The project was shifted from employing the original methodology, which involved the synthetic-analytic loop, to finding another methodology that could work. We also needed to consider that using more intelligent animals reduces the number of participants that you can have, and that's due to factors such as aging, a need for engaging and spacious environments, or ethical considerations. We need to find the right method to perform this research, and one possible way is to also conduct similar experiments with mice (p. 30) or with robotic arms (p. 42)," Manuel said.

Manuel is about to be done with his PhD, but the journey will be continued by Huu Duc Nguyen in a different project (Project 49). Duc joined SCIoI last year as a doctoral researcher, and has been taking steps to familiarize himself with the project by analyzing data from the previous experiment. "The current core idea is to apply the proposed methodology from the previous project to extract insights on the birds' strategies. We hope to identify strategies that can be implemented on our robot, which consists of a robotic arm attached atop a mobile robot. It is a challenging project, and I am very excited," said Duc.

LOCKBOX PROJECTS

- P4 Intelligent kinematic problem solving
- P22 Ecologically rational strategy selection
- P30 Analyzing human physical reasoning and strategy exploration on physical puzzles
- P49 Methods for extracting system constraints from behavioral data and application to building synthetic cockatoos

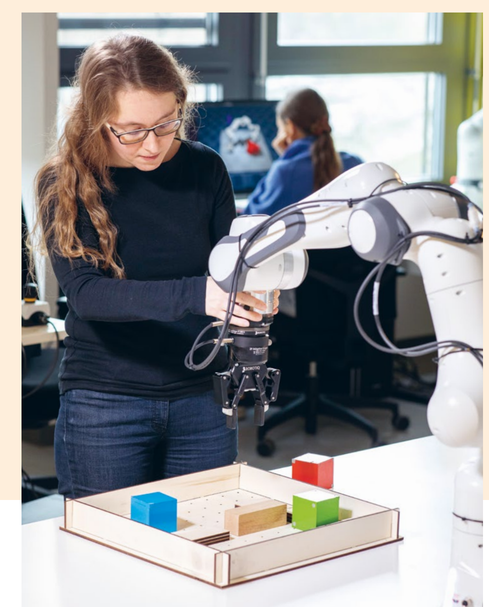
PIs: Oliver Brock, Ralph Hertwig, Alex Kacelnik, Falk Lieder, Thorsten Pachur, Josh Tenenbaum, Marc Toussaint, Alice von Auersperg

TEAM: Jinan Allan, Manuel Baum, Florian Bolenz, Svetlana Levit, Huu Duc Nguyen, Oussama Zenkri

Puzzles for humans and robots

Solving a physical puzzle can involve looking for hidden object parts, assembling and using tools, or manipulating objects in an unexpected way. This presents a challenge, as it requires lateral thinking and exploration of different strategies, in a trial-and-error manner.

To understand how humans solve these puzzles, and how this compares to strategies we can develop in AI, Svetlana Levit, together with researchers at MPIB, developed virtual physical puzzles for a human study, and AI methods to solve them. "In our experiments, we observe people pushing objects on the screen using the computer mouse, glueing hook tools, or ricocheting objects by kicking them against each other. We then analyse what people find difficult and observe the different solution strategies they use. This way we get a glimpse of how physical reasoning works, and then try to have robots do the same," said Svetlana. Her team recently produced a wooden lockbox (pictured right) to apply the puzzle-solving methods on robotic arms. Svetlana's project closely relates to another project, "Ecologically rational strategy selection," in which roboticist Oussama Zenkri and psychologist Florian Bolenz explore the high-level strategies that people follow in their decision-making process. The researchers extract these strategies by observing people as they solve simulated lockboxes and by developing models to estimate the optimal selection among these strategies to efficiently solve lockboxes and similar problems (see p. 44).



> “Our vision is to harness the collective intelligence of both artificial and natural systems. This synergy could unlock solutions to some of the world’s most pressing challenges.”

In the Field for the First Time

From deep Pacific waters to toxic Mexican ponds, SCIoI researchers reveal how their first field trips have fueled scientific discovery

SCIoI researchers observe marlin as they hunt groups of sardines off the coast of Mexico

At SCIoI, much of the research is conducted in labs, crunching numbers, comparing and evaluating data, and teaching robots. But there are a couple of projects that involve intensive – and sometimes adventurous – in-the-field research. In order to understand collective behavior in prey and predator groups and their interactions, for example, computer scientist Palina Bartashevich spent time on a small fishing boat off the coast of Mexico. Physicist Yunus Sevinchan, on the other hand, flew to Tabasco (also in Mexico) with a team to research sulphur mollies, a type of fish found to create a collective wave that scares its bird predators (see p. 28). When not in the field, Palina and Yunus share an office where they process the collected data and discuss their results. We’ve asked them to talk about their experiences.

From ocean research to inhospitable Mexican ponds: What are the most interesting aspects of being in the field?

YUNUS: With my physics background, and working mostly with computer simulations in front of a screen, I certainly did not expect I’d ever find myself doing field work in Mexico! This is of course very exciting and at the same time it helps my research tremendously: Getting to know first-hand how the biological system that we are studying behaves is something we just can't do from looking at videos.

PALINA: It is such an adventure – the thrill of exploring uncharted waters, figuratively and literally. Going to the field allows you to observe the phenomena in real time and in a wider context.

Any stories worth telling?

PALINA: Before joining the field work, I spent two years studying this biological system using computer simulations. Primarily, I was modeling predator-prey interactions, i.e., how huge predatory fishes attack smaller ones. But for me, it was always just videos, pictures and data points. It is only in the field that you really come in contact with the object of your study, that you realize that it's all … kind of real! This is the first time you truly feel that you are part of the system, one more data point, powerless within its natural framework. It is a reminder that in the face of nature, we are mere observers, unable to exert control. Also, witnessing a massive bull shark devouring a marlin in less than a second, while you're gearing up for snorkeling, leaves a lasting impression, as does sleeping on the deck of the boat beneath an incredible night sky.

A snowy egret wades in the middle of a stream

YUNUS: We spent most of our time on the banks of the sulphur river, sitting and waiting. What really fascinated me when I was there was the nature, and especially the soundscape. There's always a bird singing, and as these are the same birds that hunt the fish, you really pay a lot of attention to them. But seeing a crocodile in the river, not far from where you are? That's definitely an encounter you won't forget. And the wildlife had more in store for us: On rainy days, when "our" fish were in hiding, we would explore the nearby cave systems. These caves are inhabited by cave mollies, another interesting fish species, but they are also full of bats! Climbing through them with bats whisking past your head is really quite memorable and far beyond the scope of any lab setting.

How important was it for your project to actually be in the field?

YUNUS: Observing fish behavior in the wild helped us with many of the decisions we needed to make when designing our computer model. For this model, we need to make several abstractions, and grounding these abstractions in first-hand observations made the process much easier. Also, having been in the field helps a lot with understanding which kinds of experiments are actually possible, and this really facilitated interdisciplinary communication within the project. From home, things are just harder – we might not even realize on which topics we are not fully understanding each other's points, because of the lack of field work perspective.

PALINA: It is of crucial importance. First of all, it helps you to get out of the standard routine so that you can see your project from different angles and strengthen the connection to its biological side. Actually, one of these field trips gave me the inspiration for my presentation at our big public event, the SCIoI Fair 2023 (see p. 72). These trips also help you as a person, to find your strengths and weaknesses. It is definitely beneficial on different levels, both collectively (for the research group) and individually (for yourself and your project).

Sulphur mollies in the Baños del Azufres springs

What Finnish ice fishers reveal about decision-making in humans

A fascinating branch of research at SCIoI investigates human decision-making strategies in foraging behavior. To study this, biologist Félicie Dhellemmes and computational scientist Valerii Chirkov, together with Principal Investigator (PI) Ralf Kurvers, travelled to Finland midwinter to study the behavior of ice fishers. Ice fishing is a human foraging activity that began thousands of years ago, and although no longer used for sustenance, it is a cultural tradition in the northern regions of the world. People not only do this as a leisure activity, but also seriously compete in large scale events. This creates an ideal test bed to study human foraging in the wild. Participants need to make decisions about where to go to find fish, and how long to fish for. Should they stay and explore the available resources, or should they go explore for more profitable opportunities? The researchers equipped large groups of foragers with GPS and head cameras to study where they go, who they observe, and their catching success. Conditions were not always easy, with temperatures dropping to minus 20 degrees Celsius and heavy snow. "At one point our car got stuck, and we needed a farmer to come and rescue us," recollects Ralf Kurvers. This project resembles and is related to the more controlled work by David Mezey and Dominik Deffner (see p. 51).

How does working in the field affect your relationships with your colleagues?

PALINA: I was very lucky to be in a very professional team that had extensive experience with these field trips, so it was easy to adapt. Being on a small boat in the middle of the open ocean for 24 hours a day several days in a row is a physically challenging task. You need to support each other as much as you can. Also, filming in these conditions demands highly coordinated teamwork, not only among team members but also with the boat's captain. So, not that much has changed in our relationships as it is difficult to improve what's already very good. But if anything, this exceptional situation only deepens the bonds.

YUNUS: I went on my first field trip early on in the project and I think this really accelerated the process of getting to know the others. Being in a new context and spending a lot of time together in the heat and dirt helps you learn to work as a team, develop new ideas and carry them out together, though sometimes needing to improvise with what is feasible in the field.

How does it feel to come back with all the data?

PALINA: There's a lot of work ahead. Before these trips, we all have specific ideas about what data we are after, but the unexpected things that happen often lead to new research questions and more data.

YUNUS: At the end of the trips, I am typically responsible for organizing our data storage and making backups. There's some excitement around loading the videos onto our data server – but watching them again from the comfort of an office often feels surreal, like from a faraway place. ● *SRS*

Of Marlin and Sardines

In prey-predator interactions, collective movement can be a great protection. In some fish, these motions occur geometrically. For example, in their field trip off the coast of Mexico, Palina Bartashevich and her team observed how schools of sardines avoid marlin attacks by producing a fountain-shaped pattern, each fish quickly moving forward and outwards to create a channel in the middle of the group, and then swimming backwards to rejoin the group from behind. Back in Berlin, these results have also been simulated in a model and applied in a mixed reality for robots (pictured above). This field trip even brought a surprise discovery: while observing drone footage of the marlin attacks, SCIoI biologist Alicia Burns observed that the marlin's stripes change color when attacking the school of sardines, possibly a way for the marlin to communicate to their conspecifics that it's their turn to attack.

COLLECTIVE FISH BEHAVIOR PROJECTS

- P12 Learning of intelligent swarm behavior
- P33 Shepherding behaviour in predator-prey interactions
- P41 Self-organised criticality in animal collectives

PIs: Heiko Hamann, Jens Krause, Pawel Romanczuk, Henning Sprekeler
TEAM: Palina Bartashevich, Pia Bideau, David Bierbach, Alicia Burns, Robert Lange, Luis Nava, Yunus Sevinchan

> "By examining intelligence through the lens of evolutionary biology, we can uncover the roots of cognitive abilities across species."

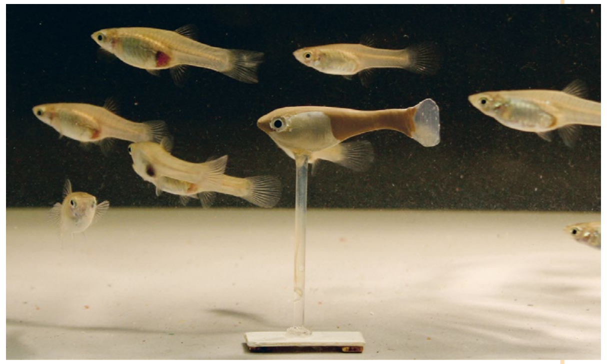
On Collective Behavior

Selected SCIoI papers on collective intelligence

Fish anticipate others' actions

Group-living animals, moving synchronously in water or air, are a fascinating sight, but what surprises most is the speed at which thousands of individuals change direction, a bit like one "super-organism." How do they manage these sudden collective movements? In ball sports, professional players anticipate their teammates' movements in order to react quicker. According to a SCIoI study, fish do the same. Using a robotic fish, our researchers showed that guppies can anticipate the behavior of their artificial conspecific and predict both the direction and dynamics of its movements. When live guppies were given the option to swim repeatedly with a robotic fish that always moved along the same path, they learned to predict its turns and moved accordingly. Also, as soon as they saw Robofish, some fish remembered which corner in the tank it would swim to, and swam there first to wait for it. We aim to use these insights to develop robots that can benefit from these mechanisms.

Bierbach et al., *Live fish learn to anticipate the movement of a fish-like robot**



Mexican waves confuse bird predators

Picture thousands of fish moving like a giant wave in the water, diving down and coming back to the surface. While humans engage in this kind of collective behavior for fun in stadiums when they perform *La Ola* waves, animals may do it to avoid getting eaten. A SCIoI-led team found that the "Mexican waves" collectively produced by a school of fish reduce its predator's propensity to attack and hunting success.

The Baños del Azufre volcanic springs in Mexico, rich in hydrogen sulphide and poor in oxygen, are inhabited by sulphur mollies (*Pocilia sulphuraria*). The fish spend their time close to the surface to breathe, becoming targets of many different bird species. But when a bird approaches, the million-fish schools react collectively by diving down, each fish touching the water surface with its tail. From a distance, the school appears to be producing conspicuous waves. "Because the waves are repeated and regular, we assume that they are more than a mere escape reaction," said David Bierbach. "Their aim might be to confuse the bird, but also a way to send a message: 'We know you are there, don't waste your time attacking us!'"

Doran et al., *Fish waves as emergent collective antipredator behavior**

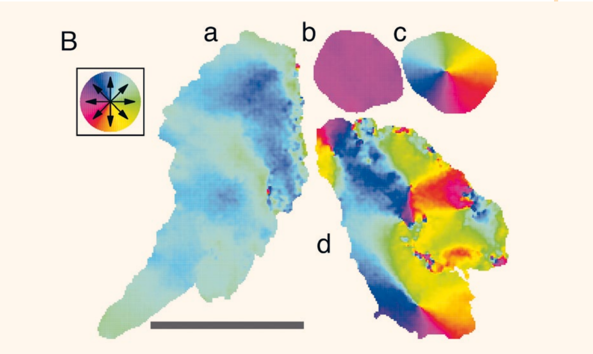
Collectives work a bit like the brain

What do the brain and a school of fish, or a even a multicellular organism, have in common? They are both capable of efficient collective information processing, although each unit only has access to local information. In the brain, the stimuli from 86 billion neurons form the basis for information processing; in shoals, this is done via the decisions of each individual on how to move and interact with neighbors. However, little is known about how these biological systems manage to optimally bring together a multitude of individual pieces of

> "Swarm behavior is often about information spreading like an avalanche."

information from different locations. According to a known hypothesis, the best performance of the brain lies at the border between order and chaos, in the so-called critical state. SCIoI researchers have now obtained evidence for this hypothesis on a large school of fish. "Swarm behavior is often about information spreading like an avalanche. In this state, the individuals react maximally quickly to external stimuli with maximally effective information transfer," said PI Pawel Romanczuk. "The resemblance between the fish's diving behavior and the brain's neuronal activity suggests some fundamental principles of collective computations, also giving clues as to how far the complex patterns displayed by animal groups can be interpreted as a 'collective mind.'"

Gómez-Nava, L. et al., *Fish shoals resemble a stochastic excitable system driven by environmental perturbations**



Marlin change color when hunting in groups

Striped marlin are among the fastest fish in the sea. In groups, they take turns attacking large schools of Pacific sardines with the help of their spear-like rostrum. How do they coordinate this high-speed hunt without injuring one another? SCIoI researchers have been investigating the group behavior of marlin and their prey for some time to study basic principles of collective behavior and intelligence. While analyzing drone videos, they noticed something unexpected: the marlin's stripes got brighter

as a fish moved in for an attack, then dimmed down again as the attacking fish swam away. Was the fish changing colors to communicate with others? To answer, the researchers analyzed twelve high-res video clips, each showing two separate attacks by two different marlin on a shoal of sardines. They also quantified the contrast of the body stripes of the two attacking marlins compared to randomly chosen, non-attacking marlin. This analysis confirmed that these predatory fish rapidly change color before and after an attack, suggesting that this could be a signal for conspecifics.

Burns et al., *Rapid color change in a group-hunting pelagic predator attacking schooling prey**

* SEE PUBLICATIONS SECTION (FROM P. 120) FOR MORE INFORMATION ABOUT THESE ARTICLES

What's on a Mouse's Mind?

A big portion of the research at SCIoI involves finding the relation between different forms of intelligence in a variety of entities, such as robots, humans, and different species of animals. One way to observe and compare these behaviors is to have these entities use lockboxes, i.e., series of mechanisms that need to be opened in a certain order. And mice are great at solving these mechanisms.

BY SOLVEIG STEINHARDT

A mouse tries to solve the lockbox to get to the reward

Mice are intelligent beings: on the one hand, they are good at solving puzzles, giving researchers clues about their intelligence, and on the other, their natural social skills allow researchers to better understand the connection between sociality and learning from others. "It's not like they will ever get a degree," says PI Lars Lewejohann. "But the adaptive behaviors we observe in our experiments fit the basic definition of intelligence that we agreed upon in the initial objectives of SCIoI. This makes them particularly suitable for our projects."

Compared to birds such as cockatoos, who are able to first think and then act when opening a lock in the lockbox, mice are more "hoppy," Lewejohann explains, displaying a trial-and-error behavior that he sometimes calls a "Homer Simpson" type of behavior, where the mouse tries out something and then appears to think "Doh! That was wrong!" "A mouse will make the same mistake over and over until it gets it right, and for research purposes, this has its advantages: exploration makes you more flexible, and helps find new solutions to the problem. If you always do things in the same way, then you're kind of stuck with the one solution you've learned. The grasping of mouse intelligence relies on understanding how to ask the mice the right questions, and on observing the type of decisions the mice make in order to find the right solution."

So how do we ask the right questions? Our researchers set up tasks of varying complexities using lockboxes, which consist of a homecage connected to an alley that leads to the test compartment, where the mouse can receive a reward if it succeeds in opening a box that can be locked via different mechanisms. The experiment has an analytical part, where researchers observe the mice's behavior and problem-solving abilities by tracking them with a live mouse tracker, and a synthetic part, exploring the mice's learning and memory behaviors and modeling the outputs to find algorithms. "This helps us come up with definitions of the behaviors and gives us insights on which strategies are used by the animals. It's a solid example of the synthetic-analytic loop (p. 16), which is an important concept in SCIoI research," said Benjamin Lang, one of the doctoral researchers involved in the project.

Another intriguing aspect of this is understanding how social interaction can lead to learning experiences between mice. "We are interested in looking at individual pictures of mice and identifying features that give scientific evidence for happy faces and positive emotions." says Benjamin. "If a mouse can read a positive affective state through another mouse's happy face (maybe because there's a reward), the other mice present might later hypothetically be more inclined to solve that lockbox too in order to get that reward, and this fosters learning."

"Exploring mouse intelligence is about asking the right questions"

MOUSE LOCKBOX PROJECTS

- P3 Mouse lock box
- P25 Understanding learning of mice in social interaction
- P40 Big mouse data
- P46 Mouse lock box 2.0

PIs: Lars Lewejohann, Olaf Hellwich, Henning Sprekeler, Christa Thöne-Reineke, Marc Toussaint

TEAM: Niek Andresen, Mark Boon, Katharina Hohlbaum, Anne Jaap, Pia Kahnau, Anna Klenova, Benjamin Lang, Paul Mieske, Arianna Novati, Friedrich Schüßler, Soledad Traverso

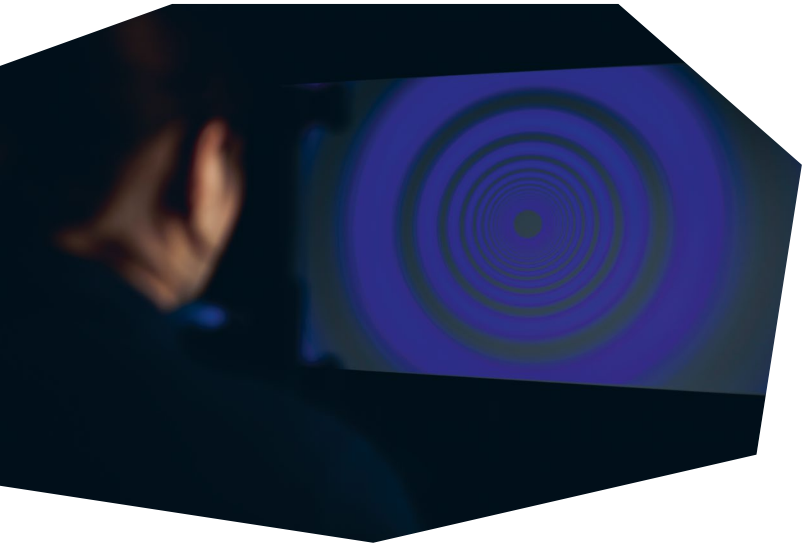
An exciting environment

Animal welfare is an extremely important part of our research, and our PIs Lars Lewejohann and Christa Thöne-Reineke are deeply involved with this topic, both at the BfR (the Bundesinstitut für Risikobewertung) and at FU Berlin.

In the specific case of mouse research, one way to improve the animals' welfare is to create appropriate housing inspired by their natural environment. This means introducing variation within the box, and making the environment more challenging and interesting. That's where the lockboxes come into play, because they can serve as cognitive enrichment, giving the mice something to do and problems to solve followed by positive rewards. In other words, we are giving the mice something to work for in order to "sing for their supper," and they enjoy that. Better housing also affects the mice's behavioral repertoires, which become more varied and diverse compared to those occurring in a traditional cage. This shows us that there's much more that these animals are able to do, and that in order to solve riddles and mechanisms that they have never seen before they are able to use skills they have acquired through evolution. And the great news is, taking quantum leaps of this kind towards improving animal welfare does not inevitably mean a setback in terms of data quality, despite the increase in responses, and therefore in variables.

Eye Movements, Decoded

When it comes to exploring the environment, there's no sense like vision. Apart from very few exceptions, humans use their eyes as their primary organ to hunt, move around, and simply understand their surroundings. Eye movement is so central in the development of behavior that its understanding is a crucial aspect of intelligence science.



The visual capture lab at SCIoI

How do we decide what to look at next?

Imagine you are looking out the window: a small bird is flying across the blue sky, a girl with a red baseball cap is walking down the street, and two people are sitting on a bench. You might think you are "just seeing" what is happening, but the truth is that we constantly make active decisions about where to look, moving our eyes two to three times per second. What exactly is catching our attention? The flapping of the bird's wings? Or the color of the baseball cap?

Vision scientist Nicolas Roth, together with PIs Martin Rolfs, Olaf Hellwich, and Klaus Obermayer have tried to answer these questions by using a computational modeling approach that compared existing human eye tracking data with computer simulations, eventually showing how important visual objects are for guiding our eye movements. "We integrated results from my colleague Olga Shurygina's work, who previously provided evidence that objects play an important role for how attention spreads. We then built a model that implements those and other experimental findings and shows that object-based attention leads to a better prediction of where people look in real-world videos."

Historically, computational models that predict what humans pay attention to have been based on so-called "space-based attention." The idea is that the brain processes the whole visual field, where everything we see is directly mapped onto a mental image of the scene from which it selects the next eye movement target. In such a map, conspicuous parts of the scene (like the location of the red color of the cap or the movement of the bird's wings) stand out, and are consequently most likely to be selected as targets for the eye movements that follow.

However, the researchers collected evidence in favor of a competing view, stating that a multi-stage process takes place instead: "The scene is first divided into individual objects, and only then does the brain decide which of these objects should be looked at next," says Roth.

Traces of light to fill the visual gaps of moving eyes

All of SCIoI's vision projects revolve around eye movement, but how does vision actually work in the face of this movement? Even if we fixate our eyes, they are never completely still. While such fixational eye-movements may lead to a blurred image for a camera, our visual system can actually make use of these movements to detect edges and hence see the world sharper, as computational work by Lynn Schmittwilken and Marianne Maertens showed.

Other movements, known as saccades, are wider and very quick, and allow us to get a general picture of the scene we are looking at. But what happens in that fraction of a second in which our eyes are moving from an object to the next? For a long time, scientists have assumed that during this time we are temporarily blind. However, a study published by SCIoI members Richard Schweitzer and Martin Rolfs shows that visual information processing takes place continuously during these movements. Hence, it is not interrupted and resumed once the movement is over, as previously assumed, as that would require the matching of two images. Schweizer and Rolfs' results show that the visual system actively uses the fleeting traces of light created by eye movements to track object positions through time.

Right and below: lab setting and tools for tracking eye movements

Getting a glimpse of how robots might see

All of these observations are of great importance for the understanding of how animals see and how they explore their environment. Vision has a very strong effect on behavior, and, according to Roth, "Getting a glimpse of what catches our attention in a scene and understanding the mechanisms underlying eye movement can help us understand how a robot can benefit from actively moving its camera to explore its environment using human-inspired object-based attention." *SRS*

ACTIVE VISION PROJECTS

- P1 Object-level scene descriptions and attention in visual research
- P23 Control models of perceptual stability in active observers
- P57 Visual information sampling

PIs: Olaf Hellwich, Marianne Maertens, Klaus Obermayer, Jörg Raisch, Martin Rolfs

TEAM: Ole Hall, Julie Ouerfelli-Éthier, Runfeng Qu, Nicolas Roth, Lynn Schmittwilken, Richard Schweitzer, Thomas Seel, Olga Shurygina

Helping Robots See

How do robots estimate depth and perceive the environment around them?

In order to successfully navigate the real world, robots need to perceive the 3D structure of their environment while in motion, continuously estimating depths and distances as these change. Animals do that all the time without any effort, and researchers have tried to reproduce the functions of animal eyes for many years. Effective robotic vision is made up of different components, and two different SCIoI projects focus on understanding the principles of vision in motion through the use of video-recording devices. In one of the projects, our researchers Guillermo Gallego and Freidhelm Hamann use event cameras, i.e., cameras that record movement as changes in brightness, while in the other project, Marah Halawa researches how visual sensors anticipate trajectories of pedestrians.

Event cameras record changes in light intensity in a moving scene

To figure out distance, the human brain uses the disparity between the views observed by each eye and analyzes the different perspectives. When trying to transfer this to robots, researchers have realized that these perspectives are difficult to obtain from simple photos, but data from multiple cameras can generate a 3D map. “This is why we use these bio-inspired sensors called ‘event cameras,’” said computer vision PI Guillermo Gallego. These cameras, sometimes dubbed “silicon retinas” have the purpose of leveraging motion information, therefore mimicking the human visual system. “Kind of like the cells in our retina, each pixel produces precisely timed, asynchronous outputs called ‘events,’ as opposed to a sequence of image frames generated by traditional cameras. The cameras naturally respond to the moving parts of the scene and to changes in illumination,” said Gallego. Thanks to this, the cameras have advantages over traditional, frame-based cameras, such as a very high dynamic range, resolution in the order of microseconds, data redundancy suppression, and very low power consumption, which also makes them suitable for working in extreme conditions.

“Every time the pixel of an event camera generates data, we can use the known camera motion to trace the path of the light ray that triggered it,” said Gallego in an interview. “Since the events are generated from the apparent motion of the same 3D structure in the scene, the points where the rays meet give us cues about the location of the 3D points in space.”

Within SCIoI, Gallego and his team also research how event cameras can be used to monitor animals to aid scientists in biology and neuroscience studies. The researchers develop algorithms to track animals like fish and mice, and to automatically detect and classify the behaviors of animals monitored remotely such as penguins (see box, right).

In another SCIoI project, researchers Marah Halawa and Florian Blume have been developing the idea that human communication is multimodal, also by exploring videos. For example, face-to-face interaction involves auditory signals (speech) and visual signals (face movements and hand gestures). The study exploits the multiple modalities needed when designing facial expression recognition systems based on machine learning. In other words, researchers employ a learning method for facial expression recognition from in-the-wild video data, conducting a study on three facial expression recognition benchmarks. This study paves the way for a better understanding of robotic vision. ● *SRS*

Visual rendition of an event camera

ROBOTIC VISION PROJECTS

- P29 Hierarchical modularized vision system for perception-action loops
- P36 Active tracking using bioinspired event-based vision – Towards improving interpretability of individual and collective behavior

PIs: Guillermo Gallego, Olaf Hellwich
TEAM: Marah Halawa, Friedhelm Hamann

A trip to the South Pole

What do penguins have to do with SCIoI? Thanks to a collaboration between Alex Kacelnik, Guillermo Gallego, and their teams, SCIoI was able to bring event cameras all the way to Antarctica and help researchers install them there in order to study interactions between chinstrap penguins.

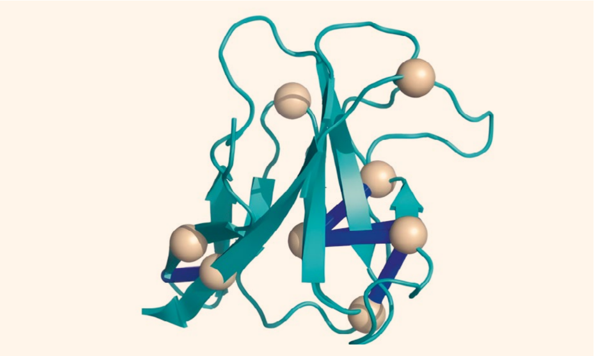
Penguins spend most of their lives at sea, but breed on land during the Antarctic summer, which goes from October to February. This is a good time of year for researchers to observe the birds and study their interactions. Our PI Alex Kacelnik participates in a long-term Oxford University study on penguin behavior and ecology. In his last trips to Antarctica, he collaborated with Guillermo Gallego, who provided the team with event cameras in order to continuously record life in an Antarctic penguin colony.

As Guillermo explains, “event cameras record changes in light intensity independently for every pixel, hence if most of the scene is static, they’ll require low power and storage.” This has potential for penguin research, Alex says. “Penguins spend long periods quietly at their nests, but show interesting behavior when interacting within a family or with neighbors. A static event camera left focused permanently on a nest can document valuable data continuously in time when we can’t be there watching.” In addition to their event-based pixel time-stream information, the cameras record conventional images every few seconds, which allows to combine information of the two data modalities.

Adapting the cameras and installing them in Antarctica required cooperation between the SCIoI team, who dealt with the technology, and the Oxford team, who went to Antarctica for the field work and the biologically relevant questions.

Selected Results

A selection of SCIoI papers



Predicting protein structure with AI

Understanding protein structure is crucial in order to comprehend how proteins interact with other molecules. AI systems in biotechnological research can contribute to this knowledge by helping predict proteins' three-dimensional structures. In a paper published in *Nature Biotechnology* by scientists from Cluster UniSysCat in collaboration with SCIoI roboticist and spokesperson Oliver Brock, the scientists presented AlphaLink, a new prediction tool that combines experimental data and deep learning. AlphaLink uses experimental information about the distances between different parts of a protein to help predict its structure. By incorporating this information, AlphaLink is able to predict the shape of challenging proteins better than its predecessors. By understanding the structure of these proteins, scientists can potentially design drugs that target the specific regions of a protein involved in diseases such as cancer, Alzheimer's disease, and cystic fibrosis.

Stahl et al., Protein structure prediction with in-cell photo-crosslinking mass spectrometry and deep learning*

Deepfake smiles matter less

Deepfakes, i.e., realistic images and videos produced by generative AI, are becoming more common. However, it has been unclear how knowing if a face is real or fake affects our perception and emotional response. In a SCIoI study, Martin Maier, Rasha Abdel Rahman, and Anna Eiserbeck analyzed participants' reactions to smiling, angry, and neutral faces believed to be real or computer-generated. Findings reveal that AI-generated smiles are perceived as less intense, elicit weaker brain responses, and cause hesitation. In contrast, angry faces are equally threatening, no matter if real or fake. These insights have broad implications for societal interactions with deepfakes.

The study involved 30 participants and explored, via EEG technology, the effects of believing whether a face is real or fake on psychological and neural responses. The study underscores the need for nuanced policies to navigate deepfake technology, emphasizing the understanding of its psychological and neural impacts. Further research into other AI-generated content domains is essential to maximize benefits and address challenges posed by deepfakes.

Eiserbeck, Maier et al., Deepfake smiles matter less – the psychological and neural impact of presumed AI-generated faces*

* SEE PUBLICATIONS SECTION (FROM P. 120) FOR MORE INFORMATION ABOUT THESE ARTICLES

An Eye for an Eye

By using robotic visual systems, we want to advance our understanding of the principles governing intelligent information processing in human vision

Humans and robots are shown the same visual phenomena, giving researchers insights about intelligent information processing

When it comes to interacting with the world, robots have the same needs as humans. They need to grapple with dynamic surroundings and process a substantial amount of information in a short time. SCIoI roboticist Aravind Battaje, together with psychologists Nina Hanning and Angelica Godinez use this insight in an exciting project to answer an important question: Could the way robots process information help us better understand human vision?

To put this to the test, the researchers used information processing algorithms from robotics to create computational models of two striking visual illusions. Like in most visual illusions, in this case what you perceive doesn't necessarily match reality. In the first illusion, people see colorful afterimages that are influenced by the shapes they just viewed. The second illusion involves objects that change in brightness. When those objects start moving, the changes in brightness seem to slow down or even stop.

Amazingly, the models based on the robotic algorithm didn't just reproduce these illusions. They also made new predictions about what people would perceive in untested scenarios. When the team ran psychological experiments, they found that people actually did experience the illusions in the ways the models had predicted. This suggests the robotic algorithm is capturing important aspects of how human vision works.

The most remarkable aspect of this project is that the robotic algorithm at the heart of these models was never designed to explain human vision. It was developed to help robots interact with the real world. And yet, with a few modifications, it was able to capture several key aspects of human visual perception, studied through the illusions. This suggests there may be some fundamental principles of information processing that are common to both biological and artificial vision systems.

"Our novel approach of using models inspired by robotics opens up a whole new way to explore and understand the complex mechanisms of human perception," said Aravind.

> "The algorithm was never designed to explain human vision"

"When robotic models closely capture the patterns of information processing in humans, they allow us to intelligently design new experiments based on the algorithmic structure of the models." As we continue to refine and expand such models, we may uncover deep principles underlying not just vision, but other aspects of human perception and behavior as well. "We can't wait to see where this innovative approach will lead us next as we work to unravel the mysteries of how we perceive and interact with the world around us," said Aravind. SRS

ROBOTIC VISION PROJECTS

- P2 A study on human and robot perception and the architecture of perceptual information processing

PIs: Oliver Brock, Martin Rolfs

TEAM: Aravind Battaje, Angelica Godinez, Nina Hanning

Socially Intelligent Robots

Who doesn't know the robots C-3PO from Star Wars, or Disney's WALL-E? Who would not dream of having such a companion at home or in the workplace? For the longest time, robots have been the stuff of utopian dreams but also dystopian nightmares in literature and pop culture. How do we fully benefit from their presence? One way is to find optimal methods of communication between them and us.

BY MARIA OTT

The small-sized Nao robots are programmed to imitate human behavior

The word "robot" actually dates back to 1921, when Czech novelist Karel Čapek first imagined the creation of artificial people. The expression has since become a fundamental term in the discussion about embodied artificial intelligence. But robots, as a concept, are not a novel invention of the twentieth century. Already back in ancient Greek mythology, Hephaestus, God of fire and craftsmanship, was said to have created so-called "automatons" to assist him in his workshop.

This long fascination with artificial companions in everyday life stems from humanity's desire to push the boundaries of technological innovation and explore the frontiers of possibilities. Intelligent machines are quite promising: from the industry to the medical field to the home, robots are in fact already an integral part of human society. Humans, however, are inherently social beings, and when it comes to interacting with them, robotic systems struggle to understand and respond to the nuances of human behavior and language. If we want the interaction between robots and humans to be effective, then robots need to behave like social agents and show social abilities.

Jonas Frenkel interacts with two Pepper robots in the Asimov Lab

At SCIoI, various projects focus on understanding social intelligence in humans and on training robots to integrate context information during communication, showing them how to predict and simulate others' actions, and how to pick up on non-verbal cues. This improves their social capabilities, making them more effective communicators and assistants. To do that, cluster researchers identify key elements of communicative behavior (essentially what is seen as "social" or "intelligent" in interactions) and use a wide range of methods, from recording teacher-student interactions in schools to EEG scans.

Imagine a classroom where every student has the opportunity to interact with a robotic tutor who understands their educational and social needs. To achieve this, our researchers need to understand how motivation influences learning and thus acquire knowledge through social interaction. The next step is to translate these psychological findings into computational models, serving multiple purposes. For example, our scientists are currently developing new feedback mechanisms for a vocab-learning application, with a virtual teacher that adapts its style based on a student's engagement level.

To further enhance social perception, we aim to better understand faces and non-verbal cues in social interaction and learning situations, and the wealth of background information they transmit. Now, to understand the role of facial expression or gestures in such interactions, we are not purely relying on the raw data that teaches patterns of faces or movement to robots. We are adding details, we are exploring how contextual information influences humans in their decision-making or knowledge acquisition. Take for example the influence of face perception on our motivation: how are we ourselves triggered by subtle cues? And how do we decide if someone is trustworthy or not? This becomes even more relevant in our time of AI technologies that produce a huge amount of (emotionally charged) deepfake images that influence us (see p. 36).

But let's go back to the classroom for a clearer picture: So, when we talk about social intelligence, what we mean is the social knowledge transfer from one individual to another. In a classroom, we have interactions between multiple individuals that all send and receive information simultaneously. In addition to the teaching content, we also have meta information regarding the importance of certain kinds of information, as well as social information about the sender or the receiver or the relationship between those two. In this, non-verbal communication is a critical aspect of knowledge transfer. If you need an example, just think back to the recent pandemic, where non-verbal aspects of interaction were reduced, leading to miscommunication, misunderstandings, or simply much more difficult communication.

In a classroom then, the teacher can determine with one simple look if a student is confused or engaged. At the same time, the teacher can use non-verbal signs to highlight the importance of certain points to motivate a student, or to guide their attention through a gaze or through using their hands. "In our project," SCIoI psychologist Jonas Frenkel says, "we use anonymized data from classroom situations and analyze interactions in this context. We use computer vision to study the non-verbal behavior in social interactions. We look at body posture and we make estimations about distances between students and teachers. And then we put all this together again, to describe, for example, the complexity of the non-verbal behaviors in such interactions. This helps us to better understand the dynamics underlying social learning situations."

"Teaching robots how to understand others' actions will improve their capabilities during social interactions"

This knowledge enhances research on social interactions, also within the context of human-robot interaction. We will better understand not only interactions among humans, but also potentially be able to study and understand interactions between social robots and humans.

Ultimately, our research aims to pave the way for robots that are not simply tools but agents that can enhance human experiences, making interactions more supportive and intuitive.

Two Pepper humanoid robots in conversation with each other

HUMAN-ROBOT INTERACTION PROJECTS

- P6 From understanding learners' adaptive motivation and emotion to designing social learning companions
- P8 Knowledge-augmented face perception
- P9 Multimodal interaction and communication
- P31 Social responsiveness and its effects on learning in human-human and human-robot interaction
- P50 Adaptivity in learner-teacher interaction
- P59 Observational learning developing human and artificial agents
- S3 Electrophysiological investigations of social intelligence

PIs: Rasha Abdel Rahman, Marcel Brass, Verena Hafner, John-Dylan Haynes, Olaf Hellwich, Rebecca Lazarides, Niels Pinkwart, Julia Rodriguez Buritica

TEAM: Helene Ackermann, Julia Baum, Pia Bideau, Florian Blume, Johann Chevalère, Anna Eiserbeck, Jonas Frenkel, Anja Henke, Eitan Hemed, Ashwin Moongathottathil James, Murat Kirtay, Anna Kuhlen, Anna Lange, Antje Lorenz, Martin Maier, Uros Petkovic, Doris Pischedda, Olga Wudarczyk, Hae Seon Yun

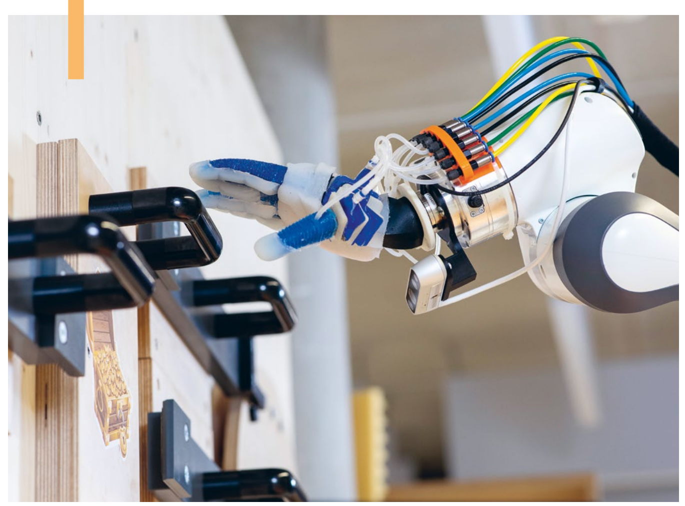
"Our educational programs are designed to equip the next generation of researchers with the interdisciplinary skills needed to meet the demands of the digital future."

5 Things You Didn't Know about Robotic Arms

Intelligence cannot exist as an abstract algorithm alone. It requires a physical body, and this is what we mean when we speak of "robot embodiment." And if this body is also anthropomorphic, it's not only better accepted by humans, but it also tends to be taught to perform actions in a human-like way. At SCIoI, roboticists Xing Li, Adrian Sieler, and Vincent Wall "teach" robotic arms and soft robotic hands to solve lockboxes and puzzles just like we would. Here are some of the most interesting facts about robotic arms at our cluster.

BY SOLVEIG STEINHARDT

1



The robotic arm can learn to solve a lockbox

It's fascinating to observe animals like cockatoos and mice solving complex mechanical puzzles, and to explore the fundamental principles that enable them to conduct these tasks. In order to apply this understanding to a robotic system, we work with researchers from many disciplines to develop a robot that can autonomously operate mechanisms similar to those in a puzzle box. Through trial and error, the robot starts to solve the puzzles of this lockbox using previously learned knowledge, understanding interdependencies and interacting with the environment. And once we've done that, we can use this knowledge to get an even better grasp of animal intelligence.

2

The arm is able to acquire skills from human demonstration

How can we quickly program various manipulation skills into robots? In SCIoI project 28, we have developed a framework that enables users to "teach" robots skills through human demonstrations, in which a user physically guides the robot through the required movements. This intuitive programming method allows the robot to quickly adapt to the user's environment with minimal human intervention, and only requires one human demonstration, actively moving the robot to seek additional task-relevant information. This innovative concept that combines human demonstrations and autonomous data collection by robots enables a data-efficient robot learning framework. The framework has been tested with a real robot on a wide range of manipulation tasks, including the manipulation of latches, chain locks, drawers with handles, insertion puzzles, and door locks with keys.

3

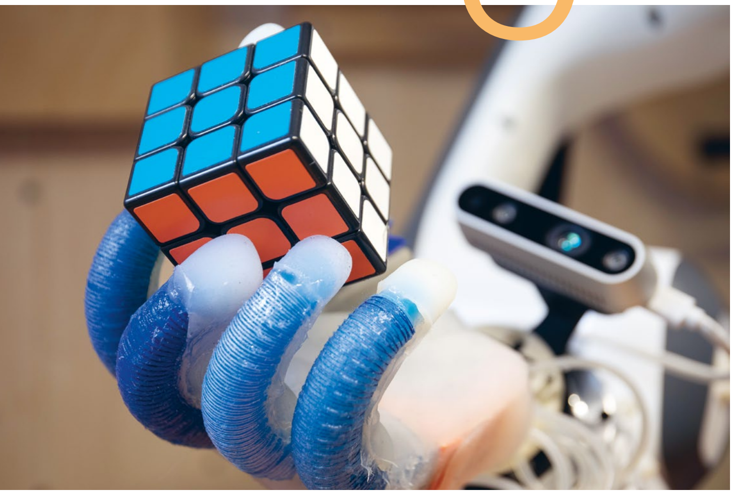
The SCIoI robotic arm has a soft hand that grasps objects like a human

Human hands are versatile tools thanks to their softness, range of movement, and sensitive sensors, and robotic hands should be similarly dexterous. The soft robotic hand developed in the RBO lab (a robotics and biology lab closely connected to SCIoI) already solves some of the dexterity-related problems by mimicking the shape of the human hand. With flexible and adaptable fingers made of soft, deformable silicone, the RBO Hand achieves stable contact surfaces and adapts to the shape of its surroundings and of the objects it touches. This makes grasping easy. The challenge now is to develop novel motion planners that make use of the capabilities of soft robotic hands. A successful implementation of this was demonstrated in solving the lockbox.

4

The hand uses sound to "feel" touch

The fingers of the soft hand are hollow, and by producing and recording sounds inside the hollow chamber, they can detect contact events, which means they can "feel" touch. Touch feelings at different portions of the finger slightly modify how the hollow chamber is shaped, hence changing the "notes" that resonate within that chamber. This way, the hand can feel what the finger is touching, including texture, location, and temperature, and all of that happens thanks to the way the sound changes inside the chamber. However, the hand is also fitted with fabric-based sensors providing tactile information, as well as soft strain sensors for proprioception, which is the sense that helps us feel our movement and location in space.



5

The robotic hand is anthropomorphic

Would a non-anthropomorphic hand work too? Yes, it would. But creating anthropomorphic agents improves the perceived sociability of the robot. That's because people tend to treat anthropomorphized objects as if they were human, and are therefore more inclined to initiate social interactions with them, applying human-like social norms. But also, the world we live in is built for humans. Robots act in the same world as humans, learning human skills. Therefore, creating anthropomorphic robots is very helpful to guarantee that they are accepted in our society.

ROBOTIC ARM & LOCKBOX PROJECTS

- P17 Dexterous and sensorized soft robotic hands
- P28 Learning to manipulate from demonstration (to escape from a room)

PIs: Oliver Brock
TEAM: Xing Li, Adrian Sieler, Vincent Wall

Haptic knowledge exchange

A useful tool to understand the strategies that humans use to solve lockbox-like problems is the haptic device, a technology that can simulate the touching of objects present on a screen by applying forces, vibrations, or motions to the user's hand. In one of our experiments, our researcher Oussama Zenkri had people play a simulated lockbox task with the haptic device, while others performed the same task with the computer mouse. We saw that the strategies employed by the persons who used the haptic device were much more efficient than those employed by the mouse users. Therefore, we can say that the haptic device allows us to understand human strategies during physical interaction, and to some extent, in this way the robot can learn how to solve problems as efficiently as humans (also see p. 21).

Oussama Zenkri operates the haptic device for an experiment on human decision-making strategies

"Science of Intelligence provides the blueprint for the next generation of AI, ensuring that the systems we are building are not only powerful but also responsible and beneficial."

STAFF

3,228
Animals
(fish, cockatoos, mice)

38
Principal Investigators

46
PostDocs

221
Robots

14
Coordination Office Members

7
External Collaborators

133
Total Academics

50
Doctoral Researchers

RESEARCH

329
Publications
(June 2024)

8
Teaching Grants

51
Research Projects

4
Research Units

7
Summer Schools and Winter Schools

6
Labs

TALKS

3
Talk Series

15
Retreats and Symposia

91
Guest Lectures

23
Distinguished Speaker Lectures

EXCHANGES

5
Global Scientific Exchange Program fellows

5
Guest Fellows

6
Lab Exchanges

COLLABORATIONS

5
Industry Collaborations

18
Academic Collaborations

4
Conference Collaborations

The Wisdom of the Crowd

Those who've been to our swarm robotics lab have certainly seen the multitude of mini-robots lying around on the tables. Those are SCIoI's Kilobots, used by our researchers to study swarm behavior. But what exactly do they do? And how do they work? We had a chat with computer scientist Mohsen Raoufi, who shed some light on the "life" and secrets of these interesting robots.

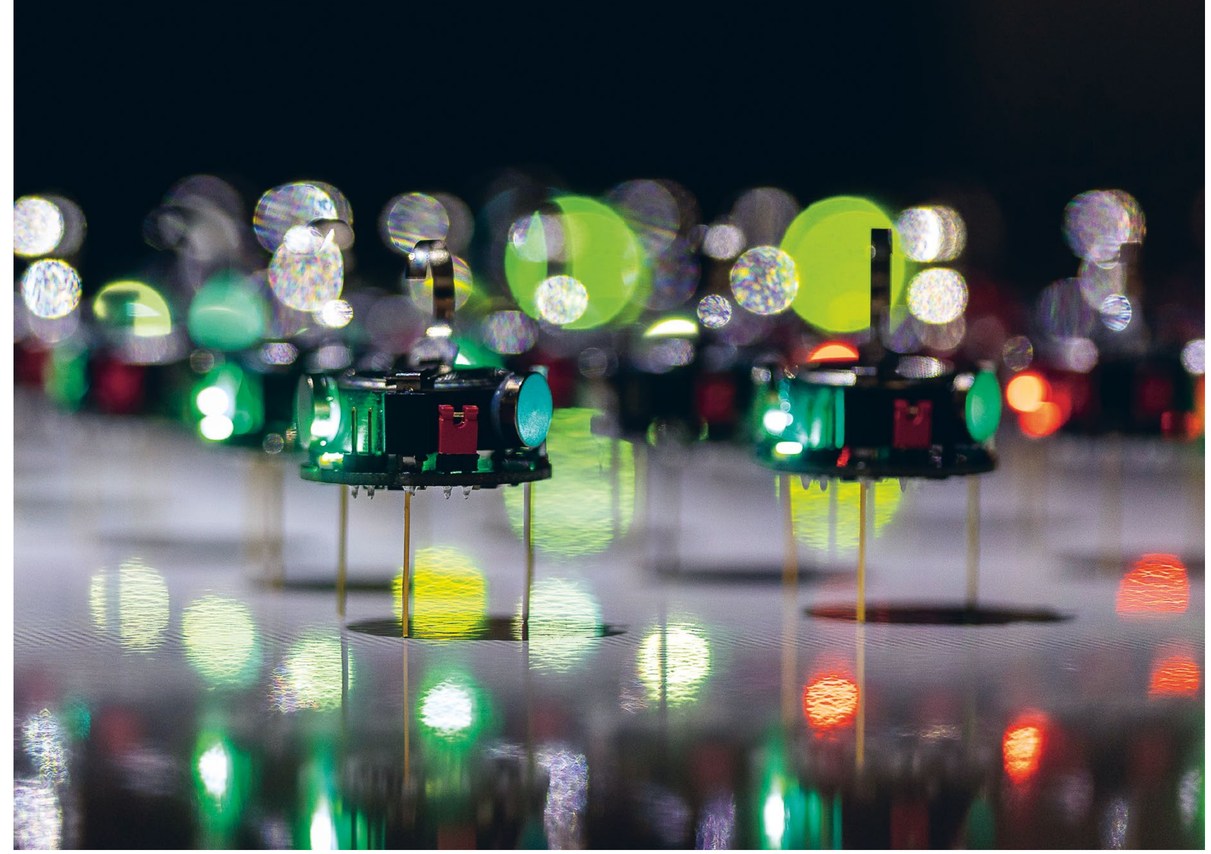
Mohsen Raoufi sets up an experiment with Kilobots at the Lange Nacht der Wissenschaften 2023

Why does SCIoI study swarms of robots?

MOHSEN: I think we first need to take a step back to a more basic question: why do we use robots, in general, to understand intelligence? SCIoI follows Richard Feynman's idea, according to which "what I cannot create, I do not understand." Therefore, we create synthetic systems – humanoid robots, robotic arms, or a group of relatively simple robots – with the aim of understanding intelligence. But why swarms? What can they tell us about intelligence? Collective systems (such as ant colonies, flocks of birds, or schools of fish) show intelligent behavior in that they are able to solve relatively complex problems. For example, they'll find an efficient route from their nest to a food source, or escape from predators. In other words, they'll do things that are beyond the capability of each single individual. Robotic swarms are a synthetic system that can exhibit this form of behavior. Studying them not only helps us understand natural collective intelligence but also opens up possibilities for practical applications, such as rescue missions, environmental monitoring and cleaning, and even space exploration.

How do Kilobots compare with other robots?

They are very simple. Swarm robots are designed very minimally because their advantages lie in their numbers rather than in their individual performance. This also applies to their sensors, processor, power supply, and actuators. In that sense, their limitations



Kilobots synchronize their blinking lights

resemble biological swarms, which usually have limited information about their surroundings and neighbors.

How do they see or communicate?

Kilobots do not have a camera to see. Instead, they have a light sensor that measures the intensity of light at their location. They can also communicate with other Kilobots using an infrared signal. The interaction network of swarm robots is decentralized, i.e., there is no central component controlling the flow of information. Furthermore, because their power supply is low-capacity, their communication range is short. As a result, each robot can only interact with a few robots around it. This decentralized network and the limited number of neighbors are regularly observed in biological swarms too.

> "Collective systems can do things that are beyond the capability of each single individual"

Can you describe one of your experiments with Kilobots?

An example scenario we worked on was about collective estimation. A group of Kilobots is supposed to measure the light intensity of the environment and estimate the average brightness of the arena. In nature, the estimation of light intensity can help a collective make the best decision. In the case of an ant colony, for example, the colony needs shaded nests, but for single ants, evaluating the light intensity of potential nests is very hard. Collectively, they can do this. Similarly, while an individual Kilobot needs to explore, measure, and discover the arena to make an accurate estimation, a swarm of Kilobots can quickly estimate the environment accurately.

The idea is similar to the so-called "wisdom of the crowd" effect, where each individual brings some imperfect piece of information to the collective. Although each piece of information may be inaccurate, the average of all these imperfect pieces can be significantly more accurate. So, if robots interact with each other and share their information with their neighbors, they can update their estimation to a

"It's the 'wisdom of the crowd' effect: Although individual pieces of information may be imperfect, the average of all these imperfections is more accurate."

A group of Kilobots and, behind, two Thymios. These are SCIoI's two fleets of swarm robots

more accurate one. In an abstract sense, being a member of a collective can provide more accuracy of estimation for individuals, and thus help their decisions.

What can Kilobots tell us about collective intelligence?

That's a great question! There are a few questions regarding collective intelligence that can be answered regardless of the system we work on, whether artificial or natural. For example: what are the requirements for a collective to behave in an intelligent way? What are the conditions needed for crowds to achieve a wise estimation? How can we obtain intelligent behavior at the collective level while the individual-level intelligence and capabilities are so restricted? Additionally, studying a group of Kilobots brings up other interesting observations about collectives. Most of these observations arise due to the embodiment of the robots in the real, physical world, which is otherwise not observable in simulations. In our latest work, we studied how each robot is slightly different than the others, a feature we called "individuality in swarms."

You say there are individual differences in Kilobots? What can we learn from that?

Despite a common belief that all robots are exactly identical, we've shown that each robot has its own unique properties. From other work in biological systems, including work by other SCIoI colleagues, we know that natural systems exhibit individuality, too. For example, some fish develop asymmetrical muscles on the left and right side of their bodies, suggesting a morphological individuality. In our robots, we studied these differences in how fast they move, how sensitive they are to environmental signals, or even in the speed of computation. A classical engineering approach is to try minimizing these differences through calibration, for instance. However, there are cases where calibrating does not improve the performance of robots, but actually reduces it! Answering these questions, and gaining insights from new perspectives is what makes swarm robot systems so interesting to us. ● *SRS*

SWARM ROBOTICS/COLLECTIVE SEARCH PROJECTS

- P27 Speed-accuracy tradeoffs in distributed collective decision making
- P34 Weighing personal and social information in cooperative problem solving
- P51 Navigating the explore-exploit tradeoff in collective search

PIs: Heiko Hamann, Ralf Kurvers, Pawel Romanczuk

TEAM: Valerii Chirkov, Dominik Deffner, Felicie Dhellemmes, David Mezey, Mohsen Raoufi

Immersive reality used by Deffner et al.

The More We Get Together

Using video games to understand how individual decisions shape collective outcomes in realistic group settings

How do human groups manage to adapt collectively to different circumstances, for example in a search and rescue operation, an ice-fishing expedition, or a mushroom-picking session? The study of collective behavior reveals how individual decisions shape collective outcomes in realistic group settings.

In one experiment by psychologist Dominik Deffner, groups of participants freely move through a 3D virtual environment similar to a video game (pictured above), searching for hidden treasures. The researchers observed that single individuals often benefited from staying close to others and taking advantage of their discoveries, but maximum group performance was observed when players independently searched new treasures. When incentives were placed on the group (vs. individual) level, people became less likely to follow social information, in turn, improving group outcomes. This experiment says a lot about key decision-making processes in collectives, and could be applied to group strategies, for example to improve the efficiency of search and rescue operations, or to better understand human decision-making strategies in foraging situations (see p. 25).

These findings were also explored from a synthetic point of view by computational neuroscientist and engineer David Mezey through a computational model. His study explores how individual decisions shape collective behavior in a group of simulated robots exploring a virtual playground like the one previously described. The results show that the environment plays an important role in how groups work efficiently together. "When resources are concentrated, it's more efficient to work closely together and rely on shared information. But when the resources are spread out it's better for individuals to work independently." The researchers also showed that visual occlusion and the field of view of individuals might fundamentally reshape optimal searching strategies. This finding has special importance in swarm robotic applications where such constraints are always present. ● *MO*

How Actions Spread

Every day, from the moment we wake up until we go to sleep, we make countless decisions. Whether it's choosing what to eat for breakfast or deciding the best route to work, each decision carries potential consequences. Researchers have long been fascinated by how we make these decisions, especially in social settings where the influence of others can significantly alter our behavior. This is where the concept of behavioral contagion comes into play.

BY MARIA OTT

An experiment with VR

Behavioral contagion refers to the phenomenon where certain behaviors spread among individuals in a group. This can be observed in the spread of laughter in a room or in the escalation of violence during a protest. The principle behind this is that individuals often mimic the actions of those around them, either consciously or unconsciously, also to validate their own choices. But why does this happen?

Understanding behavioral contagion is crucial for several reasons. For example, during emergencies, the spread of panic can lead to dangerous stampedes, whereas the spread of calm behavior can facilitate safe evacuations.

At SCIoI, researchers use various methods to study behavioral contagion, drawing from psychology, sociology, biology, and computational modeling. One innovative approach involves controlled laboratory experiments using virtual reality (VR) technology. In one of them, participants are placed in a (virtual) room with a group of virtual agents (see picture, left). They are presented with a visual stimulus composed of blue and yellow pixels. Participants are then instructed to raise their right hand if the dominant color is yellow and their left hand if it is blue, or vice versa, with the color-hand association counterbalanced among participants. The virtual agents perform the same task and, like real humans, can make correct or incorrect judgments. The researchers then observe how the information coming from virtual agents influences the participant's decisions. "By integrating VR, we can introduce virtual agents whose behavior participants can observe. These agents may sometimes make intentional errors, allowing us to study how such mistakes affect the participants' risk-taking behavior," explained biomedical engineer Asieh Daneshi, who is working on this project.

In a second research line, computational neuroscientist Maryam Karimian creates computer simulations of these VR experiments, using mathematical and computational models to analyze behavioral contagion and replicate how individual decisions and interactions lead to collective outcomes. "These models help us understand the underlying mechanisms and predict how changes in individual behaviors as well as the structure of groups can impact the behavioral contagion," she explained. In another example, our PI Ralf Kurvers has scaled this research up to larger human groups, studying information flow in groups of up to twenty participants. Participants have to find hidden predators in pictures of animals and can exchange their decision in real time with their group members. These experiments help understand how information cascades through social systems.

But behavioral contagion is not limited to humans. It is also observed in animal groups, such as flocks of birds or schools of fish, where individuals follow their neighbors, leading to coordinated movements that appear almost choreographed. By understanding the complexities of behavioral contagion, SCIoI researchers aim to develop comprehensive models that account for both individual decision-making and group dynamics. These models can lead to better strategies for fostering positive behaviors and mitigating negative ones, contributing to a more harmonious and well-functioning society.

COLLECTIVE COGNITION PROJECTS

- P26 The collective dynamics underlying personal and social information integration
- P42 Behavioral contagion in human and artificial multi-agent systems – integrating the cognitive and collective behavior perspective using VR
- P52 Evolution of collective cognition in response to novel selection pressures – how individual-level adaptations shape group-level outcomes

PIs: Robert Arlinghaus, Marcel Brass, Ralph Hertwig, Jens Krause, Ralf Kurvers, Anne Nassauer, Pawel Romanczuk

TEAM: Asieh Daneshi, Maryam Karimian, Valentin Lecheval, Tamal Roy, Alan Tump

Zebrafish attitudes

Changes in individual cognition lead to changes in collective patterns and decision making. To understand how this works, SCIoI biologists Tamal Roy and Valentin Lecheval, who work at the IGB labs in Berlin (pictured above), have been developing theoretical models and conducting cognitive behavioral studies testing perception, attention, self-control, flexibility, innovation, learning and memory in individuals and in groups of zebrafish (*Danio rerio*). This study was carried out on three populations from which either the largest, the smallest, or random individuals were selectively removed in order to mimic natural predator scenarios. "By comparing individual performance in different tests, we want to see how external agents like predators can cause prey groups to select for different behaviors, and how this can lead to changes in collective patterns and decision-making," explained Tamal Roy. "For example, we noticed that individual fish from the population where the largest fish were removed have reduced self-control (the ability to inhibit their reflex) and flexibility (the ability to modify their behavior). How does this affect the behavior of the collective, and how does the group adapt in order to efficiently find food and avoid threats? This is what we want to test."

Same Genes, Same Environment, Different Exploration Strategies

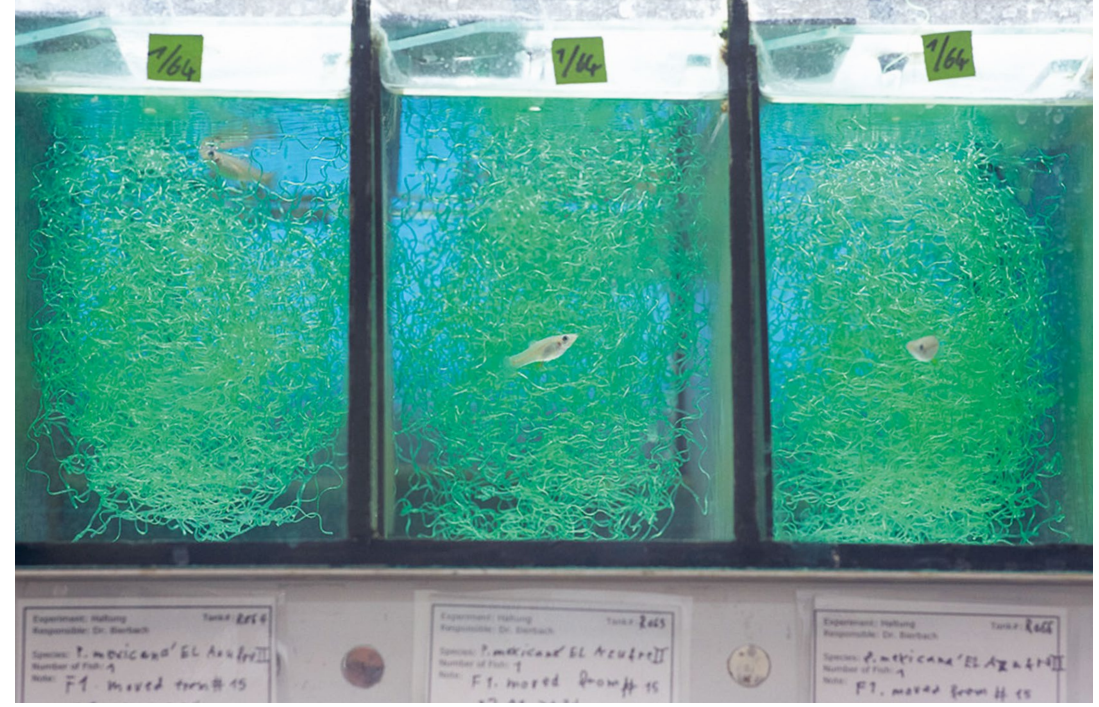
How do newborn animals develop exploration strategies? SCIoI behavioral ecologists Ulrike Scherer and Sean Ehlman, together with the rest of their team, are trying to answer these questions by using clonal fish. Ulrike explains what the project is all about.

Clonal Amazon mollies

BY ULRIKE SCHERER

One key theme at SCIoI is the "escape room" idea. Imagine a room where you must reason through a series of tasks that rely on successfully having navigated the previous ones in a specific order to "succeed" in escaping. Now extend this metaphor to newborn animals who, once born into the world, must successfully navigate their environments, growing, learning, and adjusting to a series of tasks in order to "succeed" in life. This is the "escape room" problem that our project is trying to solve. That is, being initially completely ignorant about the specifics of their natal environment, how do newborn animals develop "intelligent" (i.e., adaptive, successful, efficient) behavior? Evolution has made biological organisms extremely good at solving such tasks. However, very little is known about the behavioral mechanisms underlying this ability.

In our project, we specifically focus on generating a deeper understanding of how newborn biological organisms develop intelligent



Clonal fish at the SCIoI Aquatic Lab

"exploration strategies." We address one of the arguably most fundamental questions associated with this behavior in biological systems: how do behavioral-experiential trajectories (i.e., the trajectories of exploration) dynamically unfold in newly born organisms? In other words, when confronted with an unknown environment, what are the exact sequences of exploration behaviors and associated experiences that real-world organisms go through from day one of their life?

To answer these questions, we are using a unique biological model system: the naturally clonal Amazon molly (*Poecilia formosa*). Amazon mollies give birth to live offspring and naturally reproduce clonally, which means they produce offspring that are genetically identical to their mother, with reproduction (i.e., cloning of the mother) occurring via activation through sperm from males of similar species. Newborn fish need neither parental care nor direct social interactions and can thus be separated directly after birth and tracked individually in identical environments, thereby allowing us to make full use of one the most powerful approaches in experimental biology: the replicate-individual approach. For this purpose, we developed a high-resolution, long-term recording system with associated real-time tracking, allowing us to generate rich data sets of individual behavioral-experiential trajectories that cover a substantial period of behavioral development. Based on the observed real-world behavior of newborn individuals, we develop models of exploration behavior that on the one hand explain and predict the behavior observed, and on the other hand perform well when implemented in virtual agents (computers) that are confronted with large-scale virtual experiments simulating a broad range of conditions and tasks.

"We want to understand how newborn organisms develop intelligent exploration strategies"

Aside from generating rich behavioral datasets to understand how individuals develop intelligent exploration strategies, we are also interested in understanding variation among individuals. In short, we want to know why individuals develop different exploration strategies. Recently, we discovered that even genetically identical Amazon mollies that are being raised in individual and virtually identical environments differ substantially in how they explore their surroundings. Interestingly, and despite best efforts of calibration, we observe the same phenomenon in Kilobots (p. 48), indicating that, in complex systems, variation might be inevitable. Now we are on a path to discovering what the sources of this variation are. Could there be micro-environmental differences that somehow start a chain reaction within a developing organism, leading to much larger differences through time? Are there pre-birth processes, such as epigenetic effects, that have a large effect on variation even among genetically identical individuals? We are excited about the prospect of exploring these crucial questions and linking them to aspects of those biological phenotypes that are the true measures of "success" in a new environment: survival and reproduction.

FISH EXPLORATION BEHAVIOR PROJECTS

- P10 Anticipation, prediction and behavioral reliability in social interactions
- P11 Dynamical collective adaptation & learning
- P21 Developing exploration behavior
- P58 From exploring basic maze elements to algorithmic rules for the escape room

PIs: Verena Hafner, Jens Krause, Tim Landgraf, Jörg Raisch, Pawel Romanczuk, Henning Sprekeler, Max Wolf

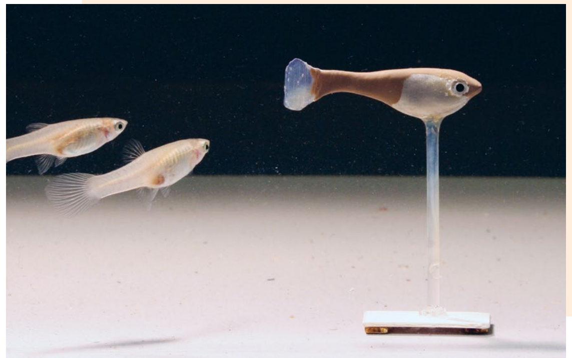
TEAM: Palina Bartashevich, David Bierbach, Sean Ehlman, Fritz Francisco, Dustin Lehmann, Lea Musiolek, Ulrike Scherer

How are fish schools so well coordinated?

When it comes to testing predictions of collective intelligence, creativity is key. Our approach is rather simple yet highly effective: To specifically control the behavior of individual animals in a social group and thus test theories on general mechanisms in collective intelligence, we built "Robofish," a robot-controlled artificial fish that integrates into groups of small freshwater fish like guppies or Amazon mollies, who accept it as one of them. Using high-definition video tracking and a feedback system that let Robofish react to the living fish's actions in real time, we were able to create the perfect follower individual. In this way, we could test how the movement decisions of the live fish influenced the group's general collective behavior.

Programming the robotic fish without any of its own movement preferences gave us the unique opportunity to investigate how individual differences in the behavior of the live fish led to group-level differences. This allowed us to isolate the effect of the fish's movement speed on the group's collective behavior. This revealed that there are large individual differences in how fast live fish tend to move, and that individual speed is an important factor in the emergence of collective behavioral patterns. Thanks to Robofish, we have also been able to show that guppies can anticipate the movements of their artificial conspecific and predict both the direction and dynamics of its movements (see p. 28), a skill that professional (human) football players aspire to have in order to be able to react quickly, or even in advance, to their adversaries' moves. This sheds light on the mechanisms behind the sudden changes in direction of large schools of fish and helps us to understand how synchronized behaviors of thousands of independent animals might be possible.

BY DAVID BIERBACH



> "Exploring intelligence across different species and systems teaches us the value of diversity in problem-solving and creativity."

Beyond Data

Machine learning challenges: addressing data scarcity to achieve deep insights

BY MARIA OTT

Deep learning has revolutionized AI, enabling machines to solve complex problems like image recognition and natural language processing that traditional machine learning once struggled with. Self-driving cars use deep learning to spot pedestrians and traffic signs, while virtual assistants like Siri and Alexa interpret voice commands. However, this progress demands vast data and computational power, and adaptable models for ever-evolving tasks. Handling big amounts of data poses many challenges. Here is how SCIoI is addressing the five challenges that are most pressing for its research.

CHALLENGE 1
How do we deal with data scarcity and high computational demands?
We optimize deep neural networks and teach them to work with less data

"Our goal is to understand the inner workings of deep neural networks so that we can optimize them in a targeted way," explains computer scientist Heiner Spieß. "We study how these networks understand input data and construct transferable features. We're trying to improve a network's ability to identify these transferable features, which are important for improving its generalization performance." In other words, by teaching a system to focus only on the relevant, general features of the data, we are helping it become better at generalizing with less data and across data sources. "If a network processes images of both cats and dogs using common features such as their ears or tails, we can adapt it to recognize a new animal, such as a fox, with smaller amounts of data, because some of its features are dog- or cat-like and are already known to the network. To do this, we use transfer learning (adapting pre-trained models to new tasks with minimal data) or multi-task learning (learning multiple tasks simultaneously)," Spieß said.

CHALLENGE 2
How can AI learn new tasks without losing its previous knowledge?
We update models so that they can correct errors without overwriting previously acquired information

One of the challenges of lifelong learning is something the researchers call "catastrophic forgetting," which is when new information overwrites existing knowledge in neural networks. Imagine a personal-assistant AI that learns to book flights, but then forgets how to schedule meetings. Our objective is to update models based on sparse feedback, allowing them to correct systematic errors without losing prior knowledge. This approach can make AI systems more efficient and contribute to our understanding of how continuous learning processes might function in artificial systems.

CHALLENGE 3
Similarly, how can we improve continuous learning in AI systems?
By simulating the brain's ability to grow new neurons

"Traditional neural networks have fixed topologies, and this can limit their ability to adapt," says computer engineer Magdalena Yordanova. "By simulating neurogenesis, we aim to create networks that grow and adapt dynamically, much like the human brain." And according to computer scientist Max Ploner, "this approach not only reduces the need for manual network configuration but also enhances a robot's ability to learn in continuously changing environments, in a way that is very similar to biological intelligence."

CHALLENGE 4
How do we deal with "noise"?
We teach systems to ignore incorrect labels

In real-world scenarios, data often comes with noise-incorrect labels that can mislead learning systems. Think of a child asking for the name of a plant but being told the name of the window behind it. Though the child is able to specify what they meant, deep neural networks are not as good at that. Computer scientist Elena Merdjanovska works on developing strategies to have models identify and correct these errors, ensuring reliable learning even with imperfect data. "Our goal is to devise mechanisms that identify and ignore incorrect labels, potentially overwriting them with pseudo-labels for better learning outcomes," explains Elena.

CHALLENGE 5
How can we bridge the gap between computer model planning and real-world execution?
We integrate perception-based control into the model right from the planning phase

Think of a robot moving around a room: it might be programmed to move objects in a cluttered space but struggles if the objects are moved during the task. One of our goals is to integrate perception-based control directly into the planning process, allowing the robot to react dynamically to changes in its environment. That way we can make robotic systems more resilient, and better understand how adaptive control mechanisms can be embedded into planning frameworks. ●

MACHINE LEARNING PROJECTS

- P15 Efficient multi-task deep learning
- P39 Physical manipulation planning with differentiable closed-loop manipulation primitives
- P44 Efficient model learning from data with partially incorrect labels
- P45 Modeling neurogenesis for continuous learning
- A2 Neural representations for lifelong learning

PIs: Alan Akbik, Verena Hafner, Klaus Obermayer, Marc Toussaint

TEAM: Christoph Alt, Danny Driess, Elena Merdjanovska, Max Ploner, Heiner Spieß, Jacek Wiland, Magdalena Yordanova

Magdalena Yordanova interacts with Nao robots

Vito Mengers observes the robotic arm to extract principles of intelligence

Principles of Intelligence

What is intelligence? In the past, the different disciplines exploring this concept have provided answers, but only in a fragmented way, each discipline just focusing on some components of intelligence. To understand intelligence as a whole, we must look at how these fragments interact with each other and how these can help us extract principles of intelligence.

To understand how important it is to find principles, let's take a historical detour to 1869. Remember chemist Dmitri Mendeleev, who was struggling to make sense of the chemical elements? By ordering the elements by their atomic weights, he noticed a periodic pattern in their properties, a principle, which led to the creation of the periodic table. Initially met with skepticism, his predictions were eventually validated, revolutionizing chemistry. This story highlights how principles can guide scientific progress by providing a structured framework to make sense of complex phenomena. Just as principles were crucial in chemistry, they are vital in studying intelligence. For example, if we identify common principles in intelligent behavior, we can create better artificial models.

Intelligent behavior happens when, for example, what we see and hear is processed and turned into suitable actions. Animals and humans gather lots of information through their senses, but just collecting this raw data isn't enough. It needs to be processed and connected to actions. In order to explore this interconnected and continuous adaptation to changing environments, our researchers set up experiments with robots. And since we can watch every step of the robots' actions and fully control their environment, we are able to come to a closer understanding of the principles at play.

"With these experiments, on a very fundamental level, we are able to understand the different states of perceiving, processing and acting, and how these are interconnected," says SCIoI roboticist Vito Mengers. "We believe that these interactions between components are more relevant than the components themselves, and this very statement is what I am trying to investigate as a candidate principle of intelligence. If this principle holds, it should apply to a variety of intelligent behaviors. And so, we're collaborating with several projects to validate this principle across different contexts, including individual, social, and collective intelligence." Now, in order to be able to observe the interactions between components, the researchers create complex tasks that trigger these interactions. They then explore how agents (an animal, a human or a smart robot) choose the most appropriate action to complete those tasks.

According to Bassel Katamish and Furkan Davulcu, who work on a related project, natural intelligent agents (i.e., humans or animals) are good at solving complex problems that are out of reach for computer programs and robots (like improvising or reacting to an upset child). "In order to equip robots with similar capabilities, we need to find a way to divide complex problems into reasonable sub-problems by exploring and exploiting the existing regularities, in the sense of finding patterns in complex problems and using them to solve these problems effectively. We would really like to understand how this works," says Furkan. In their research, Furkan and Bassel are applying this theory to scenarios such as escaping from an escape room and collective shepherding, to see how robots solve these tasks. "The aim is to provide a robust framework for generating intelligent behaviors in robots and other systems. By identifying regularities and understanding how they interact at different levels of abstraction, we are creating a systematic approach towards understanding intelligent behavior," they explain.

Let's revisit Mendeleev's periodic table. His insight into the elements' periodic nature provided a principle that structured chemical knowledge, leading to the prediction and discovery of new elements. Similarly, understanding the principles at play might provide a robust framework for studying intelligence, and our hope is that we can help design better robots and AI systems. ● *MO*

PRINCIPLES OF INTELLIGENCE PROJECTS

- P35 Differentiable interconnected recursive estimation as a principle of intelligence
- P43 Generating robust and general real-world behavior by exploiting regularities at multiple levels of abstraction
- P13 Architectural design principles for intelligence: Modularity vs Integration

PIs: Marcel Brass, Oliver Brock, Jöerg Raisch, Henning Sprekeler

TEAM: Furkan Davulcu, Kai Görgen, Bassel Katamish, Vito Mengers, Halil Yigit Özksüz, Simon Weber

Balancing modularity and integration

To uncover principles of human thought processes, we also look into cognitive architectures. These frameworks model how the brain processes information, solves problems, learns, and adapts, serving as blueprints for intelligent agents like robots and AI. A main challenge is finding the balance between modularity (sub-regions of the brain working more independently from each other) and integration (extensive communication between different sub-systems). Modular systems are energy-efficient but offer shallow processing, while integrated systems consume more power but provide deeper processing. Is it beneficial for cognitive systems to adjust modularity based on task demands? Does the human brain do this? "Modularity has several advantages: It simplifies the design process of artificial systems and acts as a regularization that reduces the system's complexity. However, when context sensitivity is required, information needs to be exchanged between many processing units, using a higher degree of integration at the cost of modularity," says control scientist Halil Yigit Öksüz, who works on this project together with cognitive scientist Kai Görgen. "By understanding the optimal balance between modularity and integration, we can enhance our understanding of intelligence and identify general principles of this performance."

“What is intelligence? Philosopher of AI and SCIoI member Dimitri Coelho Mollo highlighted four general features of behavior that characterize intelligent systems: behavior that is general, flexible, goal-directed, and adaptive.”

Hopes and Fears of AI and Robots: An Ethical Perspective

Ethicist Dafna Burema answers questions on our main AI concerns

BY MARIA OTT

Dafna Burema gives a lecture on Ethics and AI

In the rapidly evolving landscape of artificial intelligence (AI) and robotics, public debates alternate between utopian dreams and dystopian visions. Optimists believe that technology will free humanity from labor, illness, and even the confines of our planet, all tropes well reflected in pop culture. Yet, at the same time, there has always been an alarmism towards the very same technology, with fears of job displacement and economic inequality, surveillance and loss of privacy, and AI autonomy paired with ethical concerns of machines making life-and-death decisions. This dichotomy reflects societal hopes and fears tied to the use of these technologies. One of SCIoI's main objectives is to navigate these complex waters, with the ethics team leading the charge in evaluating, supervising and commenting on the latest trends in AI deployment and on the ethical dimension within SCIoI's research projects. Are AI and robots as disruptive as portrayed in the societal discourse? SCIoI researcher and ethics team member Dafna Burema elaborates on three main fears:

1. Will AI replace our jobs?

“The advent of generative AI and its potential to replace artists and other professionals has sparked debate in recent times. Such prospects, where humans might seem obsolete, are often painted in a dystopian light, stirring what is known as ‘moral panics.’ These panics are not new; they have accompanied every disruptive technological innovation, from video games and comic books to social media. Historically, technological revolutions have led to short-term job losses, which are often offset in the long term as societies and technologies adapt to each other. This pattern suggests that while the fears of AI-induced unemployment are justified, they must be contextualized within a broader historical and evolutionary framework. It is essential to maintain a long-term perspective on AI development, understanding that initial upheavals may eventually lead to the creation of new, perhaps unforeseen, job opportunities."

2. How beneficial are care robots for society?

"The use of robots in, for example, elder care is often regarded as a socially beneficial innovation. Anticipated demographic shifts towards aging societies stress the potential of care robots to alleviate the burden on care workers and enhance the autonomy of the elderly. These technologies could lessen the pressure on welfare states, presenting themselves as seemingly 'good'. However, this uncritical acceptance requires scrutiny. The preference for technological solutions in elder care might reflect a broader political agenda that emphasizes individual responsibility over

community-based or formal institutional care. What I mean is that promoting the application of care robots might implicitly push towards minimizing the state's role in providing care, and this raises ethical and societal questions about the values driving these technological advancements. The ethics team at SCIoI evaluates such assumptions on 'beneficial' technologies, and communicates this back to SCIoI wherever necessary."

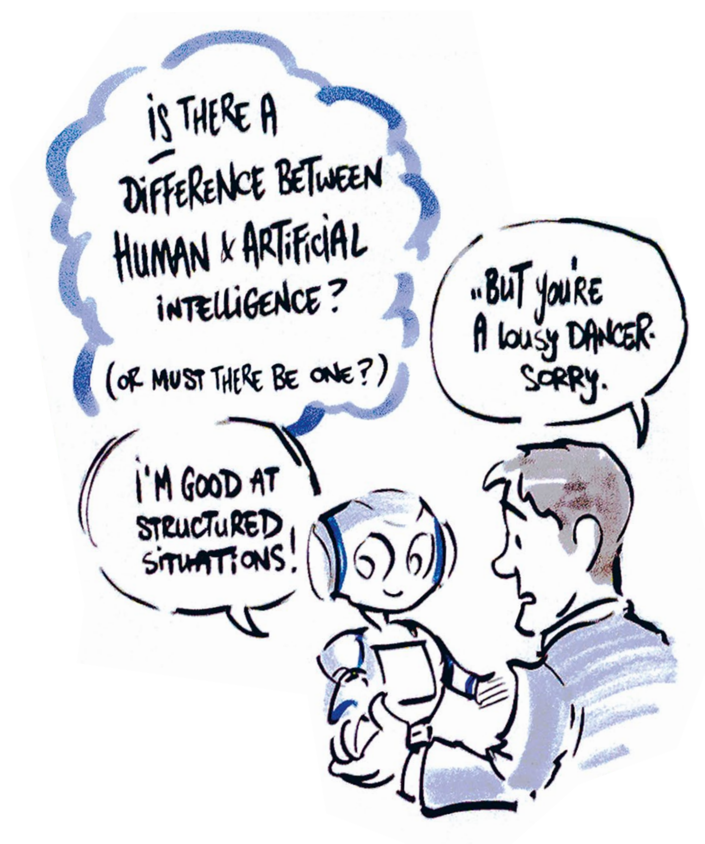
"As ethicists, we oversee SCIoI's projects and address any issues with the scientists to harness benefits and mitigate possible risks"

3. How do deepfakes impact us?

"With their ability to create videos, images and audio, deepfakes are influencing different societal domains, be it politics or pornography. The main ethical issues lie in their potential to violate intellectual property rights, and manipulate public opinion through undisclosed use of this AI, leading to legal and consent-related concerns and to the spreading of misinformation. But despite these challenges, deepfakes also hold potential for positive impact: Some cases have shown that deepfake therapy allows trauma patients to confront AI-generated representations of perpetrators, which could potentially help them in their healing process. Additionally, deepfakes enrich cultural expression through memes and satire, such as awkwardly dancing US politicians Trump and Biden or Harry Potter's characters re-imagined as high fashion models, and this demonstrates AI's capacity for fostering human creativity and humor. As ethicists at SCIoI, we oversee the cluster's projects, addressing all issues together with the researchers, in order to harness benefits and mitigate possible risks."

How does SCIoI respond to those fears?

"The ethics team plays a crucial role in examining these developments. We actively evaluate new project applications as well as ongoing projects and their anticipated outcomes in close collaboration with the researchers. Our aim is to identify possible assumptions and potential societal impacts (as in the discourses of 'good' and 'bad' technologies) through critical analysis. We also closely monitor current responses, such as the European AI Act. This set of regulations aims to mitigate potential harms in AI development and use by classifying AI systems according to their risk level as well as potential, while ethically aligning them with EU values."



Philosophy of intelligence

Philosophy at SCIoI seeks to integrate the various strands of research from the different disciplines involved to form a comprehensive view of intelligence. Unlike other fields that might focus on specific aspects such as memory, learning, or decision-making, philosophy looks at the bigger picture. It questions what intelligence fundamentally is and how it manifests across different entities and systems. How beings conceptualize their world (mental representation), how they process information (computation), and how these processes guide their actions (action-oriented beliefs) are some of the mechanics we look at to understand intelligence. Also we are moving beyond mere data processing or logical decision-making, and following the four general features of behavior that characterize intelligent systems (see p. 62).

ETHICS & PHILOSOPHY PROJECTS

- P18 Methodology of the synthetic approach
- P19 Ethics of intelligence
- P20 Concept of intelligence
- PA1 Ethical and Trustworthy Artificial and Machine Intelligence (etami)

PIs: Dimitri Coelho Mollo, John-Dylan Haynes, Miriam Kyselo, Michael Pauen, Ingo Schulz-Schaeffer

TEAM: Dafna Burema, Tobias Drewlani, Bojana Grujicic, Mattis Jacobs, Marten Kaas, Nina Poth, Rainer Mühlhoff, Ole Pütz

Recomposing the Puzzle

How project integration activities benefit interdisciplinary research


Adrian Sieler and Xing Li operate the robotic arm

Intelligence research is made of many different disciplines, from animal behavior and physics to psychology and robotics. Yet, it is often a fragmented affair; its research projects, or components, can be conceptually distant from one another, with few or no overlaps and connections between them. Bridging the gaps between those disciplines is crucial if we want to develop a comprehensive understanding of intelligence. Therefore, the integration between our projects and disciplines is one of the pillars of our cluster's mission.

We've asked three of our researchers, Yating Zheng, Pu Xu, and Dimosthenis Kontogiorgos, to walk us through the concept of integration and what it means for SCIoI.

1. What is integration?

"Integration" is the opposite of "decomposition." Since the study of intelligence is such a monumental task, it is practical to decompose this large problem into smaller ones. But intelligence is a complex phenomenon, and decomposition implies potentially missing important insights on how different components play together to generate intelligent behavior. Thus it's also important to integrate the outcome of this decomposition, which means putting the pieces back together into a larger intelligent system. And that is what we are doing at SCIoI: every project represents one component of intelligence, and we want to integrate all of these components into one comprehensive research effort.

2. Why is it important?

When we do research at SCIoI, each of the individual researchers usually focuses on their own components. However, there is an assumption called "weak decomposability." What this means is that in a larger intelligent system, although there are components, there is also this in-between area where components interact with each other, and that's where interesting holistic behavior emerges. The interaction between components is as important as the components themselves. And the only space that allows us to study this interaction are the integration projects.

In fact, most ongoing intelligence research ignores the interactions between components. And if they are considered, for example in larger systems, integration is not regarded as a scientific problem but only as a technical necessity. What usually happens is that scientists from different research fields try to make idealized assumptions and solve the issues from their own perspectives and research interests, isolated from the requirements of interactions with other components. Integration offers a general high-level research goal for scientists from different fields to consider how their research topics could be joined together to produce integrated systems.

3. How do we achieve it?

In order to create a framework for integration that brings together many of the 50+ projects at SCIoI, our cluster has created three "example behaviors" (see p. 16): escaping from an escape room, learning in social interaction, and collective shepherding. These behaviors are examples of individual intelligence, social intelligence, and collective intelligence. The idea is that we can build three systems, one for each behavior, and in these systems integrate the different outputs of the projects in Research Unit 1. Another path for integration is to directly integrate the output of two or more projects, outside of the example behaviors. For both of these integration paths, we have seen significant progress at SCIoI so far. In addition, these efforts have led to very useful insights about intelligence.

4. How does one get started on integration?

It's actually not very difficult. One wisdom says that to integrate components you have to first integrate people and ideas. So if you notice a connection between your project and somebody else's, that's already a good starting point to explore further. Can you imagine a task that requires both projects' outputs? How would you build such a system? How would the two components interface?

5. What are the main challenges of integration?

The biggest challenge is that we always feel like we are in a bit of a Catch-22 situation, because we are trying to build a large, weakly decomposable intelligent behavior, and we are doing that in order to study how to build large weakly decomposable intelligent behaviors. It's a bit like the situation where you need work experience to get a job, but you can't have that work experience unless you have a job. This makes the initial bootstrapping period very chaotic and painful, but the outcomes have been very rewarding so far. And in a way, this is exactly what science is about: venturing into the unknown to learn about the unknown. ● SRS


A robotic arm opens a door of the lockbox

"To integrate components you have to first integrate people and ideas"

INTEGRATION PROJECTS
PIs: Oliver Brock, Verena Hafner, Pawel Romanczuk

TEAM:
Heiko Hübert, Dimosthenis Kontogiorgos, Heinrich Mellmann, Pu Xu, Hae Seon Yun, Yating Zheng

Outreach

From exhibitions, press, and public events to academic talks and a Distinguished Speaker Series, SCIoI is invested in contributing to the intelligence debate

Pepper talks to visitors at the Lange Nacht der Wissenschaften 2023

Cluster Wunderkammer

An exhibition at the Humboldt Forum brings together the different research approaches of the seven Berlin clusters, SCIoI included

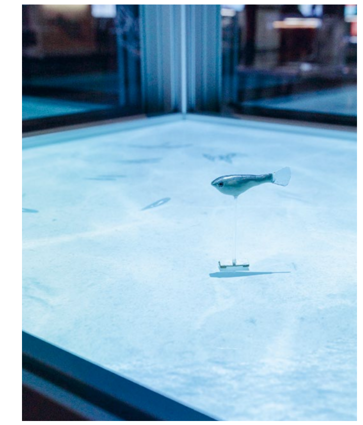
The interactive curtain reacts to visitors' movements

Creativity and science have always been an integral part of Berlin's cultural life, with citywide events such as the Lange Nacht der Wissenschaften and the Berlin Science Week bringing science closer to citizens through different formats that are accessible to all. In the past years, the city has also committed to expanding its portfolio of science museums: the Futurium, opened in 2019, showcases thought-provoking exhibitions on what our lives might look like in the future, and the Humboldt Forum, housed inside the rebuilt Berliner Schloß (the former Berlin Palace destroyed by air raids in WWII), has given a new, more central home to the FU's ethnographic collections, formerly held in Dahlem, while also becoming a space for science exhibitions. One of these exhibitions is Nach der Natur (After Nature), which brings together the wide range of research approaches of the seven Berlin Clusters of Excellence through a carefully curated selection of artifacts and demonstrators stemming from their research. The exhibition, based on the interactions between the climate crisis, biodiversity loss, and society, voices scientific concerns about man-made changes to the environment, but also showcases Germany's "Excellence Strategy."

Excellence on display

Imagine an interactive wall that moves with the visitor, fostering dialogue between scientists and the public; a dedicated room presenting the clusters through a number of videos; a fossil lizard that represents cluster Matters of Activity, and a typewriter from the SCRIPTS cluster, but also plastic trash from the ocean, and old computers. All these objects can move up and down in the room, appearing and disappearing at different heights depending on what the curators want to highlight that day.

But the exhibit that is perhaps most iconic of the exhibition is the interactive curtain created with the help of SCIoI members Pawel Romanczuk and Jens Krause, presenting a fish swarm that reacts to the visitor's presence. The curtain represents swarm behavior, but also the sensitivity of our ecosystems, so easily affected by human presence.



Above: Ralf Kurvers' decision-making experiment.
Below: the Robofish simulation

A decision-making experiment for all

Elsewhere in the exhibition, our PI Ralf Kurvers created a joint SCIoI-MPIB experiment on adaptive rationality, exploring individual and collective decision-making processes. Visitors observe pictures of animal groups on an iPad, and try to guess the number of animals in these groups. Then they observe the guesses of previous visitors and make a second judgment. Is the judgment of others beneficial or detrimental? The demonstration playfully investigates how visitors make up their minds and how they incorporate the opinions of others.

Robofish: playing with a robotic fish

Translating biological observations into simulations is always a great way to show science to a diverse audience, but for this particular exhibition one of our research teams decided to go a bit further: "We wanted a simulation that would also allow the audiences to interact with our robotic fish," said biologist David Bierbach. "So we got a team together to make this happen and created some animations that we projected into the tank, and a 'very independent' robotic fish that could drive itself to a charging station when its battery was almost empty, just like the domestic vacuum cleaner robots. We then put all that inside a tank with a projector, a camera, and a touchscreen so that visitors could control the robot. As with any real experiment, we were confronted with unexpected challenges that we had to solve creatively, but in the end we managed to get a great simulation, or game, of the Robofish experiment."

> "Translating biological observations into simulations and demonstrations is a great way to show science to the public"

In the game, players immerse themselves in the principles of swarm intelligence by taking control of the small robotic fish operating in an empty fish tank. By projecting fish into this fish tank, visitors learn to direct them into a specific area and understand basic concepts of collective behavior. The evaluation of these movement patterns and their comparison with movement models provided deeper insights into human behavior and the control of swarms. "And the great thing about this is that the Robofish demonstrator goes beyond its pure entertainment purposes," said David Bierbach. "Over a period of eleven months, we collected data while more than 15,000 visitors played the game over 19,000 times. It's a lot of data that we can use, and that's great too." ● *SRS*

VISIT THE EXHIBITION!

Open Wed–Mon
10:30am–6:30pm
Humboldt Forum
Schloßplatz,
10718 Berlin

Palina Bartashevich talks about the evading strategies of sardines

Bridging Minds

Explaining intelligence in just one day at the Science of Intelligence Fair 2023

From intelligent agents, systems and behavior to intelligence research, methods, and collaborations, we've seen it all so far in this book. But how (and why) do we tell these stories to a broader audience? It is not exactly easy to explain all of SCIoI over coffee, yet it is vital to start the conversation, both internally and externally, in order to ensure that theoretical advancements are grounded in ethical considerations and societal needs, and effectively integrated into practical applications. This is why, in the fall of 2023, we condensed the cluster's work into just one day of talks, demonstrations, and networking opportunities with the city. The event was our Science of Intelligence Fair 2023, and it took place at Berlin's Radialsystem. We guarantee, it was so inspiring to see policymakers, leading academic experts, journalists and an engaged public come together to attend keynotes, visit an interactive exhibition, listen to panel discussions, or discuss robots and birds. Or, glass of wine in hand, just to satisfy the desire to learn more about what the Science of Intelligence is and does.

Of individual, social, and collective intelligence

Explaining intelligence in individual and social beings, as well as in collectives, whether biological or artificial, requires a cross-disciplinary approach that embraces the complexity of intelligent behavior across species. When planning the Fair, SCIoI's example behaviors (p.16) turned out to be quite useful and tangible in illustrating the storyline of the different research approaches we use to uncover the principles of intelligence.

This also made it natural to organize the event into three batches of talks, one for each example behavior. In the first part, three short keynotes showed how SCIoI researchers approach individual problem-solving behavior in humans and animals (for example, parrots, or mice) and how these findings are then applied to artificial agents. The combination of behavioral biology and robotic technology showcases the potential of robotics in solving complex tasks, and also how this interplay allows us to explore potential principles of intelligence. The second set of talks explored social intelligence, emphasizing its importance in complex social interactions across humans, animals, and robots. The audience learned how people recognize and predict behaviors in various contexts, including interactions with robots, and the significance of non-verbal cues such as gestures in communication. We even got to follow

Human-robot interaction demonstration at the Science of Intelligence Fair exhibition

From left to right: Christoph Schneider (HU-Berlin's Vice-president for Research), Julia von Blumenthal (HU-Berlin's President), Ina Czyborra (Berlin Senator for Science, Health and Care), Oliver Brock (SCIoI spokesperson), and Stephan Völker (TU Berlin's Vice-president for Research and Education)

Julia von Blumenthal and Jens Krause test the interactive fish projection

a discussion on the potential of applying these insights to develop socially intelligent robots. The speakers gave insights into how social cognition can lead to advances in artificial intelligence, making robots capable of supporting and enhancing human social engagement. The last three keynotes focused on collective phenomena in animal groups. The scientists explained how SCIoI researchers develop bio-inspired algorithms for simulations and embodied robotics. Understanding collective locomotion, collective decision-making, or behavioral contagion processes in nature, and applying these principles to synthetic agents, holds promising applications for fields such as autonomous driving.

The SCIoI Fair program really made the point that figuring out intelligence isn't a "one-discipline show." Whether it's solving puzzles, getting along in social settings, or moving in groups, it is clear that we need information and ideas from all over to get a full picture of intelligence.

Advancements in safe AI technology

In the panel, experts explored human and machine intelligence, covering adaptability, the challenges of mimicking complex human actions such as dancing, and the significance of individual differences in both biological and artificial entities. They emphasized the potential of AI and robots to augment rather than replace human capabilities, and pointed out the need for strong ethical guidelines and international collaborations to ensure that AI advancements align with societal values and contribute positively to humanity, while also addressing concerns about misuse and governance disparities.

Exhibition – Demonstrators straight from the labs

In the exhibition, SCIoI scientists presented their research with interactive demonstrators, showing the capabilities and complexities of natural and artificial intelligence. The Kilobots – robots that mimic the collective intelligence of a school of fish or a swarm of bees (see p. 48) demonstrated decentralized decision-making. Visitors could also experience walking through a simulated fish swarm that adapts to human presence, offering insights into collective behavior and bio-inspired robotics. A robotic arm solving puzzles displayed the convergence of behavioral biology and robotics, and Robofish highlighted robots' problem-solving and social skills. ● *MO*

Katharina Hohlbaum talks about individual intelligence in mice

Futures of Air

What happens when you put two clusters and a few dozen citizens around a table filled with robotic hands, kombucha cultures, Kilobots, 3D prints of human bone structures, materials with different textures, and wearable bark? They come up with new ideas, they imagine the future, and design possible scenarios for our present. CollActive Materials was created by the Clusters of Excellence SCIoI and Matters of Activity to start conversations about our possible futures.

Speculating and creating at a CollAcitve Materials workshop

Science communication is many things: at its simplest, it's any effort to make science understandable to others beyond the barriers of one's discipline. But it's also a way to inform and engage, to reach non-scientists and let them participate, more or less marginally, in our scientific adventures. And if we dig deeper into the meaning of "science communication," we'll see that it's also a way of starting conversations with the public about how our actions of today can influence our lives in the future.

In 2021, SCIoI and fellow Cluster of Excellence Matters of Activity got together to brainstorm ideas for a joint science communication project. A year later, with the generous funding of the Berlin University Alliance, the "CollActive Materials" project was born.

The three-year project, which is now nearing its end, was conceived based on the idea that the active and intelligent materials of today can help us invent new ways to deal with the issues of tomorrow. And the best way to put this concept into practice, according to researchers and science communicators from SCIoI and Matters of Activity, was to plan a long-term design process involving individuals from civil society, design, and research in order to explore the extent to which speculative design can enable a new mode of interaction between science and society.

Keeping in mind the ultimate goal to later create an exhibition on possible future scenarios, we developed a number of full-day workshops that took place in the spring of 2023 at different locations around Berlin, including a theater school, a yoga studio, a former crematorium, and, later, the Futurium museum. During the workshops, researchers and guests provided insights from science that the participating individuals used for their speculations, and based on the results, designers and artists ultimately created the interactive exhibits and experiences for the exhibition, which took place during the Berlin Science Week 2023 in Kreuzberg.

Why air?

"We believe that air will be the decisive material in the Anthropocene," said Martin Müller, cultural scientist and researcher at Cluster of Excellence Matters of Activity, who co-leads the project together with Léa Perraudin. "Air as a material will play a fundamental role in determining which futures become possible for us as humans. Many important concerns are at stake: the debate on climate change, the destructive use of resources, and the related ecological and social injustices." To present this idea to the participants, the team interspersed the workshops with inspiring air-based activities: for example, one of the workshops featured a multisensorial performance that happened entirely in the dark, where visitors could go from station to station for olfactory stimulation, witness smoke bubbles that popped mid-flight, and cloud images forming on a screen. In another workshop, participants focused on the theme of breathing with bodywork exercises. All of these experiences were then used as inspiration for speculating together, designing the objects and the materials of the future, and actually building physical and three-dimensional sketches of them. After that, the team hired four designers to interpret the thoughts of the participants and translate them into the tangible objects that would be presented in the exhibition.

Rapid prototyping, or imagining through making, a central aspect of the project's speculative method

> "Air as a material will play a fundamental role in determining which futures become possible for us humans"

Collective inflating of a balloon-like structure on the closing night of the *Airbound* exhibition

Testing the grounds with a workshop at the Naturkundemuseum

We are all "airbound"

"We wanted to focus on air as a collective material that we all share responsibility for, but air is also an active and intelligent material that can move matter, one that adapts, and transports," said Kristin Werner, the project coordinator. "With our exhibition, called *Airbound*, we wanted to create opportunities for visitors to reflect on the role of air in their current and future daily lives." Approximately 650 visitors admired snapshots from the cultural history of air, site-specific experimental setups in the exhibition space, and speculative scenarios. These scenarios explored questions such as: What would a climate future look like if survival were only possible through technological interventions on the weather? How would people come together in a future without clean air? What if urban coexistence became shaped by new forms of cooperation with air?

Speculation to imagine what's possible

Through speculation, conversations become possible in an entirely new and unique way: everyday and academic knowledge, personal experiences, and current research topics complement each other. The scenarios that arise from speculation, in turn, provide a materialized basis for exchange, discussion, and negotiation. "It was particularly important for us to move out of the university premises into the city, thereby facilitating an open exchange," explained Léa Perraudin. "For such collaborative and experimental design processes, there is still a lack of role models in the academic context." This project's fundamental approach was also reflected on-site at the exhibition: With a ground-level window front, the exhibition invited passersby to take a look and contribute their own thoughts to the growing exhibition – right at Moritzplatz in Berlin. ● *SRS*

Objects to inspire speculation at one of the CollActive Materials workshops

COORDINATOR: Kristin Werner
PROJECT PIs: Oliver Brock, Claudia Mareis, Martin Müller (co-lead), Antje Nestler, Léa Perraudin (co-lead), Wolfgang Schäffner, Solveig Steinhardt

"Creating a global network for intelligence research allows us to share knowledge and push the boundaries of what we know about intelligent behavior."

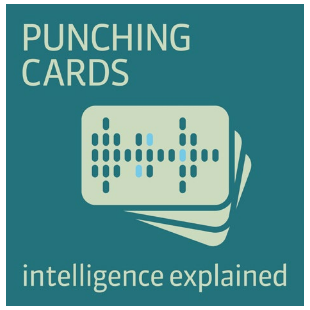
What Makes a Bonobo Intelligent?

A podcast explains the different perspectives of intelligence research

BY VALERIA BECATTINI

Recording session at SCIoI

In the summer of 2020, only one year after the birth of our cluster, eight SCIoI members with different backgrounds decided to start working on a podcast about intelligence. The result was "Punching Cards," named after the punched cardboard sheets used in early automated machines to store digital data. Consisting of six episodes and meant for a lay audience, the show explores different aspects of intelligence: human, animal, artificial, and collective, as well as the evolution and boundaries of intelligence. Throughout the series, rigorous inquiry, scholarly dialogue, interdisciplinary discussions, but also anecdotes and trivia, revolve around the intriguing phenomenon that we call intelligence.



"What makes a person, a cat, a bonobo, a dolphin, an octopus, a cockatoo intelligent? What is it that these living organisms have or do, when we say that they are intelligent? And what about things like computer programs, or robots? Can they be intelligent? If so, how? If not, why not?"

With these words, our researcher Dimitri Coelho Mollo starts the first episode of "Punching Cards," setting the tone for what's to come: A series of reflections by our researchers, as well as fun facts and important questions, intertwined with contributions by notable guests from the world of intelligence research. "It's a sort of Distinguished Speaker Lecture series about intelligence, but in podcast version," said Nicolas Roth, one of the podcast producers. "It was great to be able to get in touch with all these great scientists and have long, relaxed conversations with them."

Each episode is dedicated to a different question about the notion of intelligence, starting with the most basic one: what is intelligence, really? It is a term that we tend to use mostly when talking about humans, and indeed this 'prejudice' has shaped how intelligence is studied to this day. But, as we discuss in episode one, even what human intelligence is remains far from clear. IQ tests and the like have been around for long, but what is it that they test, and how meaningful are their results?

It is likely in any case that a human-centric view of intelligence is too limited. Non-human animals, and perhaps even artificial machines, are or may be intelligent. But how can we understand those different kinds of intelligence? How do we study them, and perhaps engineer them? We delve into these questions in episodes two and three, mixing perspectives from comparative psychology, philosophy, and computer science to discuss things like the concept of meaningful engagement, or the impressive linguistic capabilities of Kanzi the bonobo, who has learned to use a keyboard by simply watching another bonobo.

Expanding the horizon further, we go into even more controversial terrain. In episode four we ask ourselves (and our guests): can intelligence be a feature of collectives, such as ant colonies, fish schools, or even human crowds crossing a busy intersection? Is there a wisdom of the crowds that goes over and beyond the intelligence of the single individual in a group? In a similarly explorative vein, episode six focuses on a question that at first glance seems rather outlandish: does intelligence extend to plants, or even to bacteria? We debate the arguments and evidence for and against such an idea with our interdisciplinary guests.

The picture we end up painting in the series is that intelligence is better understood in the plural. There are different shapes intelligence can take: human, animal, artificial, collective, and perhaps even bacterial. Why, though, is intelligence a thing at all? What is it for, and how did it show up? This is the guiding question for episode five. There, we look at the evolution of intelligence from the perspective of cognitive and comparative psychology as well as philosophy.

"Intelligence is one of the most puzzling concepts out there, and it looks like the more we talk about it, the more we can engage in further discussions," says Dimitri. And that was the aim of this podcast: to widen the discussion about intelligence beyond what we know. ●

Curious? Scan the QR code below and get listening right now, or check out the podcast web page, www.scienceofintelligence.de/punchingcards/ And stay tuned for a new season of "Punching Cards"!

PODCAST TEAM
CREATED BY Aravind Battaje, Valeria Becattini, Dimitri Coelho Mollo, Benjamin Lang, Nicolas Roth, Olga Shurygina, Solveig Steinhardt
MUSIC BY Aravind Battaje, Dimitri Coelho Mollo, Solveig Steinhardt, loosely inspired by Claudio Monteverdi's "Torna Zefiro"

Interactive Spaces

One of our big upcoming projects is the creation of a showroom, a lab designed to connect SCIoI's research with the broader community through hands-on demonstrators and simulations

Testing the fish projection in the new showroom

In the coming year, the SCIoI showroom will showcase our latest findings through interactive technical installations, helping visitors understand the principles of artificial and biological intelligence. Exhibits will include an augmented-reality projection of collectives, humanoid robot showcases, and robots solving lockboxes. By making our research accessible to all, we aim to foster greater understanding and engagement. This interactive space will also provide our scientists with a collaborative environment to integrate diverse perspectives and gather more real-world data from interactions with visitors.

Building the structure for the fish projection

SCIoI in the News

Check out some of the most popular newspaper articles and TV shows about our cluster! From *The New York Times* to *Newsweek* and the popular German TV show *Terra-X*, in the last few years we have been pretty much all over the news.

Newsweek

Video Reveals Top Predators 'Light Up' as They Take Turns to Attack Prey

February 2024

The New York Times

Why These Mexican Fish Do the Wave

January 2022

ZDF: Terra-X

Schlaue Schwärme – Rätselhafte Kräfte

March 2023

Nature Index

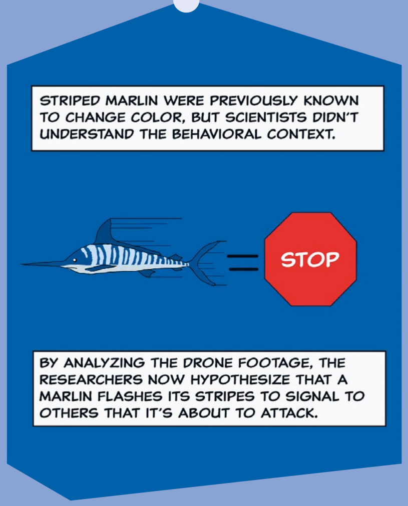
Clusters of Excellence: the new 'brains trusts' of German science

November 2020

Scientific American

Massive groups of fish create waves to deter predators

January 2022



A comic about SCIoI's marlin paper on www.hakai.org

FOR MORE PRESS COVERAGE, VISIT WWW.SCIOI.DE/WHAT-THEY-WRITE-ABOUT-US/

Synergies in Collaboration

The collaborative power of Berlin's Clusters of Excellence brings evenings of fun and science for all

BY MARIA OTT

With its seven Clusters of Excellence, Berlin can be seen as a hotspot for scientific research – and an excellent one, too. The clusters cover a broad variety of topics, such as active materials for the future, application-oriented math, liberal democracy and its global challenges, chemistry, and the effects of literature across time and space. But how do we ensure that this great research output does not only remain within the confines of the academic community? We want to actively democratize knowledge, promote equality and inclusiveness and empower informed decision-making with and through our science. This is why the seven clusters meet monthly and collaborate closely to create event formats that harness the variety of subjects covered to engage with the general public in exciting ways.

The "Excellent Pub Quiz"

Enter the inter-cluster Pub Quiz, a highlight at the Long Night of Science and a real crowd-pleaser. It's laid back, a bit of fun, and sneakily educational. Picture this: a mix of curious people, a pint in hand, tackling brain-teasers that span the spectrum of all clusters' research. It's a hit because it's not just a quiz. It's a way to discuss, laugh, and learn, all while decoding complex scientific concepts. Questions like, "Who described the three laws of robotics?" "What did Shakespeare leave his wife in his will?" and "How many neurons does the human brain contain?" keep the participants on the edge of their seats and let them walk away with fun facts and new insights, possibly even triggered to explore a scientific path themselves. Plus, it's a great way for us to listen and learn what people find fascinating or puzzling, and think about how we share science.

Intercluster science slam

Another standout inter-cluster activity that shines during Berlin Science Week is the annual Science Slam of the Berlin clusters. Think of Berlin turning into a carnival where science meets festival vibes. The slam itself? It's where the magic happens. Early-career scientists step into the spotlight, their research tucked into stories and jokes, ready to wow and educate. Last year, Maryam Karimian from SCIoI rocked the stage with insights on behavioral contagion, proving just how cool and accessible science can be. It's all about making those scientific breakthroughs as engaging as they are enlightening, far removed from stuffy lecture halls.

Through events like these, we're not just talking science; we're making it part of the community vibe using the knowledge of all seven clusters. It's about keeping the conversation open, engaging, and, most importantly, inspirational.

Above: SCIoI member Maryam Karimian, who won the 2023 Science Slam
Opposite page: The audience at the clusters' Science Slam

Conversations Across Disciplines

Talks and lectures

At SCIoI, three interdisciplinary lecture series give members direct contact with the important ideas in intelligence research and foster networking and scientific exchanges within SCIoI and the scientific community, both in Germany and internationally. Thursday Morning Talks are meant for members to discuss their research progress or invite notable external guests to talk about their research activities. PI Lectures walk audiences through the Principal Investigators' research topics presented in bi-weekly lectures, and Distinguished Speaker Series talks bring prominent academics from the world of intelligence research to Berlin to dive deeper into the topic of intelligence from different perspectives. Distinguished speakers, such as Patricia Churchland, Lars Chittka, Serge Belongie, or Antonio Bicchi to mention a few, bring their unique insights and experiences to our community promoting academic exchange and inspiring innovative thinking.

Oliver Brock speaks at the Scientific Networking Days 2022

Networking and socializing in the garden of Ballhaus Wedding at the Scientific Networking Days 2022

Preparing posters for our events

An opportunity for networking

In order to foster scientific networking within and beyond our community, our academic management team organizes different events throughout the year, from PhD and Postdoc retreats out in the Brandenburg countryside to admission symposia for new cohorts and open days, all aimed at promoting interdisciplinary connections and scientific exchange. But the most important event of them all is the Scientific Networking Days, a three-day event for all SCIoI members, taking place every summer at different locations. "We want to give our researchers time and a space to network with the entirety of the cluster, a place where they can present their projects, their current work, and their progress to the all the others," says Julten Abdelhalim, SCIoI's academic coordinator. At the SNDs everyone has a chance to ask questions and discuss, both during the presentation sessions and over lunch. "Interdisciplinary research lives off the interactions between scientists from different disciplines, and our main goal when we organize these events is to make sure that researchers gain insights and inspiration from others in order to give their research that added value," says Julten.

COMMUNICATION ACHIEVEMENTS

3 Pub quizzes

€600,000 Granted to SCIoI and MoA for CollActive Materials project

602 "Punching Cards" podcast downloads

77 International news articles featuring SCIoI

144 News features on our website

44 Outreach Events

236,674 Visitors to *Nach der Natur* exhibition

304,372 Social Media impressions in the last year

The Scientific Networking Days, an annual event dedicated to scientific exchange within the cluster

People and Facilities

The study of intelligence is transdisciplinary. Our community is made up of 133 researchers from twelve disciplines working at six institutions. Our labs provide scientists with the latest equipment for their experiments.

SCIoI members during the Scientific Networking Days 2023

People

The SCIoI community is a varied group of scientists with diverse backgrounds that encompass many disciplines. Our researchers also belong to different institutions, including the six partner universities that constitute SCIoI (TU Berlin, HU-Berlin, Uni Potsdam, FU, the Max Planck Institute for Human Development, and Charité – Universitätsmedizin Berlin), as well as other external institutes. Our cluster consists of principal investigators (PIs), postdoctoral researchers, and doctoral researchers. Student assistants offer help on many projects, while the coordination office team provides administrative, technical, and logistical support.

Principal Investigators

Rasha Abdel Rahman
Psychology

Alan Akbik
Machine Learning

Sabine Ammon
Philosophy

Robert Arlinghaus
Fisheries Science, Ichthyology

Marcel Brass
Psychology

Oliver Brock
Robotics

Dimitri Coelho Mollo
Philosophy of Artificial Intelligence

Guillermo Gallego
Computer Vision

Verena Hafner
Developmental Robotics

Heiko Hamann
Swarm Robotics

John-Dylan Haynes
Cognitive Neuroscience

Olaf Hellwich
Computer Vision

Ralph Hertwig
Psychology, Cognitive Science

Alex Kacelnik
Biology

Jens Krause
Biology

Ralf Kurvers
Behavioral Biology

Miriam Kyselo
Philosophy of Embodiment, Cognition

Tim Landgraf
Biorobotics

Rebecca Lazarides
Educational Science

Lars Lewejohann
Behavioral Biology

Falk Lieder
Computational Cognitive Science

Marianne Maertens
Psychology

Anne Nassauer
Sociology


Klaus Obermayer
Computational Neuroscience


Thorsten Pachur
Psychology


Michael Pauen
Philosophy of Mind


Niels Pinkwart
Computer Science


Jörg Raisch
Control


Scott Robbins
Philosophy of AI

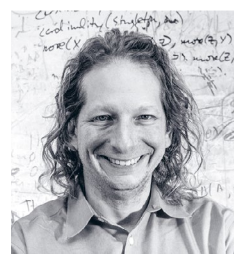

Julia Rodriguez Buritica
Psychology


Martin Rolfs
Psychology


Pawel Romanczuk
Physics


Ingo Schulz-Schaeffer
Sociology

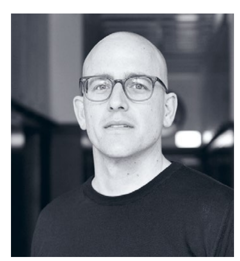

Henning Sprekeler
Computational Neuroscience


Josh Tenenbaum
Computational Cognitive Science


Christa Thöne-Reineke
Behavioral Biology


Marc Toussaint
Robotics


Alice Von Auersperg
Behavioral Biology


Max Wolf
Behavioral Biology

Postdocs


Jinan Allan
Cognitive Psychology


Christoph Alt
Computer Science


Palina Bartashevich
Computer Mathematics


Julia Baum
Psychology


Pia Bideau
Computer Vision, Robotics


David Bierbach
Biology, Biorobotics, Fish Behavior

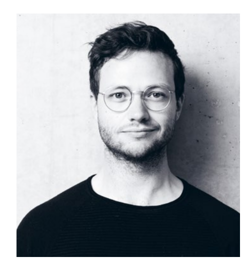

Florian Bolenz
Psychology, Cognitive Science


Dafna Burema
Sociology


Alicia Burns
Biology


Johann Chevalère
Psychology


Asieh Daneshi
Biomedical Engineering, Cognitive Science


Dominik Deffner
Evolutionary Behavioral Science, Computational Behavioral Science


Raphael Deimel
Robotics


Félicie Dhellemmes
Behavioral Ecology, Biology


Sean Ehlman
Behavioral Ecology

Angelica Godinez
Vision Science

Luis Gómez Nava
Physics

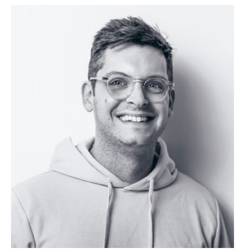
Kai Görgen
Cognitive Science, Neuropsychology

Nina Hanning
Psychology

Eitan Hemed
Psychology

Katharina Hohlbaum
Veterinary Science

Anne Jaap
Animal Science



Marten Kaas
Philosophy

Maryam Karimian
Computational Cognitive Neuroscience

Murat Kirtay
Biorobotics

Anna Klenova
Biology

Dimosthenis Kontogiorgos
Human Robot Interaction

Anna Kuhlen
Psychology

Valentin Lecheval
Collective Behavior, Ethology

Antje Lorenz
Psychology

Martin Maier
Experimental Psychology

Paul Mieske
Animal Physiology, Biology

Rainer Mühlhoff
Philosophy

Alan Novaes Tump
Behavioral Ecology, Cognitive Science

Arianna Novati
Biology, Neurobiology

Julie Ouerfelli-Ethier
Psychology

Doris Pischedda
Neuroscience

Nina Poth
Philosophy of Cognitive Science

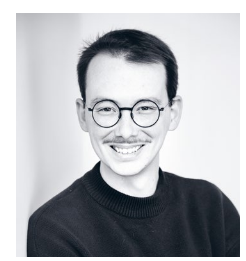
Ole Pütz
Sociology

Tamal Roy
Behavioral Ecology, Biology

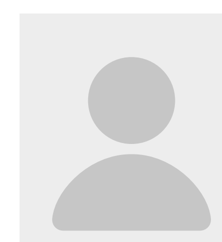
Ulrike Scherer
Biology, Evolution of Behavior, Ecology

Friedrich Schüßler
Neuroscience, Physics, Ethology

Richard Schweitzer
Psychology



Yunus Sevinchan
Physics



Nicolas Spatola
Psychology

Olga Wudarczyk-Markett
Psychology

Yating Zheng
Swarm Robotics

PhDs


Helene Ackermann
Psychology

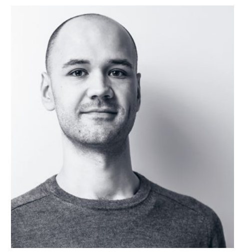

Niek Andresen
Computer Vision


Aravind Battaje
Robotics


Manuel Baum
Robotics


Florian Blume
Computer Vision


Mark Boon
Computational Neuroscience


Valerii Chirkov
Computational Social Science


Furkan Davulcu
Robotics


Tobias Drewlani
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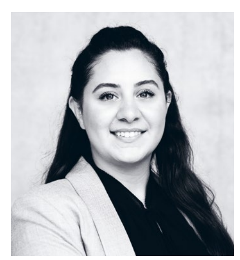
Danny Driess
Machine Learning


Anna Eiserbeck
Psychology


Jonas Frenkel
Human-Robot Interaction


Fritz Francisco
Biology


Bojana Grujicic
Philosophy

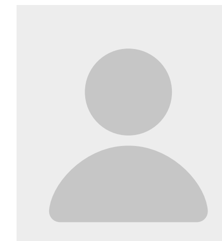

Marah Halawa
Computer Science


Ole Hall
Computational Neuroscience


Friedhelm Hamann
Computer Science


Anja Henke
Educational Sciences


Mattis Jacobs
Philosophy


Pia Kahnau
Behavioral Biology


Bassel Katamish
Control, Computational Engineering


Benjamin Lang
Biosciences, Molecular Biology


Robert Tjarko Lange
Computational Neuroscience


Anna Lena Lange
Computer Science


Dustin Marlon Lehmann
Control Systems


Svetlana Levit
Computer Science


Xing Li
Robotics


Heinrich Mellmann
Robotics


Vito Mengers
Computer Science, Robotics


Elena Merdjanovska
Computer Science


David Mezey
Theoretical Biology

Ashwin Moongathottathil James
Comp. Cognitive Science

Lea Musiolek
Psychology, Cognitive Neuroscience

Huu Duc Nguyen
Robotics

Halil Yigit Öksüz
Control Systems

Uroš Petković
Computer Science

Max Ploner
Computer Science

Pu Xu
Robotics

Runfeng Qu
Computer Science, Machine Learning

Mohsen Raoufi
Computer Science

Nicolas Roth
Conputational Neuroscience

Lynn Schmittwilken
Vision Science

Olga Shurygina
Psychology

Adrian Sieler
Robotics

Heiner Spieß
Computer Science

Soledad Traverso
Computer Science

Vincent Wall
Robotics

Jacek Wiland
Machine Learning

Magdalena Yordanova
Computer Engineering

Hae Seon Yun
Computer Science

Oussama Zenkri
Robotics

Coordination Office

Managing Director
Kathleen Waak

Project Management
Konstantin Olschofsky

Academic Coordination
Julten Abdelhalim

Lab Management
Mathis Kaiser, Michael Brück

Communication
Maria Ott, Solveig Steinhardt

Equal Opportunities
Lujain Kretzschmar

IT
Stephan Rosenzweig, Sascha Bauer

Finances
Anne Herms, Susanne Hölzemann

Front Office
Antje Kaczmarek

Our Boards

Our boards advise on the cluster's main decisions in day-to-day matters, scientific affairs, and ethical issues.

The SCIoI Executive Board

Elected by the cluster members, the SCIoI Executive Board is responsible for all major decisions within the cluster and for developing the SCIoI research program. The Board also decides on policies and funding applications, determines the admission of external PIs, advises on budgeting decisions, and oversees quality assurance within the cluster.

The Executive Board consists of the SCIoI spokesperson, Oliver Brock, four Principal Investigators (Jörg Raisch, Christa Thöne-Reineke, Marcel Brass, and Jens Krause) a Postdoc representative (David Bierbach), and a PhD representative (Furkan Davulcu).

The Scientific Advisory Board

SCIoI's Scientific Advisory Board consists of external, highly accomplished scientists possessing extensive interdisciplinary research experience, who advise on scientific matters.

The Ethics Advisory Board

The Ethics Advisory Board is made up of external leading scholars with expertise in the fields of philosophy of artificial intelligence, digital ethics, and robotics. The EAB guides and advises SCIoI's research activities.

Selected Grants and Awards

Major Awards

Humboldt Preis
Richard Schweitzer (2021)

Young Investigator Award
Katharina Hohlbaum (2021)

Werner Heisenberg Medaille
Oliver Brock (2024)

Animal Welfare Award
(Dr Wilma von Düring Research Prize)
Katharina Hohlbaum (2019)

Outstanding Associate Editor
(IEEE Robotics Automation Letters)
Guillermo Gallego (2021)

EACL's Outstanding Paper Award
Alan Akbik (2023)

Lieslotte Pongratz Dissertation Award
(The German Academic Scholarship Foundation)
Richard Schweitzer (2022)

Best Practice Communication Award in Animal Research
(Tiervesuche verstehen)
Christa Thöne-Reineke and Lars Lewejohann (2021)

Grants

ERC Consolidator Grant
Martin Rolfs (2019)

Google Cloud Research Credit Grant
Robert Lange

Emmy Noether Grant
Alan Akbik (2021)

G-Research Grant for PhD Students in a Quantitative Field
Robert Lange (2023)

NSF AccelNet NeuroPac Fellowship
Friedhelm Hamann

Teaching grants from the Berlin Senate Fund (2024)
Aravind Battaje, Mark Boon, Jonas Frenkel, Friedhelm Hamann, Benjamin Lang, Svetlana Levit, David Mezey, Nicolas Roth, Mohsen Raoufi, Olga Shurygina

Experimental Labs for Science Communication 2021 (Berlin University Alliance)
Oliver Brock, Dimitri Coelho Mollo, Solveig Steinhardt

X-Student Research Group Grants (BUA)
Doris Pischedda (summer 2021), Pia Bideau (summer 2023), Pia Bideau (winter 2023/2024), Valentin Lecheval (summer 2024)

DFG Eigene Stelle Fellowship
Sean Ehlman

Research Fellow Chair MIAI (Grenoble Alpes, France)
Pia Bideau

SCIoI Research Grants
Nicolas Roth (2022), Aravind Battaje (2023), Mohsen Raoufi (2023)

Other Awards

Best Workshop Poster Award (ICRA 2024)
Heiko Hamann, Mohsen Raoufi, Pawel Romanczuk

Best Paper Award (ECVP 2021)
Lynn Schmittwilken, Marianne Maertens

Best Poster Award (VISAPP 2023)
Niek Andresen, Katharina Hohlbaum, Christa Thöne-Reineke, Lars Lewejohann, Olaf Hellwich

Student Travel Award (CECCO 2023 Conference)
Robert Lange

VSS Travel Awards
Olga Shurygina (2022)

A busy day in the Asimov Lab

Where Research Happens

Our lab managers present the SCIoI Labs

BY MATHIS KAISER AND MICHAEL BRÜCK

The Asimov Lab

Fittingly named after the Russian-American science-fiction author known for his "Three Laws of Robotics," the 240 sqm Asimov lab at TU Berlin is where our researchers transfer the insights gathered from human-human interactions onto well known robots such as Pepper, NAO, and Cozmo. The goal is to improve human-robot interaction and overcome the so-called "uncanny valley" (a common unsettling feeling people experience when androids or humanoid robots closely resemble humans in many respects but aren't quite convincingly realistic) to develop intelligent robotic tutors and learning companions for educational purposes.

Next to the humanoid robots, the Asimov lab also houses the motion capture arena, where visitors might encounter swarms of smaller robots buzzing about. Here, our researchers test algorithms for imitating swarming behavior that has been previously observed in nature, which is done by tracking the movement patterns of small, independently moving robots. Additionally, Asimov's motion capture system is used as a ground truth for developing computer vision models.

SCIoI Lab Guide

- **Asimov Lab**: humanoid robots, VR, motion capture
- **Čapek Lab:** swarm robotics, lockboxes, robotic arms
- **EEG Lab:** electroencephalography studies
- **Visual Capture Lab:** eye movement studies
- **Media Lab:** podcast and video creation
- **Aquatic Lab at HU-Berlin Nord Campus:** collective behavior

The Čapek Lab

Located on the second floor of the MAR building at TU Berlin, this big, open-space robotics lab was named after the Czech writer and playwright who coined the term "robot," and it's where most of our robotic "magic" happens: here researchers work with robotic arms, trying to teach them the problem-solving abilities that are necessary for autonomously mastering an escape room or besting a physical lockbox puzzle (see p. 42). Sometimes, the soothing hum of PC fans and the calming tap of keyboards is accompanied by red, green, and blue blinking lights and the sound of dozens of small metal feet tapping on a flat surface. That's when the swarm of Kilobots starts moving through its arena: these small, three-legged robots – you can easily fit three or four into the palm of your hand – help us get a better understanding of how small changes in the individual affect collective estimation (see p. 48)

The EEG Lab

In the EEG Lab, SCIoI researchers conduct electroencephalography studies, recording and analyzing electrical brain activity while human participants perform psychological experiments. EEG enables us to observe the brain "at work" with high temporal resolution, and to draw conclusions about the mental operations and their interplay during information processing.

> "The labs are the heart of SCIoI's research"

The lab consists of a control room and an electrically and acoustically shielded chamber with two participant seats, allowing us to record EEG and other signals simultaneously during social interaction. Besides EEG, it is possible to measure participants' pulse, eye movements, muscle activity, skin conductance, and breathing. Participants are presented with visual and auditory stimuli, and can provide responses by pressing buttons and talking.

The experiments conducted in this lab so far have included investigations on whether collaborating with a robot when naming pictures speeds up object recognition, on the neural signatures of sudden insights (eureka moments) when perceiving other people, and on the perceptual and emotional processing of AI-generated (deepfake) faces.

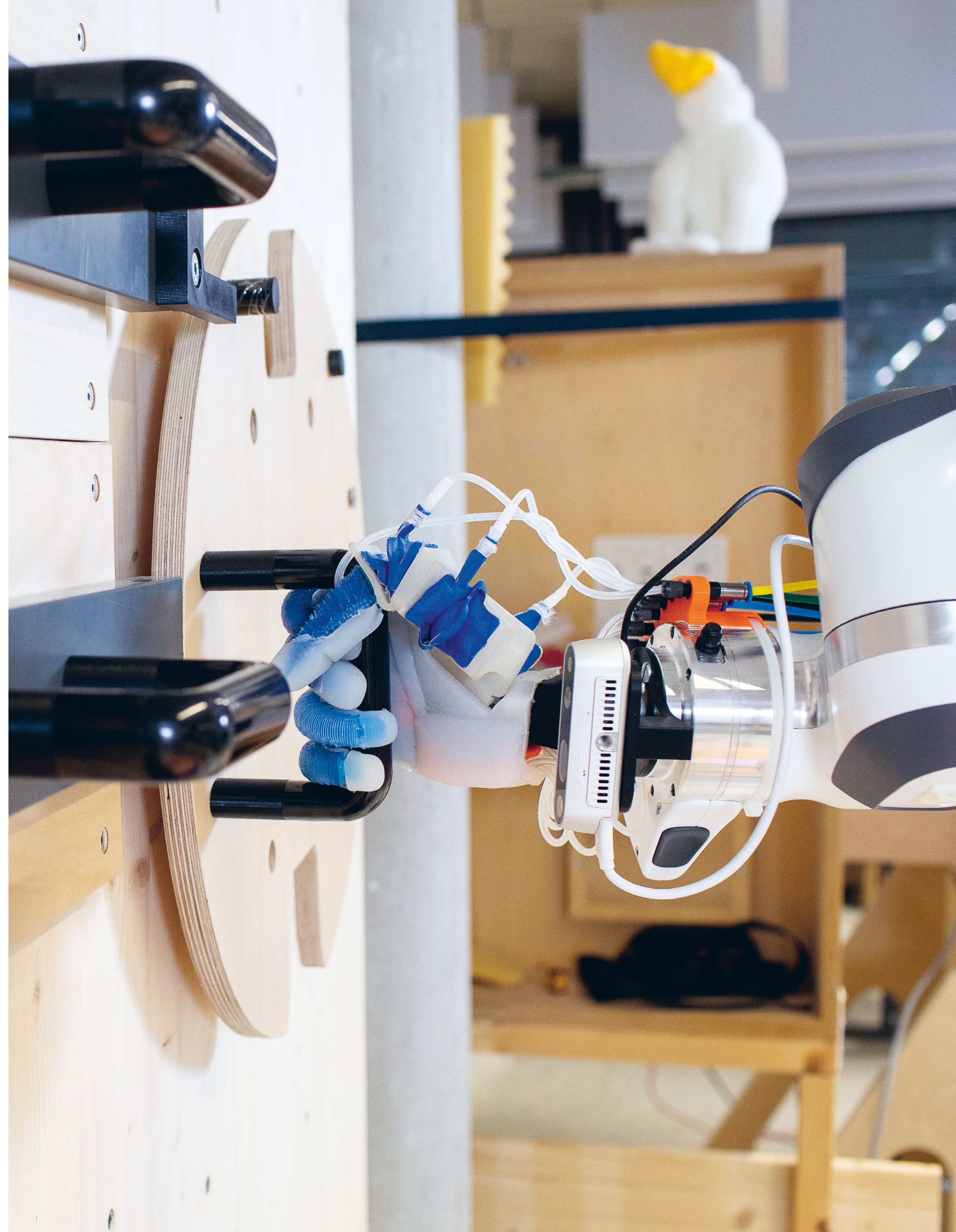
Visual Capture Lab

The Visual Capture Lab consists of three adjacent rooms: the Light Lab for video recordings under controlled lighting conditions, the Dark Lab for eye-tracking studies, and an intermediate control room to manage experiments in both labs. The Light Lab features a set for a moving scene consisting of a large, functioning, model train that moves around a rural German landscape, as well as multiple cameras used for different aspects of visual scenes: high-speed cameras, depth cameras, and event cameras. Additionally, a truss system and robot arms can be used to mount and move cameras and lighting equipment. Using these cameras, our researchers were able to record a large video data set for eye-tracking studies, also augmenting robotic systems and improving their perceptual abilities.

The Dark Lab has a high-speed projection system, eye-trackers, and 3D-glasses to investigate which features of visual scenes catch humans' attention, and how gaze fixations and rapid gaze shifts support visual perception in the first place. The lab is equipped to conduct eye-tracking experiments in total darkness and in the absence of visual reference points, allowing researchers to investigate control mechanisms for eye movements in isolation.

Why Asimov? Why Čapek?

Finding names for our robotics labs was a bit of a challenge: although each lab has its own identifiable purpose, we didn't want to limit ourselves in case of future setup changes. So, after a call for lab-name proposals, we voted for the names of two important science-fiction authors who have contributed to the concept of robot and inspired the development of the robotics field: Karel Čapek, the Czech author and playwright who became best known for his science fiction novels *War with the Newts* (1936) and the play *R.U.R*, in which the word "robot" appears for the first time, and Isaac Asimov (1920–1992) the Russian-born American author and biochemist, best known for his works of science fiction, where he introduced his famous "Three Laws of Robotics." The SCIoI lab doors were illustrated by Berlin artist Léon Giogoli with themes inspired by the two authors and their connection to SCIoI.



Exploring the Aquatic Lab

Paying a visit to SCIoI's Aquatic Lab, between robotic fish, mollies, and guppies

BY CHRISTOPHER SCHUTZ

Opposite page: David Bierbach checks on the fish at the Aquatic Lab. Above: zebrafish

Welcome to the Aquatic Lab, where we take a closer look at the behaviors of different small freshwater fishes with the help of video-tracking systems, robotic fish setups, and more.

One of the things we do here is analyze the behavior of more than 48 fish simultaneously from birth onwards and throughout their lives – a sort of Big Brother process that helps us answer questions about individual differences. This is especially helpful with clonal Amazon mollies (*Poecilia formosa*), an all-female species made of identical clones, which we observe in order to conduct large-scale twin studies.

But clones are not the only stars – our rarest fish here is the sulphur molly (*Poecilia sulphuraria*). This species is known for its ability to live in highly toxic, low-oxygen sulphur springs in Mexico, withstanding water temperatures of more than 43°C and reacting to birds that want to eat them by producing "Mexican waves" (see p. 28). Given that we are the only lab in the world that harbors this fish species, we hope to gain invaluable insights into its collective behavior and conservation.

We also have a superstar, i.e., *Poecilia reticulata*, aka the Trinidadian guppy. This species has been used as model organism for research since the early 1950s, and we study its social interaction mechanisms through our very own Robofish (see p. 28), a 3D-printed, live-sized guppy model, that is magnetically attached to a robotic unit that drives on a second level below the test aquarium. The guppies accept Robofish as one of their own, following it through the tank and often copying its actions. It's a perfect system to study all kinds of social interaction phenomena like collective decision-making, leader-follower dynamics, or anticipation abilities.

Of course all these fish need special care, and we adhere to the strictest animal welfare and health regulations. For example, we are at the forefront in developing standard husbandry protocols for scientific animal care facilities and follow the 3R principle (reduce, refine, replace) in all our experimental setups.

Regarding daily routines, we of course start our day by checking all technical devices necessary to maintain our fish's water quality and safety. After that, we do the first of two feedings of the day – powder food (for the babies) or granulate food for "bigger" fish. Meanwhile, we also check if all the fish are fine, and often we then discover new babies, as every adult female reproduces roughly once per month. In the afternoon, the fish get their second meal and a final checkup. Overall, we roughly have 3,000 individual fish from several different species, most of them belonging to the family of livebearing toothcarps (Poeciliidae).

Cluster Introspection

SCIoI researcher Tobias Drewlani explains what happens when a cluster becomes the object of its own research

Intelligence research is interdisciplinary by nature, and putting its disciplines together is one of our cluster's main objectives. In order to counter what we call "disciplinary fragmentation," SCIoI has made it its mission to promote scientific collaborations between researchers from different fields, and this happens not only conceptually but also tangibly. For example, when we assign office spaces to new scientists, we make sure to place them together with researchers coming from different disciplines, hoping to create the mind space and physical opportunities for serendipitous discoveries, i.e., those casual and fortuitous eureka moments that often occur when we talk to people from a totally different background. But how do scientists from different fields really collaborate?

Our doctoral researcher Tobias Drewlani has made this the main object of his research, trying to answer questions such as, how do SCIoI researchers see and shape their collaboration efforts? How can heterogenous knowledge be integrated? What are suitable organizational structures facilitating collaboration? Read below for an overview of Tobias' findings in his own words.

Collaboration at SCIoI

The question of how SCIoI researchers collaborate has kept me busy for almost three years now. I think the main finding is that there is not an ideal or single way of how researchers from different fields can collaborate, but many. One of the most interesting aspects that I have found in my conversations with scientists is that each of them has a different way of conceptualizing interdisciplinary collaborations, but there's something that all these descriptions have in common. First, all researchers believe that interdisciplinary collaboration is an exploratory and open-ended process, and not one that follows a linear set of instructions. Secondly, many SCIoI members have provided metaphors to describe the way they see these collaborations.

Here are some of the most interesting metaphors for the concept of collaboration:

"It's like …

… an experiment"

Collaboration resembles conducting an experiment, where individuals practically work together, experimenting with tools and concepts, despite uncertainty about the outcome.

… a leaf"

Collaboration is likened to leaf growth, originating from a common point and branching out into multiple veins in different directions while maintaining a unified surface.

… clouds"

Collaboration mirrors the continuous process of cloud formation, where ideas and goals continually reshape, connect, and separate, with each cloud symbolizing specific project ideas or goals.

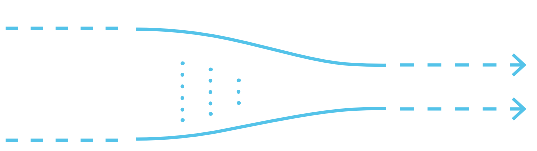
… a swarm of ants"

Collaboration is like a swarm of ants working collectively on a project, with different parts gathering knowledge and insights, which are then shared and integrated into a collective repository.

There's another aspect that we need to consider: SCIoI research projects usually have a synthetic (i.e., artificial, or computer-based) and an analytic (or natural) part. When it comes to collaboration between these two sides, SCIoI researchers have shown that there are three different modes to integrate the knowledge from these two sides:

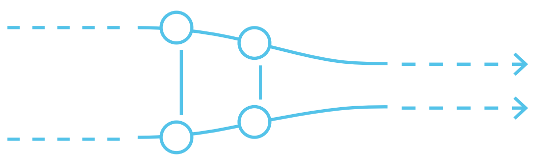
Selective Alignments: The collaborating parties retain a high degree of disciplinary autonomy. In this type of collaboration, researchers are not obliged to reach a consensus regarding the interpretation of particular research objects, but mutual support and inspiration still informs and stimulates the advancement of knowledge.

For instance, researchers working with swarm robots and schools of fish may not necessarily share specific scientific concepts, because the organisms in question are very different. However, insights from analogously designed experiments may serve as important inspirations for the other side.



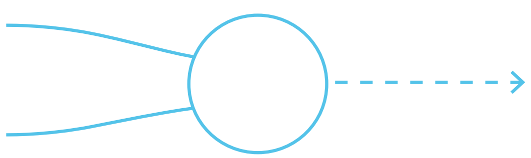
Partial Consensus: Collaborating parties define and share specific research objects over which they develop a partial consensus. Debates over the precise meaning of such "boundary objects" become crucial for this mode of collaboration. Researchers not only typically agree on the details of these objects when they engage with each other but also use them independently, altering meanings at different times and in various contexts.

For instance, researchers working with biological and synthetic (or artificial) agents may collaboratively develop a model to explain certain aspects of behavior. However, they may still use these insights to address independent research questions.



Merging Perspectives: The third collaboration strategy works well when research questions cross existing disciplinary understandings. In these cases, pre-existing disciplinary knowledge serves only as a proxy, and researchers must define research objects that lie outside their previous understandings.

This is typically the case for collaborations that explore "principles of intelligent behavior" as these principles are argued to exist independently of their embodiment in biological or synthetic agents.

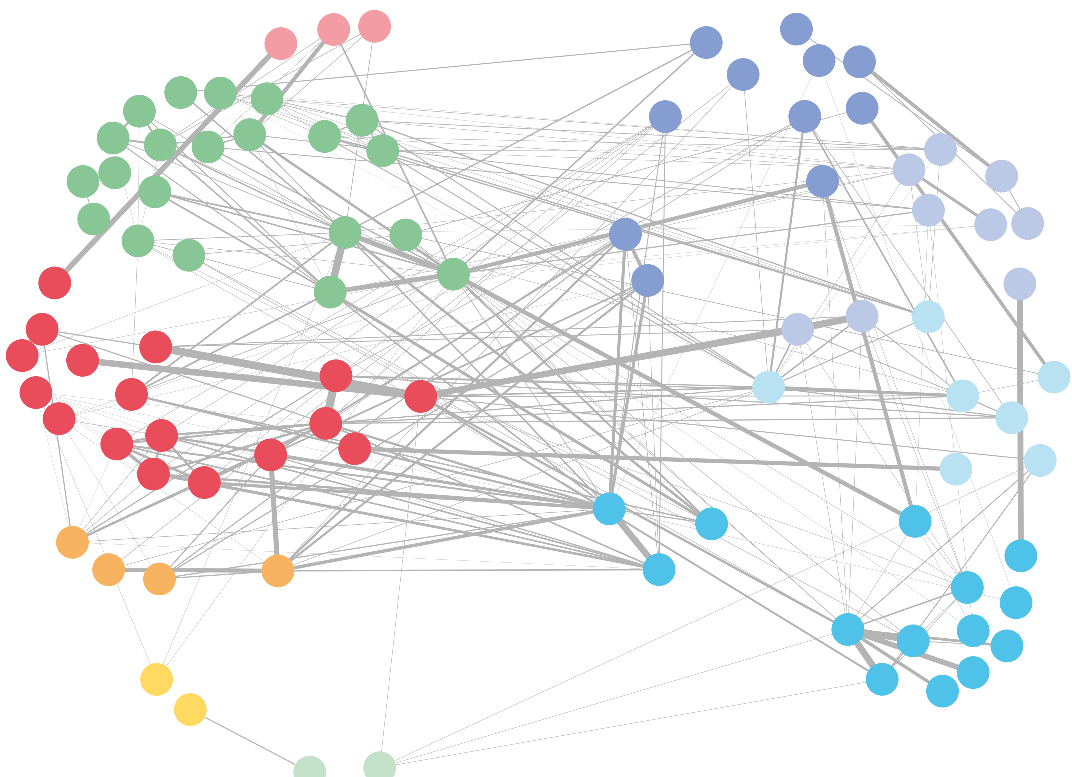


These types of findings are useful for research: By identifying these collaboration processes we can also compare their levels of efficiency and pinpoint which of them are best for an interdisciplinary endeavor such as ours. ●

How Interdisciplinary is SCIoI?

This graph shows all SCIoI collaborations between scientists from different disciplines and is based on the collaborations in SCIoI publications. Each dot represents a SCIoI member, while the different colors are the disciplines, with the analytic side on the left and the synthetic side on the right.

GRAPH BY MAX PLONER



ANALYTIC DISCIPLINES

- Computational Neuroscience
- Psychology
- Educational Science
- Sociology
- Philosophy
- Cognitive Science
- Behavioral Biology

SYNTHETIC DISCIPLINES

- Robotics
- Computer Vision
- Machine Learning
- Computer Science

Collaborations

SCIoI collaborates with various institutions from industry and academia in order to exchange knowledge, skills, and resources for mutual benefit. Here is a list of some of our recent alliances.

DAAD Deutscher Akademischer Austauschdienst German Academic Exchange Service

Berlin University Alliance

Berlin School of Mind and Brain

Humboldt-Universität zu Berlin

AIMS

Einstein Center Digital Future

RBO

Center for Brains Minds+ Machines

Andrews University

htw. Hochschule für Technik und Wirtschaft Berlin University of Applied Sciences

ISAB

BIFOLD

bccn berlin

Centre for the Advanced Study of Collective Behaviour

Einstein Center 3R

Humboldt Forum im Berliner Schloss

Matters of Activity Image Space Material

IGB Leibniz-Institut für Gewässerökologie und Binnenfischerei

BfR Bundesinstitut für Risikobewertung

University of Oxford

Aarhus University

vetmeduni

More partners:

Global Research Center for Diverse Intelligences at the University of St. Andrews

Dahlem Research School (FU Berlin)

Humboldt Graduate School (HU-Berlin)

Graduate Studies Support (Charité)

Center for Junior Scholars

Industry collaborations:

amazon Development Center Germany GmbH

etami

BDV Big Data Value Association

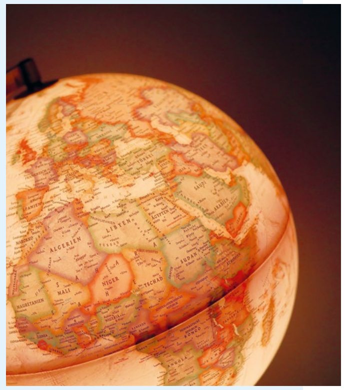
VW

Merantix AI Campus Berlin

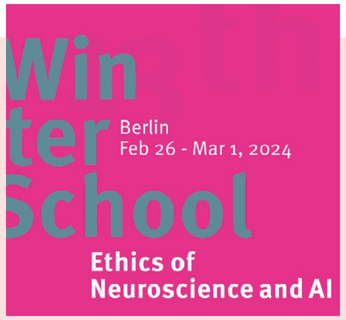
*starcode

Academic Programs

Global Scientific Educational Program (GSEP)



In 2021, SCIoI awarded fully-funded GSEP fellowships to six students from African countries. Aimed at Master's level students who wish to gain research experience in a subject of their interest at SCIoI, these fellowships were intended to increase their chances of successfully applying to a doctoral program in the Global North and to provide fellows with hands-on research experience in an interdisciplinary environment. This GSEP round was organized together with the African Institute for Mathematical Sciences (AIMS).



The Winter School "Ethics of Neuroscience and AI"

Every year in late February, the Bernstein Center for Computational Neuroscience, the Berlin School of Mind and Brain, and SCIoI get together to organize the Winter School Ethics of Neuroscience and AI, an event tailored for Master's and doctoral students. The Winter School covers a range of topics with particular focus on the ethical and societal consequences of modern neuroscience.

Summer Schools

Efficient AI for individual artificial agents and teams is a critical area of research. To explore paths towards efficient and sustainable robot perception and learning, in 2023 we got together with the International Society of Adaptive Behavior (ISAB, UK) and hosted a one-week summer school in Berlin on the theme of "Embodied Intelligence – Perception and Learning in Nature and Robotics." Designed for early-career researchers from all over, this summer school explored alternative paths towards efficient and sustainable robot perception and learning, and efficient AI for individual artificial agents and teams. In addition, we have collaborated with BIFOLD and the Weizenbaum Institute and co-organised the Berlin Summer School of Artificial Intelligence and Society, titled "AI and the Urban: Making Cities Smart(er)?" (September 2024).

The SCIoI Master's Track

With an interdisciplinary curriculum, this Master's track prepares TU Computer Science students for a career in intelligence research and is ideal for aspiring SCIoI candidates. The program offers training on intelligence-related topics (perception, reasoning, learning, etc.,) from the complementary perspectives of computer science and psychology, and prepares Master's students for bridging synthetic and analytic disciplines.
www.scienceofintelligence.de/master-track-tu-berlin

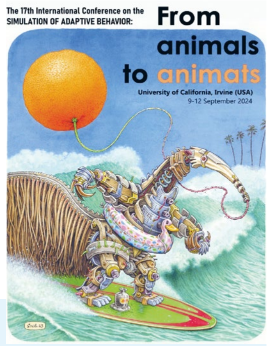
CLIMATE CHANGE CENTER
Berlin Brandenburg

Einstein Visiting Fellows

In 2022 and 2023, SCIoI welcomed five Einstein Visiting Fellows. Elke Weber from Princeton University, Eric Johnson from the Center for Decision Sciences at Columbia University, Lubna Rashid from Princeton's Behavioral Science for Policy Lab, Jonas Ludwig from TU Berlin, and Arian Trieb, a predoctoral researcher. These fellows are affiliated with the Einstein Center Climate Change (which links climate research with behavioral sciences and economics) and with Science of Intelligence.

Advanced SCIoI Lectures

In 2024, the Berlin Senate has granted us funding for various teaching projects. Designed and organised by SCIoI doctoral students and supervised by their respective PIs, these projects give SCIoI researchers the opportunity to divulge their SCIoI research through teaching opportunities within the Berlin universities. These projects are also a way for SCIoI to enhance and expand its international network of scientists by inviting notable speakers to participate in the teaching program. The courses can be used as part of the SCIoI Master's Track program and of the curriculum of the Berlin School of Mind and Brain. Please visit www.scienceofintelligence/master-track for an overview.

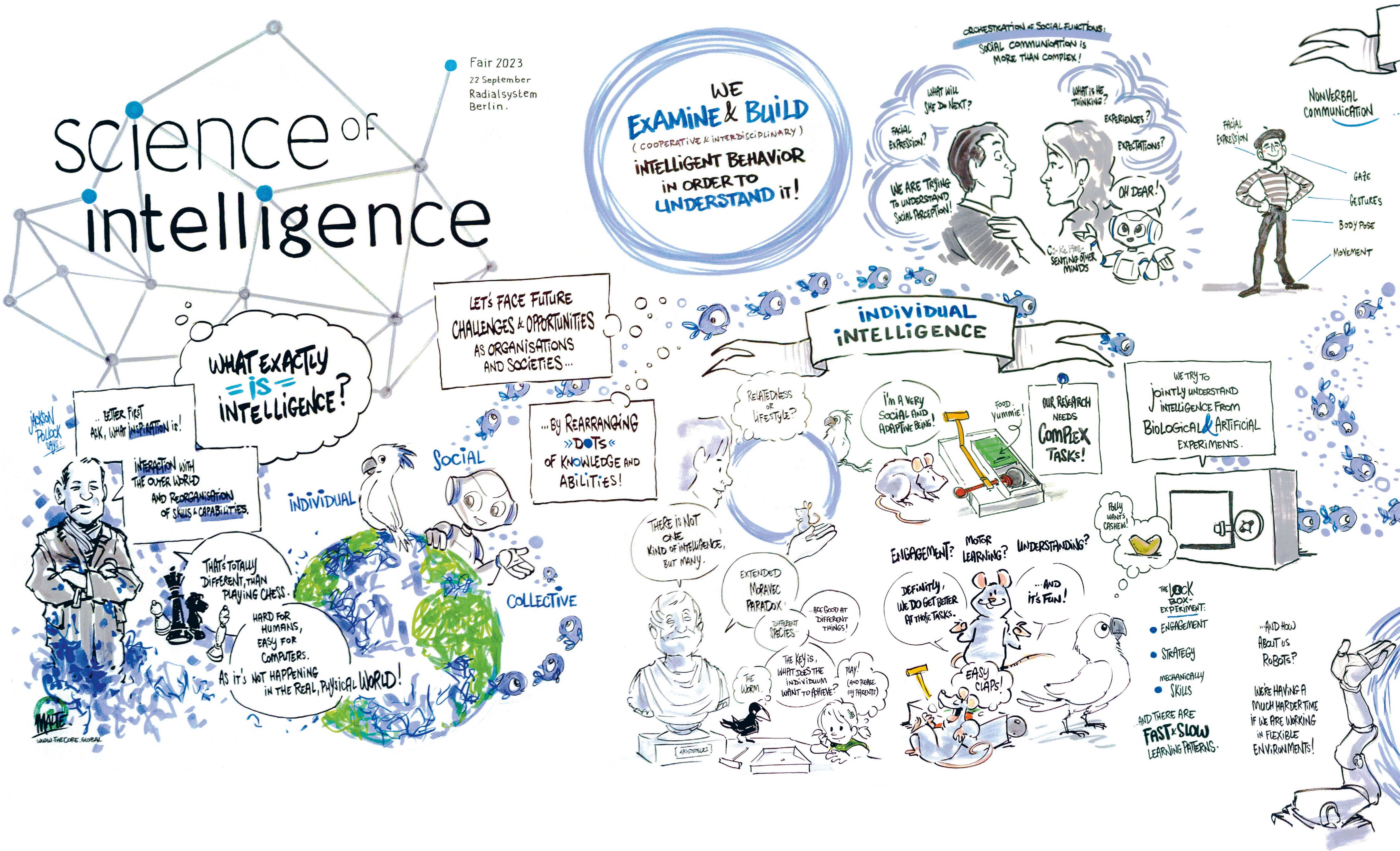


17th International Conference on the Simulation of Adaptive Behavior (SAB 2024)

This conference is co-organized by University of California Irvine (UCI) and SCIoI, and brings together researchers in computer science, artificial intelligence, artificial life, control, robotics, neurosciences, ethology, evolutionary biology and related fields in order to further our understanding of the behaviors and underlying mechanisms that allow natural and artificial animals to adapt and survive in uncertain environments. The conference focuses on models of adaptive behavior and on experiments grounded on well-defined models including robot and computer simulation and mathematical models designed to help characterize and compare various principles or architectures underlying adaptive behavior in real animals and in synthetic agents, the "animats."

SCIoI: an Artistic Rendition

During the SCIoI Fair in September 2023, graphic visualizer Malte von Thiesenhausen took visual notes of all that was said during the keynote lectures, talks, and panel discussion. The result is an artistic summary of the true essence of SCIoI.


Science of intelligence
Fair 2023
22 September
Radialsystem
Berlin.
WE EXAMINE & BUILD (COOPERATIVE & INTERDISCIPLINARY) INTELLIGENT BEHAVIOR IN ORDER TO UNDERSTAND IT!
ORCHESTRATION OF SOCIAL FUNCTIONS: SOCIAL COMMUNICATION IS MORE THAN COMPLEX!
WHAT WILL SHE DO NEXT?
FACIAL EXPRESSION?
WE ARE TRYING TO UNDERSTAND SOCIAL PERCEPTION!
WHAT IS HE THINKING?
EXPERIENCES?
EXPECTATIONS?
OH DEAR!
CO-RE-PRESENTING OTHER MINDS
NONVERBAL COMMUNICATION
FACIAL EXPRESSION
GAZE
GESTURES
BODY POSE
MOVEMENT
WHAT EXACTLY = IS = INTELLIGENCE?
LET'S FACE FUTURE CHALLENGES & OPPORTUNITIES AS ORGANISATIONS AND SOCIETIES...
...BY REARRANGING »DOTS« OF KNOWLEDGE AND ABILITIES!
JACKSON POLLOCK SAYS:
... BETTER FIRST ASK, WHAT INSPIRATION IS!
INTERACTION WITH THE OUTER WORLD AND REORGANISATION OF SKILLS & CAPABILITIES.
THAT'S TOTALLY DIFFERENT, THAN PLAYING CHESS.
HARD FOR HUMANS, EASY FOR COMPUTERS.
AS IT'S NOT HAPPENING IN THE REAL, PHYSICAL WORLD!
SOCIAL
INDIVIDUAL
COLLECTIVE
WWW.THECORE.GLOBAL
INDIVIDUAL INTELLIGENCE
RELATEDNESS OR LIFESTYLE?
I'M A VERY SOCIAL AND ADAPTIVE BEING!
FOOD. YUMMIE!
OUR RESEARCH NEEDS COMPLEX TASKS!
WE TRY TO JOINTLY UNDERSTAND INTELLIGENCE FROM BIOLOGICAL & ARTIFICIAL EXPERIMENTS.
THERE IS NOT ONE KIND OF INTELLIGENCE, BUT MANY.
EXTENDED MORAVEC PARADOX
DIFFERENT SPECIES
...ARE GOOD AT DIFFERENT THINGS!
THE KEY IS, WHAT DOES THE INDIVIDUUM WANT TO ACHIEVE?
THE WORM.
PLAY! (AND PLEASE MY PARENTS)
ARISTOTELES
ENGAGEMENT? MOTOR LEARNING? UNDERSTANDING?
DEFINITLY, WE DO GET BETTER AT THOSE TASKS.
...AND IT'S FUN!
EASY CLAPS!
POLLY WANTS CASHEW!
THE LOCK BOX-EXPERIMENT:
ENGAGEMENT
STRATEGY
MECHANICALLY SKILLS
...AND THERE ARE FAST & SLOW LEARNING PATTERNS.
...AND HOW ABOUT US ROBOTS?
WE'RE HAVING A MUCH HARDER TIME IF WE ARE WORKING IN FLEXIBLE ENVIRONMENTS!

SOCIAL INTELLIGENCE
...ESPECIALLY IMPORTANT DURING SOCIAL KNOWLEDGE TRANSFER BETWEEN AGENTS.
EXTRACT PRINCIPLES FROM PSYCHOLOGY
MANIPULABILITY
BEHAVIORAL MIRRORS
LONGTERM INTERACTIONS
LOOK INTO »MIND«
"OF COURSE WE'RE NOT AIMING AT REPLACING HUMANS."
..AND MODEL THE PRINCIPLES ON EMBODIED AGENTS.
...WE'RE TRYING TO UNDERSTAND BETTER!
SOME DRINKS, ANYBODY?
WITH OUR SCIENCE & STUDIES, WE'RE TRYING TO BE ETHICALLY RESPONSIBLE!
COLLECTIVE INTELLIGENCE
SELF-ORGANISATION:
IN THE SWARM, WE FOLLOW SIMPLE RULES
...TO PERFORM COLLECTIVE BEHAVIOR!
...AND OUTSMART INDIVIDUAL WISDOM!
MEXICAN WAVE
USEFULL FOR EXAMPLE IN AUTONOMOUS DRIVING?!
LESS IS MORE IN COLLECTIVE INTELLIGENCE!
AND IN THE END...
...OUR NEURONS
...FORM THE SAME STRUCTURES!
UNDER THE SEA...
"THERE IS WAR!"
FOUNTAIN EFFECT
WHAT WE'RE DOING HERE, ISN'T ORGANISED.
IN FACT, WE FISH DON'T EVEN KNOW, WHAT WE ARE DOING.
I'LL FOLLOW YOU!
WE'RE BASICALLY CHECKIN', WHAT THE OTHERS ARE DOING.
LET'S GET BEHIND THE MARLIN!
FOLLOW ME!
YOU KNOW WHAT?! WE SHOULD TEAM UP, TOO!
THIS CONCEPT WAS REBUILD IN SCIOI'S KILOBOTS.
RESULTING IN FISH-SWARM-ALIKE COLLECTIVE MOVEMENTS.
THE LOOP!
WE STUDY ORGANISMS, REBUILD THE PRINCIPLES OF OUR INSIGHTS IN ROBOTS AND REUSE OUR LEARNING ON ORGANISMS.
IS THERE A DIFFERENCE BETWEEN HUMAN & ARTIFICIAL INTELLIGENCE? (OR MUST THERE BE ONE?)
...OF COURSE, THERE A LOT OF DIFFERENT KINDS OF INTELLIGENCE.
COMBINED WITH INDIVIDUAL TALENTS & INTERESTS.
...AND WHAT MAKES A HUMAN?
PANEL DISCUSSION
I'M GOOD AT STRUCTURED SITUATIONS!
BUT YOU'RE A LOUSY DANCER. SORRY.
EVEN ROBOTS CAN BE SLIGHTLY DIFFERENT.
...WITH AN EFFECT ON THE RESULT THEY PRODUCE.
OVER-MENTALIZING
BIASED
EMOTIONAL
WHAT'S ITS PURPOSE?
IN THE END, PHYSICAL EMBODIMENT OF ARTIFICIAL INTELLIGENCE IS DESIGNED BY HUMANS, DEPENDING ON WHAT IT IS SUPPOSED TO DO.
MACHINE LEARNING: IS MORE SHALLOW, LEARNS PATTERNS & STRUCTURES.
...AND NON-PREDICTABLE NOW & THEN.
»A HUMAN WOULD NEVER DO THAT«
CAN WE LEARN FROM THAT?
WE WANT TO "ANTROPOMORPHISE" OUR VIEW OF THE ROBOT.
WE WANT TO TRUST.
BUT WE DON'T WANT TO BE MANIPULATED.
DEEP LEARNING: COPIES NEURONAL LEARNING TO SOME EXTEND.
...AND IS IT ABLE TO ADAPT TO NEW SITUATIONS?
...IN A ROBUST & RESILIENT WAY?
...ESPECIALLY, AS WE DON'T KNOW ALL FEATURES OF NATURE.
NEXT TO MORAL: HOW ABOUT ETHICAL RISKS?
OUR GOALS ARE CRUCIAL. BUT EVEN IF THEY ARE FAIR...
CAN WE UNDERSTAND, WHAT WE'RE DEVELOPING?
...OR EVEN CONTROL?!
FIRST THE DIAGNOSIS, THEN THE »CURE«!
WE'RE ALL USERS. THAT'S WHY OUR SOCIETIES HAVE TO BECOME MORE ETHICALLY EDUCATED.
GENERALLY! NOT ONLY TOWARDS ARTIFICIAL INTELLIGENCE!
...BECAUSE MAYBE, THAT IS AN IMPORTANT PART OF INTELLIGENCE: THAT WE CAN ENVISION THE OUTCOME!
QUO VADIS, SCIOI?
WE'LL GO ON WITH INTERACTION.
AND THAT ALWAYS MEANS TO LEARN TO UNDERSTAND EACH OTHER FIRST.
THE MOMENTUM!
WE'VE FOUND PATTERNS & FUNDAMENTAL TRADE-OFFS.
THE LONG-TERM.
KEEP UP THE WORK, EXCHANGE & COLLABORATION!
THE RESPONSIBILITY.
...AND LET'S KEEP SOCIETY INFORMED!
SUBSCRIBE OUR NEWSLETTER: WWW.SCIENCEOFINTELLIGENCE.DE/ABOUT-US/NEWSLETTER/
SCIENCE OF INTELLIGENCE (SCIOI) IS FUNDED BY
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HUMBOLDT-UNIVERSITÄT ZU BERLIN
Freie Universität Berlin
Universität Potsdam
CHARITÉ
MAX-PLANCK-INSTITUT FÜR BILDUNGSFORSCHUNG

Belonging Matters

SCIoI's comprehensive vision for a diverse and participatory academic future

BY LUJAIN KRETZSCHMAR

SCIoI's commitment to fostering an environment of diversity, equity, and inclusion (DE&I) embraces innovative and dynamic methods. This is because we believe true participation begins right from the conception phase, rather than just in the final steps of implementing DE&I measures. We acknowledge that diversity is an ongoing process that requires continuous management and commitment. By continuously integrating diverse perspectives, we aim to create a truly equitable workspace that drives innovation and excellence.

Our inclusive measures begin in the recruitment phase, when we utilize international job search engines and platforms to reach a diverse pool of candidates. Early career researchers at SCIoI engage with applicants through Q&A sessions before interviews, providing transparent and open communication in a peer-to-peer style. All recruitment stages offer hybrid participation options. The interviews are supported by the diversity manager, while the onboarding process is facilitated by Academic Coordination.

As an integral part of our organizational structure, SCIoI has established an Equal Opportunities Committee (EOC) and appointed a diversity manager to coordinate necessary tools, improve infrastructure, and implement awareness measures. They both play a crucial role in managing diversity-related statistics, keeping track of our progress and offering valuable advice and assistance on equal opportunity matters. Comprising members from all academic levels, the committee ensures comprehensive access and representation across SCIoI. This structured approach ensures that efforts to create an inclusive and supportive environment are systematic, consistent, and sustained over time.

The intersectionality of belonging to different aspects of diversity (such as cultural affiliations, gender, age, religion, and ability) led us to implement a comprehensive strategy that integrates all members into our decision-making processes. This comprehensive-participative approach involves our diverse community in the early stages of planning our diversity programs, initiatives, and events. By doing so, we ensure everyone's input is considered. This fosters a sense of belonging and respect for each individual. For example, with the help of many SCIoI members including the Equal Opportunities Committee and myself, the diversity manager, we have developed a survey that successfully engaged participants in formulating measures to promote diversity, equity, and inclusion, identifying areas for improvement, and understanding workplace diversity from members' perspectives. This voluntary and anonymous survey highlighted the participative concept by encouraging active involvement and providing valuable educational insights, ultimately fostering long-term engagement and progress tracking.

Our perspective is complemented by targeted support for underrepresented groups. By acknowledging gender-related challenges in STEM, SCIoI has made significant strides in promoting gender equality. In the 2023 recruitment round (Cohort 5), SCIoI achieved its highest milestone in gender equality, with 50 % of the new Early Career Researchers being women.

Targeted measures such as unconscious bias workshops for PIs and Postdocs, establishing a parent-child office, and our family-friendly policies, adaptable work hours, and childcare support, reflect our commitment to work-life balance for all members. Through our actions, SCIoI aims to level the playing field, ensuring every member feels valued, respected, and empowered to contribute to our collective research endeavors, setting a new standard for participation, inclusion, and belonging in the academic world.

What is diversity for you?

The "word cloud" that resulted from the participation of SCIoI members in the Scientific Networking Days 2023

The parent-child room at SCIoI offers a space for parents to work alongside their children

A Nao robot imitates the motions of its human companion

Publications

Our researchers regularly publish peer-reviewed scientific journal articles that contribute to the understanding of intelligence

Publications

SCIoI research consists of many intedisciplinary collaborations on the diverse range of intelligence-related themes. Here below is a selection of our publications from the past five years.

2024
(June)

Breen, A., & Deffner, D. (2024). **Risk-sensitive learning is a winning strategy for leading an urban invasion.** Elife. https://doi.org/10.7554/eLife.89315.3

Dallabetta, M., Dobberstein, C., Breiding, A., & Akbik, A. (2024). **Fundus: a simple-to-use news scraper optimized for high quality extractions.** ACL 2024. https://doi.org/10.48550/arXiv.2403.15279

Deffner, D., Mezey, D., Kahl, B., Schakowski, A., Romanczuk, P., Wu, C. M., & Kurvers, R. (2024). **Collective incentives reduce over-exploitation of social information in unconstrained human groups.** Nature Communications. https://doi.org/10.1038/s41467-024-47010-3

Eiserbeck, A., Enge, A., Rabovsky, M., & Abdel Rahman, R. (2024). **Distrust before first sight? Examining knowledge- and appearance-based effects of trustworthiness on the visual consciousness of faces.** Consciousness and Cognition, 117, 103629. https://doi.org/10.1016/j.concog.2023.103629

Garbaciauskas, L., Ploner, M., & Akbik, A. (2024). **Choose your transformer: Improved transferability estimation of transformer models on classification tasks.** ACL 2024.

Golde, J., Haller, P., Hamborg, F., Risch, J., & Akbik, A. (2024). **Fabricator: An open source toolkit for generating labeled training data with teacher LLMs.** EMNLP 2023. https://doi.org/10.18653/v1/2023.emnlp-demo.1

Golde, J., Hamborg, F., & Akbik, A. (2024). **Large-scale label interpretation learning for few-shot named entity recognition.** EACL 2024. https://doi.org/10.48550/arXiv.2403.14222

Guo, S., & Gallego, G. (2024). **CMax-SLAM: Event-based rotational-motion bundle adjustment and SLAM system using contrast maximization.** IEEE Transactions on Robotics. https://doi.org/10.1109/TRO.2024.3378443

Halawa, M., Blume, F., Bideau, P., Maier, M., Abdel Rahman, R., & Hellwich, O. (2024). **Multi-task multi-modal self-supervised learning for facial expression recognition.** IEEE Computer Vision and Pattern Recognition Conference Workshops (CVPRW) 2024.

H

Haller, P., Aynetdinov, A., & Akbik, A. (2024). **OpinionGPT: Modelling explicit biases in instruction-tuned LLMs.** NAACL 2024. https://doi.org/10.48550/arXiv.2309.03876

Haller, P., Golde, J., & Akbik, A. (2024). **PECC: Problem extraction and coding challenges.** COLING 2024.

Hamann, F., Ghosh, S., Martínez, I. J., Hart, T., Kacelnik, A., & Gallego, G. (2024). **Low-power, continuous remote behavioral localization with event cameras.** CVPR. https://doi.org/10.48550/arXiv.2312.03799

Hübert, H., & Yun, H. S. (2024). **Sobotify: A framework for turning robots into social robots.** Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction (HRI '24), March 11–14, 2024, Boulder, CO, USA.

M

Mellmann, H., Arbuzova, P., Kontogiorgos, D., Yordanova, M., Haensel, J. X., Hafner, V. V., & Bryson, J. J. (2024). **Effects of transparency in humanoid robots – a pilot study.** HRI '24 Companion. https://doi.org/10.1145/3610978.3640613

Mezey, D., Deffner, D., Kurvers, R. H., & Romanczuk, P. (2024). **Visual social information use in collective foraging.** PLoS Computational Biology, 20, 1–24.

Musiolek, L., Bierbach, D., Weimar, N., Hamon, M., Krause, J., & Hafner, V. V. (2024). **Evolving artificial neural networks for simulating fish social interactions**. EvoStar2024. https://doi.org/10.1007/978-3-031-56852-7_10

P

Pacher, K., Hernández-Román, N., Juarez-Lopez, A., Jiménez-Jiménez, J. E., Lukas, J., Sevinchan, Y., Krause, J., Arias-Rodríguez, L., & Bierbach, D. (2024). **Thermal tolerance in an extremophile fish from Mexico is not affected by environmental hypoxia.** Biology Open. https://doi.org/10.1242/bio.060223

Pham, D., Hansen, M., Dhellemmes, F., Krause, J., & Bideau, P. (2024). **Watching swarm dynamics from above: a framework for advanced object tracking in drone videos.** IEEE Computer Vision and Pattern Recognition Conference Workshops (CVPRW) 2024.

Ploner, M., & Akbik, A. (2024). **Parameter-efficient fine-tuning: Is there an optimal subset of parameters to tune?** EACL 2024. https://doi.org/https://aclanthology.org/2024.findings-eacl.122/

Puy, A., Gimeno, E., Torrents, J., Bartashevich, P., Miguel, M. C., Pastor-Satorras, R., & Romanczuk, P. (2024). **Selective social interactions and speed-induced leadership in schooling fish.** Proceedings of the National Academy of Sciences. https://doi.org/10.1073/pnas.2309733121

R

Rücker, S., & Akbik, A. (2024). **CleanCoNLL: A nearly noise-free named entity recognition dataset.** EMNLP 2023. https://doi.org/10.18653/v1/2023.emnlp-main.533

S

Shiba, S., Klose, Y., Aoki, Y., & Gallego, G. (2024). **Secrets of event-based optical flow, depth and ego-motion estimation by contrast maximization.** IEEE Transactions on Pattern Analysis and Machine Intelligence, 1–18

T

Trunk, J., Cottenceau, B., Hardouin, L., & Raisch, J. (2024). **Event-variant and time-variant (max,+) systems.** IEEE Transactions on Automatic Control, 1045–1051. https://doi.org/10.1109/TAC.2023.3275955

Tump, A. N., Wollny-Hutarsch, D., Molleman, L., & Kurvers, R. H. (2024). **Earlier social information has a stronger influence on judgments.** Scientific Reports. https://doi.org/10.1038/s41598-023-50345-4

W

Wiland, J., Ploner, M., & Akbik, A. (2024). **BEAR: A unified framework for evaluating relational knowledge in causal and masked language models.** NAACL 2024. https://doi.org/10.48550/arXiv.2404.04113

Wischow, M., Irmisch, P., Boerner, A., & Gallego, G. (2024). **Real-time noise source estimation of a camera system from an image and metadata.** Advanced Intelligent Systems, 2300479, 1–15. https://doi.org/10.1002/aisy.202300479

Z

Zorzenon, D., Komenda, J., & Raisch, J. (2024). **Switched max-plus linear-dual inequalities: Cycle time analysis and applications.** Discrete Event Dynamic Systems, 199–250. https://doi.org/10.1007/s10626-023-00389-5

2023

A

Ajuwon, V., Cruz, B., Carriço, P., Champalimaud, Kacelnik, A., Tiago Monteiro, T. (2023). **GoFish: A low-cost, open-source platform for closed-loop behavioural experiments on fish.** Behavior Research Methods. https://doi.org/10.3758/s13428-022-02049-2

Avanesi, V., Rockstroh, J., Mildner, T., Zargham, N., Reicherts, L., Friehs, M. A., Kontogiorgos, D., Wenig, N., Malaka, R. (2023). **From C-3PO to HAL: Opening the discourse about the dark side of multi-modal social agents.** Proceedings of the 5th International Conference on Conversational User Interfaces.

Aynetdinov, A., Alt, C., Akbik, A. (2023). **Parameter-efficient tuning under weak supervision.**

B

Battaje, A., Brock, O., Rolfs, M. (2023). **An interactive motion perception tool for kindergarteners (and vision scientists).** IPerception. https://doi.org/10.1177/20416695231159182

Baum, M., Froessl, A., Battaje, A., Brock, O. (2023). **Estimating the motion of drawers from sound.** ICRA 2023.

Bolenz, F., Pachur, T. (2023). **Older adults select different but not simpler strategies than younger adults in risky choice**. PsyArXiv. https://doi.org/10.31219/osf.io/9vhy8

Breen, A., Deffner, D. (2023). **Leading an urban invasion: risk-sensitive learning is a winning strategy.** BioRxiv. https://doi.org/10.1101/2023.03.19.533319

Burema, D., Jacobs, M., & Rozborski, F. (2023). **Elusive technologies, elusive responsibilities: On the perceived responsibility of basic AI researchers.** AI and Ethics. https://doi.org/10.1007/s43681-023-00358-6

C

Chevalère, J., Lazarides, R., Yun, H. S., Henke, A., Lazarides, C., Pinkwart, N., Hafner, V. (2023). **Do instructional strategies considering activity emotions reduce students' boredom in a computerized open-ended learning environment?** Computers & Education, 196. https://doi.org/10.1016/j.compedu.2023.104741

D

Davidescu, M. R., Romanczuk, P., Gregor, T., Couzin, I. D. (2023). **Growth produces coordination trade-offs in Trichoplax adhaerens, an animal lacking a central nervous system**. Proceedings of the National Academy of Sciences. https://doi.org/10.1073/pnas.2206163120

Dolokov, O., A, Andresen, N, Hohlbaum, K, Thöne-Reineke, C, Lewejohann, L, Hellwich. (2023). **Upper bound tracker: A multi-animal tracking solution for closed laboratory settings.** 18th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP 2023) / VISAPP, 5, 945–952. https://doi.org/10.5220/0011609500003417

Driess, D., Xia, F., Sajjadi, M. S. M., Lynch, C., Chowdhery, A., Ichter, B., Wahid, A., Tompson, J., Vuong, Q., Yu, T., Huang, W., Chebotar, Y., Sermanet, P., Duckworth, D., Levine, S., Vanhoucke, V., Hausman, K., Toussaint, M., Greff, K., … Florence, P. (2023). **PaLM-E: An embodied multimodal language model.** ICML 2023. https://doi.org/10.48550/arXiv.2303.03378

E

Ehlman, S., Scherer, U., Bierbach, D., Francisco, F., Laskowski, K., Krause, J., Wolf, M. (2023). **Leverging big data to uncover the eco-evolutionary factors shaping behavioural development.** Proceedings of the Royal Society B.

Enge, A., Süß, F. S., Abdel Rahman, R. (2023). **Instant effects of semantic information on visual perception.** Journal of Neuroscience.

Eppinger, B., Ruel, A., & Bolenz, F. (2023). **Diminished state space theory of human aging.** Perspectives on Psychological Science. https://doi.org/10.1177/17456916231204811

F

Foerster, F., Romeo, M., Holthaus, P., Wood, L., Dondrup, C., Fischer, J. E., Liza, F. F., Kaszuba, S., Hough, J., Nesset, B., García, D. H., Kontogiorgos, D., Williams, J., Özkan, E. E., Barnard, P., Berumen, G., Price, D., Cobb, S., Wiltschko, M., … Huang, G. (2023). **Working with troubles and failures in conversation between humans and robots.** Frontiers in Robotics and AI.

G

Godinez, A., Battaje, A., Brock, O., Rolfs, M. (2023). **Probing perceptual mechanism of shape-contingent color after-images via interconnected recursive filters.** Journal of Vision 23 / VSS 2023. https://doi.org/10.1167/jov.23.9.4885

Gómez-Nava, L., Lange, R. T., Klamser, P. P., Lukas, J., Arias-Rodriguez, L., Bierbach, D., Krause, J., Sprekeler, H., Romanczuk, P. (2023). **Fish shoals resemble a stochastic excitable system driven by environmental perturbations.** Nature Physics. https://doi.org/10.1038/s41567-022-01916-1

Grapentin, A., Sterle, A., Raisch, J., & Hans, C. A. (2023). **LQ optimal control for power tracking operation of wind turbines.** IFAC-PapersOnLine 22nd IFAC World Congress, 2759–2766. https://doi.org/10.1016/j.ifacol.2023.10.1374

Grote, P., Ortiz-Haro, J., Toussaint, M., & Oguz, O. S. (2023). **Neural field representations of articulated objects for robotic manipulation planning.** arXiv: 2309.07620. https://doi.org/10.48550/arXiv.2309.07620

K

Kacelnik, A., Vasconcelos, M., Monteiro, T. (2023). **Testing cognitive models of decision-making: Selected studies with starlings.** Animal Cognition, 26, 117–127. https://doi.org/10.1007/s10071-022-01723-4

Kahnau, P., Mieske, P., Wilzopolski, J., Kalliokoski, O., Mandillo, S., Hölter, S. M., Voikar, V., Amfim, A., Badurek, S., Bartelik, A., Caruso, A., Čater, M., Ey, E., Golini, E., Jaap, A., Hrncic, D., Kiryk, A., Lang, B., Loncarevic-Vasiljkovic, N., … Hohlbaum, K. (2023). **A systematic review of the development and application of home cage monitoring in laboratory mice and rats.** BMC Biology, 256(21). https://doi.org/10.1186/s12915-023-01751-7

Kirtay, M., Hafner, V. V., Asada, M., Oztop, E. (2023). **Trust in robot-robot scaffolding. IEEE** Transactions on Cognitive and Developmental Systems. https://doi.org/10.1109/TCDS.2023.3235974

Kontogiorgos, D. (2023). **Explanations as communicative acts in human-robot miscommunication.** IEEE International Conference on Robot and Human Interactive Communication – Workshops, IEEE RO-MAN-W 2023.

Kontogiorgos, D. (2023). **Utilising explanations to mitigate robot conversational failures.** ACM/IEEE International Conference on Human-Robot Interaction Workshops (HRI-W).

Kontogiorgos, D., & Schlangen, D. (2023). **Explainable embodied intelligence for collaborative robots: an interactive approach**. IPrA 2023 – International Pragmatics Conference 2023.

Kurvers, R. H., Nuzzolese, A. G., Russo, A., Barabucci, G., Herzog, S. M., Trianni, V. (2023). **Automating hybrid collective intelligence in open-ended medical diagnostics.** Proceedings of the National Academy of Sciences. https://doi.org/10.1073/pnas.2221473120

L

Lang, B., Kahnau, P., Hohlbaum, K., Mieske, P., Andresen, N. P., Boon, M. N., Thöne-Reineke, C., Lewejohann, L., & Diederich, K. (2023). **Challenges and advanced concepts for the assessment of learning and memory function in mice.** Frontiers in Behavioral Neuroscience, 17. https://doi.org/10.3389/fnbeh.2023.1230082

Lehmann, D., Drebinger, P., Seel, T., & Raisch, J. (2023). **Data-driven dynamic input transfer for learning control in multi-agent systems with heterogeneous unknown dynamics.** 62nd IEEE Conference on Decision and Control (CDC). https://doi.org/10.1109/CDC49753.2023.10383433

Li, X., Baum, M., Brock, O. (2023). **Augmentation enables one-shot generalization in learning from demonstration for contact-rich manipulation.** IROS 2023.

Lukas, J., Krause, J., Träger, A.S., Piotrowski, J. M., Romanczuk, P., Sprekeler, H., Arias-Rodriguez, L., Krause, S., Schutz, C., Bierbach, D. (2023). **Multispecies collective waving behaviour in fish.** Philosophical Transactions of the Royal Society B. https://doi.org/10.1098/rstb.2022.0069

M

Mengers, V., Battaje, A., Baum, M., Brock, O. (2023). **Combining motion and appearance for robust probabilistic object segmentation in real time.** ICRA 2023.

Milich, M., Akbik, A. (2023). **ZELDA: A comprehensive benchmark for supervised entity disambiguation.** EACL 2023.

Mottelson, A., & Kontogiorgos, D. (2023). **Replicating replicability modeling of psychology papers.** PNAS.

O

Oksuz, H. Y., Molinari, F., Sprekeler, H., & Raisch, J. (2023). **Federated learning in wireless networks via over-the-air computations.** 62nd IEEE Conference on Decision and Control (CDC), 4379–4386. https://doi.org/10.1109/CDC49753.2023.10384001

P

Patidar, S., Sieler, A., & Brock, O. (2023). **In-hand cube reconfiguration: Simplified.** IROS 2023. https://doi.org/10.1109/IROS55552.2023.10341521

Pischedda, D., Erener, S., Kuhlen, A., & Haynes, J.-D. (2023). **How do people discriminate conversations generated by humans and artificial intelligence? The role of individual variability on people's judgment**. ESCOP 2023.

Pischedda, D., Kaufmann, V., Wudarczyk, O., Abdel Rahman, R., Hafner, V. V., Kuhlen, A., & Haynes, J.-D. (2023). **Human or AI? The brain knows it! A brain-based Turing Test to discriminate between human and artificial agents.** RO-MAN 2023. https://doi.org/10.1109/RO-MAN57019.2023.10309541

Poth, N. (2023). **Probabilistic learning and psychological similarity.** Entropy. https://doi.org/10.3390/e25101407

R

Raoufi, M., Romanczuk, P., Hamann, H. (2023). **Estimation of continuous environments by robot swarms: Correlated networks and decision-making.** ICRA 2023.

Raoufi, M., Romanczuk, P., Hamann, H. (2023). **Individuality in swarm robots with the case study of kilobots: Noise, bug, or feature?** Artificial Life (ALife) 2023.

Raoufi, M., Romanczuk, P., Hamann, H. (2023)**. Inter-individual variations in swarm robotics with the case study of kilobots.** ICRA 2023/workshop "Heterogeneity in Multi-Robot Systems."

Roth, N., McLaughlin, J., Obermayer, K., & Rolfs, M. (2023). **Looking for potential action: Differences in exploration behavior of static and (potentially) dynamic scenes**. Journal of Vision. https://doi.org/10.1167/jov.23.9.5293

Roth, N., Rolfs, M., Hellwich, O., Obermayer, K. (2023). **Objects guide human gaze behavior in dynamic real-world scenes.** bioRxiv. https://doi.org/10.1101/2023.03.14.532608

S

Sarkanych, P., Krasnytska, M., Gomez-Nava, L., Romanczuk, P., & Holovatch, Y. (2023). **Individual bias and fluctuations in collective decision making: from algorithms to Hamiltonians**. Physical Biology. https://doi.org/10.1088/1478-3975/acd6ce

Scherer, U., Laskowki, K., Kressler, M., Ehlman, S. M., Wolf, M., & Bierbach, D. (2023). **Perceived predation risk affects the development of among-individual behavioral variation in a naturally clonal freshwater fish.** BioRxiv. https://doi.org/10.1101/2023.11.25.568653

Scherer, U., Ehlman, S. M., Bierbach, D., Krause, J., & Wolf, M. (2023). **Reproductive individuality of clonal fish raised in near-identical environments and its link to early-life behavioral individuality.** Nature Communications. https://doi.org/10.1038/s41467-023-43069-6

Schweitzer, R., Doering, M., Seel, T., Raisch, J., Rolfs, M. (2023). **Saccadic omission revisited: What saccade-induced smear looks like.** bioRxiv.

Shiba, S., Hamann, F., Aoki, Y., & Gallego, G. (2023). **Event-based background-oriented schlieren.** IEEE Transactions on Pattern Analysis and Machine Intelligence, 1–16. https://doi.org/10.1109/TPAMI.2023.3328188

Sieler, A., & Brock, O. (2023). **Dexterous soft hands linearize feedback-control for in-hand manipulation.** IROS 2023. https://doi.org/10.1109/IROS55552.2023.10341438

Snell-Rood, E., Ehlman, S. (2023). **Developing the genotype-to-phenotype relationship in evolutionary theory: A primer of developmental features.** Evolution and Development, 1–17. https://doi.org/10.1111/ede.12434

Stahl, K., Graziadei, A., Dau, T., Brock, O., Rappsilber, J. (2023). **Protein structure prediction with in-cell phot-crosslinking mass spectrometry and deep learning.** Nature Biotechnology. https://doi.org/10.1038/s41587-023-01704-z

Sterle, A., Grapentin, A., Hans, C., & Raisch, J. (2023). **Model predictive control of wind turbines with piecewise-affine power coefficient approximation.** 62nd IEEE Conference on Decision and Control (CDC), 3586–3591. https://doi.org/10.1109CDC49753.2023.10383567

T

Taliaronak, V., Lange, A. L., Kirtay, M., Oztop, E., & Hafner, V. V. (2023). **Advancing humanoid robots for social integration: Evaluating trustworthiness through a social cognitive framework.** 2023 32nd IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), 2112–2119. https://doi.org/10.1109/RO-MAN57019.2023.10309519

Tavernier, N., Wisniewski, D., & Brass, M. (2023). **Manipulating free will beliefs using online video games.** Psychological Research. https://doi.org/10.1007/s00426-023-01815-x

Tump, A., Deffner, D., Pleskac, T., Romanczuk, P., Kurvers, R. (2023). **A cognitive computational approach to social and collective decision-making.** OSF. https://doi.org/10.31219/osf.io/7aykm

Tump, A. N., Wollny-Hutarsch, D., Molleman, L., Kurvers, R. H. (2023). **Evidence accumulation from social information: Earlier social information has a stronger influence on individuals' judgments.** PsyArXiv. https://doi.org/10.31234/osf.io/shje5

W

Wall, V., Zöller, G., Brock, O. (2023). **Passive and active acoustic sensing for soft pneumatic actuators.** The International Journal of Robotics Research. https://doi.org/10.1177/02783649231168954

W

Winklmayr, C., Kao, A. B., Bak-Coleman, J. B., Romanczuk, P. (2023). **Collective decision strategies in the presence of spatio-temporal correlations.** Collective Intelligence.

Y

Yun, H. S., Hübert, H., Chevalere, J., Pinkwart, N., Hafner, V., Lazarides, R. (2023). **Analyzing learners' emotion from an HRI experiment using facial expression recognition systems.** 25th International Conference on Human-Computer Interaction.

Yun, H. S., Hübert, H., Sardogan, A., Pinkwart, N., Hafner, V., Lazarides, R. (2023). **Humanoid robot as a debate partner.** 25th International Conference on Human-Computer Interaction.

Z

Zhou, H., Schubert, I., Toussaint, M., & Oguz, O. S. (2023). **Spatial reasoning via deep vision models for robotic sequential manipulation.** IROS 2023. https://doi.org/10.1109/IROS55552.2023.10342010

Zorzenon, D., Zaiets, N., Raisch, J. (2023). **Switched max-plus linear-dual inequalities for makespan minimization: the case study of an industrial bakery shop.** IFAC-PapersOnLine 22nd IFAC World Congress, 8628–8634. https://doi.org/10.1016/j.ifacol.2023.10.038

2022

A

Ajuwon, V., Ojeda, A., Murphy, R., Monteiro, T., Kacelnik, A. (2022). **Paradoxical choice and the reinforcing value of information.** Animal Cognition, 26. https://doi.org/10.1007/s10071-022-01698-2

B

Battaje, A., Brock, O. (2022). **One object at a time: Accurate and robust structure from motion for robots.** IROS 2022. https://doi.org/10.1109/IROS47612.2022.9981953

Baum, M., Brock, O. (2022). **"The world is its own best model": Robust real-world manipulation through online behavior selection.** ICRA 2022. https://doi.org/10.1109/ICRA46639.2022.9811845

Baum, M., Schattenhofer, L., Rössler, T., Osuna-Mascaró, A., Auersperg, A., Kacelnik, A., Brock, O. (2022). **Yoking-based identification of learning behavior in artificial and biological agents.** SAB 2022. https://doi.org/10.1007/978-3-031-16770-6_6

Bierbach, D., Gómez-Nava, L., Francisco, F. A., Lukas, J., Musiolek, L., Hafner, V. V., Landgraf, T., Romanczuk, P., Krause, J. (2022). **Live fish learn to anticipate the movement of a fish-like robot.** Bioinspiration & Biomimetics.

Bolenz, F., Eppinger, B. (2022). **Valence bias in metacontrol of decision making in adolescents and young adults.** Child Development. https://doi.org/10.1111/cdev.13693

Bolenz, F., Pachur, T. (2022). **Exploring the structure of predecisional information search in risky choice.** Proceedings of the 44th Annual Conference of the Cognitive Science Society, 2297–2302.

Bolenz, F., Profitt, M., Stechbarth, F., Eppinger, B., Strobel, A. (2022). **Need for cognition does not account for individual differences in metacontrol of decision making.** Scientific Reports. https://doi.org/10.1038/s41598-022-12341-y

C

Chen, Y., Mikkelsen, J., Binder, A., Alt, C., Hennig, L. (2022). **A comparative study of pre-trained encoders for low-resource named entity recognition.** Proceedings of the 7th Workshop on Representation Learning for NLP. https://doi.org/10.18653/v1/2022.repl4nlp-1.6

Chevalère, J., Kirtay, M., Hafner, V., Lazarides, R. (2022). **Who to observe and imitate in humans and robots: The importance of motivational factors.** International Journal of Social Robotics. https://doi.org/10.1007/s12369-022-00923-9

Coelho Mollo, D. (2022). **Intelligent behaviour.** Erkenntnis. https://doi.org/10.1007/s10670-022-00552-8

D

Deffner, D., & McElreath, R. (2022). **When does selection favor learning from the old? Social learning in age-structured populations.** Plos One. https://doi.org/10.1371/journal.pone.0267204

Deffner, D., Kandler, A., Fogarty, L. (2022). **Effective population size for culturally evolving traits.** Plos Computational Biology. https://doi.org/10.1371/journal.pcbi.1009430

Doran, C., Bierbach, D., Lukas, J., Klamser, P., Landgraf, T., Klenz, H., Habedank, M., Arias-Rodriguez, L., Krause, S., Romanczuk, P., Krause, J. (2022). **Fish waves as emergent collective antipredator behavior.** Current Biology. https://doi.org/10.1016/j.cub.2021.11.068

Driess, D., Huang, Z., Li, Y., Tedrake, R., Toussaint, M. (2022). **Learning multi-object dynamics with compositional neural radiance fields.** CoRL 2022. https://doi.org/10.48550/arXiv.2202.11855

Driess, D., Schubert, I., Florence, P., Li, Y., Toussaint, and M. (2022). **Reinforcement learning with neural radiance fields.** NeurIPS 2022. https://doi.org/10.48550/arXiv.2206.01634

E

Ehlman, S., Scherer, U., Wolf, M. (2022). **Developmental feedbacks and the emergence of individuality.** Royal Society Open Science.

G

Ghosh, S., Gallego, G. (2022). **Event-based stereo depth estimation from ego-motion using ray density fusion.** ECCVW Ego4D 2022.

Gómez-Nava, L., Bon, R., Peruani, F. (2022). **Intermittent collective motion in sheep results from alternating the role of leader and follower.** Nature Physics, 8. https://doi.org/10.1038/s41567-022-01769-8

Goris, J., Braem, S., Herck, S. V., Simoens, J., Deschrijver, E., Wiersema, J. R., Paton, B., Brass, M., Todd, J. (2022). **Reduced primacy bias in autism during early sensory processing.** Journal of Neuroscience, 19(42). https://doi.org/10.1523/JNEUROSCI.3088-20.2022

H

Ha, J.-S., Driess, D., Toussaint, M. (2022). **Deep visual constraints: Neural implicit models for manipulation planning from visual input.** IEEE Robotics and Automation Letters. https://doi.org/10.1109/LRA.2022.3194955

Halawa, M., Hellwich, O., Bideau, P. (2022). **Action based contrastive learning for trajectory prediction.** European Conference on Computer Vision (ECCV), 143–159. https://doi.org/10.1007/978-3-031-19842-7_9

H

Hamann, F., Gallego, G. (2022). **Stereo co-capture system for recording and tracking fish with frame- and event cameras**. International Conference on Pattern Recognition (ICPR), Workshop on Visual observation and analysis of Vertebrate And Insect Behavior.

Hansen, M., Krause, S., Dhellemmes, F., Pacher, K., Kurves, R., Domenici, P., & Krause, J. (2022). **Mechanisms of prey division in striped marlin, a marine group hunting predator.** Communications Biology.

Harbecke, D., Chen, Y., Hennig, L., Alt, C. (2022). **Why only Micro-F1? Class weighting of measures for relation classification**. Proceedings of the 1st Workshop on Efficient Benchmarking in NLP. https://doi.org/10.18653/v1/2022.nlppower-1.4

Harris, J., Driess, D., Toussaint, M. (2022). **FC3: Feasibility-based control chain coordination**. IROS 2022. https://doi.org/10.1109/IROS47612.2022.9981758

Henke, L., Guseva, M., Wagemans, K., Pischedda, D., Haynes, J.-D., Jahn, G., Anders, S. (2022). **Surgical face masks do not impair the decoding of facial expressions of negative affect more severely in older than in younger adults**. Cognitive Research: Principles and Implications, 7, 63. https://doi.org/10.1186/s41235-022-00403-8

K

Kamat, J., Ortiz-Haro, J., Toussaint, M., Pokorny, F. T., Orthey, A. (2022). **BITKOMO: Combining sampling and optimization for fast convergence in optimal motion planning**. IROS 2022. https://doi.org/10.1109/IROS47612.2022.9981732

Kirtay, M., Oztop, E., Kuhlen, A. K., Asada, M., Hafner, V. V. (2022). **Trustworthiness assessment in multimodal human-robot interaction based on cognitive load**. 2022 31st IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), 469–476. https://doi.org/10.1109/RO-MAN53752.2022.9900730

Kirtay, M., Oztop, E., Kuhlen, A. K., Asada, M., Hafner, V. V. (2022). **Forming robot trust in heterogeneous agents during a multimodal interactive game**. 2022 IEEE International Conference on Development and Learning (ICDL), 307–313. https://doi.org/10.1109/ICDL53763.2022.9962212

L

Lange, R., Sprekeler, H. (2022). **Learning not to learn: Nature versus Nurture in Silico**. AAAI 2022. https://doi.org/10.48550/arXiv.2010.04466

Laskowski, K., Bierbach, D., Jolles, J., Doran, C., Wolf, M. (2022). **The emergence and development of behavioral individuality in clonal fish**. Nature Communications. https://doi.org/10.1038/s41467-022-34113-y

Li, X., Brock, O. (2022). **Learning from Demonstration Based On Environmental Constraints**. IEEE Robotics and Automation Letters with IROS Option. https://doi.org/10.1109/LRA.2022.3196096

M

Maier, M., Leonhardt, Alexander, Abdel Rahman, R. (2022). **Bad robots? Humans rapidly attribute mental states during the perception of robot faces**. KogWis 2022.

Maier, M., Blume, F., Bideau, P., Hellwich, O., Abdel Rahman, R. (2022). **Knowledge-augmented face perception: Prospects for the bayesian brain-framework to align AI and human vision.** Consciousness and Cognition, 101.

Maier, M., Frömer, R., Rost, J., Sommer, W., Abdel Rahman, R. (2022). **Linguistic and semantic influences on early vision: evidence from object perception and mental imagery.** Cognitive Neuroscience of Language Embodiment and Relativity.

Makowicz, A. M., Bierbach, D., Richardson, C., Hughes, K. A. (2022). **Cascading indirect genetic effects in a clonal vertebrate.** Proceedings of the Royal Society B.

McNamara, J., Wolf, M. (2022). **Social interaction can select for reduced ability**. Proceedings of the Royal Society B: Biological Sciences. https://doi.org/10.1098/rspb.2022.1788

Meindl, M., Lehmann, D., & Seel, T. (2022). **Bridging reinforcement learning and iterative learning control: Autonomous motion learning for unknown, nonlinear dynamics.** Frontiers in Robotics and AI. https://doi.org/10.3389/frobt.2022.793512

Meindl, M., Molinari, F., Lehmann, D., & Seel, T. (2022). **Collective iterative learning control: Exploiting diversity in multi-agent systems for reference tracking tasks.** IEEE Transactions on Control Systems Technology. https://doi.org/10.1109/TCST.2021.3109646

Molinari, F., Agrawal, N., Stańczak, S., Raisch, J. (2022). **Over-the-air max-consensus in clustered networks adopting half-duplex communication technology**. IEEE Transactions on Control of Network Systems, Early access. https://doi.org/10.1109/TCNS.2022.3212870

Muscinelli, F., Roth, N., Shurygina, O., Obermayer, K., Rolfs, M. (2022). **Object-based spread of attention affects fixation duration during free viewing**. Perception/ ECVP2022.

O

Ortiz-Haro, J., Karpas, E., Katz, M., Toussaint, M. (2022). **A conflict-driven interface between symbolic planning and nonlinear constraint solving**. IEEE Robotics and Automation Letters. https://doi.org/10.1109/LRA.2022.3191948

Ortiz-Haro, J., Ha, J.-S., Driess, D., Toussaint, M. (2022). **Structured deep generative models for sampling on constraint manifolds in sequential manipulation**. CoRL 2021.

P

Pachur, T. (2022). **Strategy selection in decisions from givens: Deciding at a glance?** Cognitive Psychology. https://doi.org/10.1016/j.cogpsych.2022.101483

Pannen, T. J., Puhlmann, S., Brock, O. (2022). **A low-cost, easy-to-manufacture, flexible, multi-taxel tactile sensor and its application to in-hand object recognition**. IEEE International Conference on Robotics and Automation (ICRA). https://doi.org/10.48550/arXiv.2111.09687

Poel, W., Daniels, B. C., Sosna, M. M. G., Twomey, C. R., Blanc, S. L., Couzin, I., Romanczuk, P. (2022). **Subcritical escape waves in schooling fish.** Science Advances.

Puhlmann, S., Harris, J., Brock, O. (2022). **RBO Hand 3 – A platform for soft dexterous manipulation**. IEEE Transactions on Robotics. https://doi.org/10.48550/arXiv.2201.10883

R

Reverberi, C., Pischedda, D., Mantovani, M., Haynes, J.-D., Rustichini, A. (2022). **Strategic complexity and cognitive skills affect brain response in interactive decision-making**. Scientific Reports, 12, 15896. https://doi.org/10.1038/s41598-022-17951-0

Romanczuk, P., Daniels, B. C. (2022). **Phase transitions and criticality in the collective behavior of animals – self-organization and biological function**. Order, Disorder and Criticality.

Roth, N., Rolfs, M., Obermayer, K. (2022). **ScanDy: Simulating realistic human scanpaths in dynamic real-world scenes**. MODVIS 2022.

Roth, N., Rolfs, M., Obermayer, K. (2022). **Scanpath prediction in dynamic real-world scenes based on object-based selection**. Journal of Vision / VSS 2022.

Ruel, A., Bolenz, F., Li, S.-C., Fischer, A., Eppinger, B. (2022). **Neural evidence for age-related deficits in the representation of state spaces**. Cerebral Cortex. https://doi.org/10.1093/cercor/bhac171

S

Schafaschek, G., Hardouin, L., Raisch, J. (2022). **A novel approach to the modeling and control of timed event graphs with partial synchronization**. IFAC-PapersOnLine 16th IFAC Workshop on Discrete Event Systems, 55, 204–211. https://doi.org/10.1016/j.ifacol.2022.10.344

Schmittwilken, L., Maertens, M. (2022). **Fixational eye movements enable robust edge detection**. Journal of Vision. https://doi.org/10.1167/jov.22.8.5

Schmittwilken, L., Maertens, M. (2022). **Medium spatial frequencies mask edges most effectively**. Journal of Vision. https://doi.org/10.13140/RG.2.2.11382.06726

Schweitzer, R., Rolfs, M. (2022). **Definition, modeling and detection of saccades in the face of post-saccadic oscillations**. Eye Tracking: Background, Methods, and Applications.

Schweitzer, R., Watson, T., Balsdon, T., Rolfs, M. (2022). **The sources of peri-saccadic mislocalization: Evidence from the perception of intra-saccadic motion streaks**. VSS 2022.

Shiba, S., Aoki, Y., Gallego, G. (2022). **A fast geometric regularizer to mitigate event collapse in the contrast maximization framework**. Advanced Intelligent Systems, 11.

Shiba, S., Aoki, Y., Gallego, G. (2022). **Fast event-based optical flow estimation by triplet matching**. Signal Processing Letters, 29, 2712–2716.

Shiba, S., Aoki, Y., Gallego, G. (2022). **Secrets of event-based optical flow**. European Conference on Computer Vision (ECCV), 628–645. https://doi.org/10.1007/978-3-031-19797-0_36

Shurygina, O., & Rolfs, M. (2022). **Eye movement characteristics reflect object-based attention.** Journal of Vision / VSS 2022, 3481–3481. https://doi.org/10.1167/jov.22.14.3481

Shurygina, O., Rolfs, M. (2022). **Saccade kinematics reflect object-based attention in realistic but not in simplified stimuli**. Perception/ ECVP2022.

S

Srivastava, A., Rastogi, A., Rao, A., Shoeb, A. A. M., Abid, A., Fisch, A., Brown, A. R., Santoro, A., Gupta, A., Garriga-Alonso, A., Kluska, A., Lewkowycz, A., Agarwal, A., Power, A., Ray, A., Warstadt, A., Kocurek, A. W., Safaya, A., Tazarv, A., … Wu, Z. (2022). **Beyond the imitation game: Quantifying and extrapolating the capabilities of language models**.

Sultan, M., Tump, A. N., Geers, M., Lorenz-Spreen, P., Herzog, S. M., Kurvers, R. H. J. M. (2022). **Time pressure reduces misinformation discrimination ability but does not alter response bias**. Scientific Reports. https://doi.org/10.1038/s41598-022-26209-8

T

Toussaint, M., Harris, J., Ha, J.-S., Driess, D., Hönig, W. (2022). **Sequence-of-Constraints MPC: Reactive timing-optimal control of sequential manipulation**. IROS 2022. https://doi.org/10.1109/IROS47612.2022.9982236

Tump, A. N., Wolf, M., Romanczuk, P., Kurvers, R. (2022). **Avoiding costly mistakes in groups: The evolution of error management in collective decision making**. PLOS Computational Biology. https://doi.org/10.1371/journal.pcbi.1010442

Tump, A., Pleskac, T., Romanczuk, P., Kurvers, R. (2022). **How the cognitive mechanisms underlying fast choices influence information spread and response bias amplification in groups**. Proceedings of the 44th Annual Conference of the Cognitive Science Society, 44, 658–664.

V

Vischer, M., Lange, R., Sprekeler, H. (2022). **On lottery tickets and minimal task representations in deep reinforcement learning**. ICLR 2022. https://doi.org/10.48550/arXiv.2105.01648

W

Wall, V., Brock, O. (2022). **A virtual 2D tactile array for soft actuators using acoustic sensing**. IROS 2022. https://doi.org/10.1109/IROS47612.2022.9981225

Wirth, L., Shurygina, O., Rolfs, M., Ohl, S. (2022). **Target-location rather than target-object specific saccadic selection in visual working memory**. Perception/ ECVP2022.

Wisniewski, D., Cracco, E., Gonzalez-Garcia, C., & Brass, M. (2022). **Relating free will beliefs and attitudes.** Royal Society Open Science. https://doi.org/10.1098/rsos.202018

Y

Yun, H. S., Hübert, H., Taliaronak, V., Mayet, R., Kirtay, M., Hafner, V. V., Pinkwart, N. (2022). **AI-based open-source gesture retargeting to a humanoid teaching robot**. AIED 2022: The 23rd International Conference on Artificial Intelligence in Education.

Yun, H. S., Taliaronak, V., Kirtay, M., Chevelère, J., Hübert, H., Hafner, V. V., Pinkwart, N., Lazarides, R. (2022). **Challenges in designing teacher robots with motivation based gestures**. 17th Annual ACM/IEEE International Conference on Human-Robot Interaction (HRI 2022).

Yun, H. S., Hübert, H., Taliarona, V., Sardogan, A. (2022). **Utilizing machine learning based gesture recognition software, mediapipe, in the context of education and health**. AI Innovation Summit 2022.

Z

Zhang, Z., Yezzi, A., Gallego, G. (2022). **Formulating event-based image reconstruction as a linear inverse problem with deep regularization using optical flow**. IEEE Transactions on Pattern Analysis and Machine Intelligence.

Z

Zhao, Y., Huepe, C., Romanczuk, P. (2022). **Contagion dynamics in self-organized systems of self-propelled particles**. Scientific Reports. https://doi.org/10.1038/s41598-022-06083-0

Ziletti, A., Akbik, A., Berns, C., Herold, T., Legler, M., Viell, M. (2022). **Medical coding with biomedical transformer ensembles and zero/few-shot learning**. NAACL, 176–187. https://doi.org/10.18653/v1/2022.naacl-industry.21

Zorzenon, D., Schafaschek, G., Tirpák, D., Moradi, S., Hardouin, L., Raisch, J. (2022). **Implementation of procedures for optimal control of timed event graphs with resource sharing**. IFAC-PapersOnLine 16th IFAC Workshop on Discrete Event Systems, 55, 220–227. https://doi.org/10.1016/j.ifacol.2022.10.346

Zorzenon, D., Komenda, J., & Raisch, J. (2022). **Switched max-plus linear-dual inequalities: Application in scheduling of multi-product processing networks**. IFAC-PapersOnLine 16th IFAC Workshop on Discrete Event Systems, 55, 196–203. https://doi.org/10.1016/j.ifacol.2022.10.343

Zorzenon, D., Komenda, J., & Raisch, J. (2022). **The non-positive circuit weight problem in parametric graphs: A solution based on dioid theory**. Discrete Applied Mathematics, 315, 56–70. https://doi.org/10.1016/j.dam.2022.03.008

Zorzenon, D., Balun, J., & Raisch, J. (2022). **Weak consistency of P-time event graphs.** IFAC-PapersOnLine COSY 2022, 19–24. https://doi.org/10.1016/j.ifacol.2023.01.042

2021

A

Amjadi, A. S., Raoufi, M., Turgut, A. E. (2021). **A self-adaptive landmark-based aggregation method for robot swarms**. Adaptive Behavior, 30(3), 223–236. https://doi.org/10.1177/1059712320985543

B

Bak-Coleman, J. B., Alfano, M., Barfuss, W., Bergstrom, C. T., Centeno, M. A., Couzin, I. D., Donges, J. F., Galesic, M., Gersick, A. S., Jacquet, J., Kao, A. B., Moran, R. E., Romanczuk, P., Rubenstein, D. I., Tombak, K. J., Bavel, J. J. V., Weber, E. U. (2021). **Stewardship of global collective behavior**. Proceedings of the National Academy of Sciences, 118(27). https://doi.org/10.1073/pnas.2025764118

Battaje, A., Brock, O. (2021). **Interconnected recursive filters in artificial and biological vision**. DGR Days 2021, 32–32.

Baum, M., Brock, O. (2021). **Achieving robustness in a drawer manipulation task by using high-level feedback instead of planning.** DGR Days.

Bhatt, A., Sieler, A., Puhlmann, S., Brock, O. (2021). **Surprisingly robust in-hand manipulation: An empirical study**. Proceedings of Robotics: Science and Systems. https://doi.org/10.15607/RSS.2021.XVII.089

Bierbach, D., Francisco, F., Lukas, J., Landgraf, T., Maxeiner, M., Romanczuk, P., Musiolek, L., Hafner, V. V., Krause, J. (2021). **Biomimetic robots promote the 3Rs Principle in animal testing**. ALIFE 2021: The 2021 Conference on Artificial Life. https://doi.org/10.1162/isal_a_00375

Bierbach, D., Wenchel, R., Gehrig, S., Wersing, S., O'Connor, O. L., Krause, J. (2021). **Male sexual preference for female swimming activity in the guppy (Poecilia reticulata)**. Biology, 10(2). https://doi.org/10.3390/biology10020147

C

Chouzouris, T., Roth, N., Cakan, C., Obermayer, K. (2021). **Applications of optimal nonlinear control to a whole-brain network of FitzHugh-Nagumo oscillators**. Physical Review E, 104(2), 24213. https://doi.org/10.1103/PhysRevE.104.024213

Coelho Mollo, D. (2021). **Deflationary realism: Representation and idealisation in cognitive science**. Mind & Language, 1–19. https://doi.org/10.1111/mila.12364

Coelho Mollo, D. (2021). **Why go for a computation-based approach to cognitive representation**. Synthese, 199(3), 6875–6895.

Coelho Mollo, D., Millière, R., Rathkopf, C., Stinson, C. (2021). **Conceptual combinations – benchmark task for beyond the imitation game benchmark**. Github.

D

Daniels, B. C., Romanczuk, P. (2021). **Quantifying the impact of network structure on speed and accuracy in collective decision-making**. Theory in Biosciences. https://doi.org/10.1007/s12064-020-00335-1

Demandt, N., Bierbach, D., Kurvers, R. H. J. M., Krause, J., Kurtz, J., Scharsack, J. P. (2021). **Parasite infection impairs the shoaling behaviour of uninfected shoal members under predator attack**. Behavioral Ecology and Sociobiology. https://doi.org/10.1007/s00265-021-03080-7

Driess, D., Ha, J.-S., Toussaint, M., Tedrake, R. (2021). **Learning models as functionals of signed-distance fields for manipulation planning**. CoRL 2021. https://doi.org/10.48550/arXiv.2110.00792

Driess, D., Ha, J.-S., Toussaint, M. (2021). **Learning to solve sequential physical reasoning problems from a scene image**. The International Journal of Robotics Research, 40(12–14), 1435–1466. https://doi.org/10.1177/02783649211056967

G

Gu, C., Learned-Miller, E., Gallego, G., Sheldon, D., Bideau, P. (2021). **The spatio-temporal Poisson point process: A simple model for the alignment of event camera data**. International Conference on Computer Vision (ICCV), 13495–13504. https://doi.org/10.1109/ICCV48922.2021.01324

K

Kahnau, P., Guenther, A., Boon, M. N., Terzenbach, J. D., Hanitzsch, E., Lewejohann, L., Brust, V. (2021). **Lifetime observation of cognition and physiological parameters in male mice**. Frontiers in Behavioral Neuroscience, 15, 709775. https://doi.org/10.3389/fnbeh.2021.709775

Kirtay, M., Chevalère, J., Lazarides, R., Hafner, V. V. (2021). **Learning in social interaction: Perspectives from psychology and robotics**. 2021 IEEE International Conference on Development and Learning (ICDL), 1–8. https://doi.org/10.1109/ICDL49984.2021.9515648

Kirtay, M., Oztop, E., Asada, M., Hafner, V. V. (2021). **Modeling robot trust based on emergent emotion in an interactive task**. 2021 IEEE International Conference on Development and Learning (ICDL), 1–8. https://doi.org/10.1109/ICDL49984.2021.9515645

K

Kirtay, M., Oztop, E., Asada, M., Hafner, V. V. (2021). **Trust me! I am a robot: an affective computational account of scaffolding in robot-robot interaction**. 2021 30th IEEE International Conference on Robot & Human Interactive Communication (RO-MAN), 189–196. https://doi.org/10.1109/RO-MAN50785.2021.9515494

Klamser, P., Romanczuk, P. (2021). **Collective predator evasion: Putting the criticality hypothesis to the test**. PLOS Computational Biology. https://doi.org/10.1371/journal.pcbi.1008832

Klamser, P. P., Gómez-Nava, L., Landgraf, T., Jolles, J. W., Bierbach, D., Romanczuk, P. (2021). **Impact of variable speed on collective movement of animal groups**. arXiv:2106.00959 [physics, q-bio]. https://doi.org/10.3389/fphy.2021.715996

Krause, J., Romanczuk, P., Cracco, E., Arlidge, W., Nassauer, A., Brass, M. (2021). **Collective rule-breaking**. Trends in Cognitive Sciences.

Kurvers, R. H. J. M., Herzog, S. M., Hertwig, R., Krause, J., Wolf, M. (2021). **Pooling decisions decreases variation in response bias and accuracy**. IScience, 24(7), 102740. https://doi.org/10.1016/j.isci.2021.102740

L

Laskowski, K. L., Seebacher, F., Habedank, M., Meka, J., Bierbach, D. (2021). **Two locomotor traits show different patterns of developmental plasticity between closely related clonal and sexual fish**. Frontiers in Physiology, 12, 740604. https://doi.org/10.3389/fphys.2021.740604

Lazarides, R., Chevalère, J. (2021). **Artificial intelligence and education: Addressing the variability in learners' emotion and motivation with adaptive teaching assistants**. Bildung Und Erziehung, 74(3), 264–279. https://doi.org/10.13109/buer.2021.74.3.264

Lazarides, R., Raufelder, D. (2021). **Control-value theory in the context of teaching: does teaching quality moderate relations between academic self-concept and achievement emotions?** British Journal of Educational Psychology, 91(1), 127–147. https://doi.org/10.1111/bjep.12352

Leonhardt, A., Maier, M., Abdel Rahman, R. (2021). **The impact of affective knowledge on the perception and evaluation of robot faces**. 5th Virtual Social Interactions (VSI) Conference.

Lois-Milevicich, J., Cerrutti, M., Kacelnik, A., Reboreda, J. (2021). **Sex differences in learning flexibility in an avian brood parasite, the shiny cowbird**, 189. https://doi.org/10.1016/j.beproc.2021.104438

Lu, Y., Bierbach, D., Ormanns, J., Warren, W. C., Walter, R. B., Schartl, M. (2021). **Fixation of allelic gene expression landscapes and expression bias pattern shape the transcriptome of the clonal Amazon molly**. Genome Research. https://doi.org/10.1101/gr.268870.120

Lukas, J., Auer, F., Goldhammer, T., Krause, J., Romanczuk, P., Klamser, P., Arias-Rodriguez, L., Bierbach, D. (2021). **Diurnal changes in hypoxia shape predator-prey interaction in a bird-fish system**. Frontiers in Ecology and Evolution, 9. https://doi.org/10.3389/fevo.2021.619193

Lukas, J., Kalinkat, G., Miesen, F. W., Landgraf, T., Krause, J., Bierbach, D. (2021). **Consistent behavioral syndrome across seasons in an invasive freshwater fish.** Frontiers in Ecology and Evolution, 8. https://doi.org/10.3389/fevo.2020.583670

Lukas, J., Romanczuk, P., Klenz, H., Klamser, P., Arias Rodriguez, L., Krause, J., Bierbach, D. (2021). **Acoustic and visual stimuli combined promote stronger responses to aerial predation in fish**. Behavioral Ecology, arab043.

M

Mieske, P., Diederich, K., Lewejohann, L. (2021). **Roaming in a land of milk and honey: Life trajectories and metabolic rate of female inbred mice living in a semi naturalistic environment.** Animals, 11(10), 3002. https://doi.org/10.3390/ani11103002

Monteiro, T., Hart, T., Kacelnik, A. (2021). **Imprinting on time-structured acoustic stimuli in ducklings**, 17. https://doi.org/10.1098/rsbl.2021.0381

Mühlhoff, R. (2021). **Predictive privacy: Towards an applied ethics of data analytics.** Ethics and Information Technology. https://doi.org/10.1007/s10676-021-09606-x

P

Páll, E., & Brock, O. (2021). **Analysis of open-loop grasping from piles.** IEEE International Conference on Robotics and Automation (ICRA), 2591–2597. https://doi.org/10.1109/ICRA48506.2021.9561065

Pischedda, D., Lange, A., Kirtay, M., Wudarczyk, O. A., Abdel Rahman, R., Hafner, V. V., Kuhlen, A. K., Haynes, J.-D. (2021). **Am I speaking to a human, a robot, or a computer? Neural representations of task partners in communicative interactions with humans or artificial agents**. Neuroscience 2021.

Pischedda, D., Lange, A., Kirtay, M., Wudarczyk, O. A., Abdel Rahman, R., Hafner, V. V., Kuhlen, A. K., Haynes, J.-D. (2021). **Who is my interlocutor? Partner-specific neural representations during communicative interactions with human or artificial task partners**. 5th Virtual Social Interactions (VSI) Conference.

Poel, W., Winklmayr, C., Romanczuk, P. (2021). **Spatial structure and information transfer in visual networks**. Frontiers in Physics. https://doi.org/10.3389/fphy.2021.716576

Pütz, O. (2021). **Managing exactness and vagueness in computer science work: Programming and self-repair in meetings**. Social Studies of Science, 51(6), 938–961. https://doi.org/10.1177%2F03063127211010972

R

Raoufi, M., Hamann, H., Romanczuk, P. (2021). **Speed-vs-accuracy tradeoff in collective estimation: An adaptive exploration-exploitation case**. IEEE 2021 International Symposium on Multi-Robot and Multi-Agent Systems (MRS).

Rolfs, M., Schweitzer, R. (2021). **Coupling perception to action through incidental sensory consequences of motor behaviour**. Nature Reviews Psychology, 1, 112–123. https://doi.org/10.1038/s44159-021-00015-x

R

Roth, N., Bideau, P., Hellwich, O., Rolfs, M., Obermayer, K. (2021). **A modular framework for object-based saccadic decisions in dynamic scenes**. CVPR EPIC Workshop / arXiv: 2106.06073. https://doi.org/10.48550/arXiv.2106.06073

Roth, N., Bideau, P., Hellwich, O., Rolfs, M., Obermayer, K. (2021). **Modeling the influence of objects on saccadic decisions in dynamic real-world scenes**. PERCEPTION / 43rd European Conference on Visual Perception (ECVP) 2021.

S

Schmittwilken, L., Matic, M., Maertens, M., Vincent, J. (2021). **BRENCH: An open-source framework for b(r)enchmarking brightness models**. Journal of Vision. https://doi.org/10.1167/jov.22.3.36

Schubert, I., Driess, D., Oguz, O. S., Toussaint, M. (2021). **Learning to execute: Efficient learning of universal plan-conditioned policies in robotics**. NeurIPS 2021. https://doi.org/10.48550/arXiv.2111.07908

Schweitzer, R., Rolfs, M. (2021). **Intrasaccadic motion streaks jump-start gaze correction**. Science Advances, 7(30), eabf2218. https://doi.org/10.1126/sciadv.abf2218

Shurygina, O., Rolfs, M. (2021). **Visual sensitivity and reaction time measures show no evidence for purely exogenous object-based attention**. Journal of Vision / VSS 2021, 2571–2571. https://doi.org/10.1167/jov.21.9.2571

Shurygina, O., Pooresmaeili, A., Rolfs, M. (2021). **Pre-saccadic attention spreads to stimuli forming a perceptual group with the saccade target**. Cortex, 140, 179–198. https://doi.org/10.1016/j.cortex.2021.03.020

Spatola, N., & Wudarczyk, O. (2021). **Ascribing emotions to robots: Explicit and implicit attribution of emotions and perceived robot anthropomorphism.** Computers in Human Behavior, 124, 106934. https://doi.org/10.1016/j.chb.2021.106934

Spatola, N., Chevalère, J., Lazarides, R. (2021). **Human vs computer: What effect does the source of information have on cognitive performance and achievement goal orientation?** Paladyn, Journal of Behavioral Robotics, 12(1), 175–186. https://doi.org/10.1515/pjbr-2021-0012

W

Weber, L., Sänger, M., Garda, S., Barth, F., Alt, C., Leser, U. (2021). **Humboldt@ DrugProt: Chemical-protein relation extraction with pretrained transformers and entity descriptions**. Proceedings of the BioCreative VII challenge evaluation workshop.

Wudarczyk, O. A., Kirtay, M., Kuhlen, A. K., Abdel Rahman, R., Haynes, J.-D., Hafner, V. V., Pischedda, D. (2021). **Bringing together robotics, neuroscience, and psychology: Lessons learned from an interdisciplinary project**. Frontiers in Human Neuroscience, 15. https://doi.org/10.3389/fnhum.2021.630789

Wudarczyk, O. A., Kirtay, M., Pischedda, D., Hafner, V. V., Haynes, J.-D., Kuhlen, A. K., Abdel Rahman, R. (2021). **Robots facilitate human language production**. Scientific Reports, 11(1), 16737. https://doi.org/10.1038/s41598-021-95645-9

Y

Yun, H. S., Chevalère, J., Karl, M., Pinkwart, N. (2021). **A comparative study on how social robots support learners' motivation and learning**. 14th Annual International Conference of Education, Research and Innovation, 2845–2850. https://doi.org/10.21125/iceri.2021.0708

2020

A

Andresen, N., Wöllhaf, M., Hohlbaum, K., Lewejohann, L., Hellwich, O., Thöne-Reineke, C., Belik, V. (2020). **Towards a fully automated surveillance of well-being status in laboratory mice using deep learning: Starting with facial expression analysis**. PLOS ONE, 15(4), e0228059. https://doi.org/10.1371/journal.pone.0228059

B

Bastien, R., Romanczuk, P. (2020). **A model of collective behavior based purely on vision**. Science Advances, 6(6), eaay0792. https://doi.org/10.1126/sciadv.aay0792

Bierbach, D., Krause, S., Romanczuk, P., Lukas, J., Arias-Rodriguez, L., Krause, J. (2020). **An interaction mechanism for the maintenance of fission–fusion dynamics under different individual densities**. PeerJ, 8, e8974. https://doi.org/10.7717/peerj.8974

Bierbach, D., Mönck, H. J., Lukas, J., Habedank, M., Romanczuk, P., Landgraf, T., Krause, J. (2020). **Guppies prefer to follow large (robot) leaders irrespective of own size.** Frontiers in Bioengineering and Biotechnology, 8. https://doi.org/10.3389/fbioe.2020.00441

Botvinik-Nezer, R., Holzmeister, F., Camerer, C. F., Dreber, A., Huber, J., Johannesson, M., Kirchler, M., Iwanir, R., Mumford, J. A., Adcock, A., others, Pischedda, D., others, Schonberg, T. (2020). **Variability in the analysis of a single neuroimaging dataset by many teams**. Nature, 582, 84–88. https://doi.org/10.1038/s41586-020-2314-9

C

Coelho Mollo, D. (2020). **Against computational perspectivalism**. The British Journal for the Philosophy of Science. https://doi.org/10.1093/bjps/axz036

H

Halawa, M., Wollhaf, M., Vellasques, E., Sanchez Sanz, U., Urko Sanz, Hellwich, O. (2020). **Learning disentangled expression representations from facial images**. arxiv and WiCV at ECCV2020. https://doi.org/10.48550/arXiv.2008.07001

J

Jolles, J. W., Weimar, N., Landgraf, T., Romanczuk, P., Krause, J., Bierbach, D. (2020). **Group-level patterns emerge from individual speed as revealed by an extremely social robotic fish**. Biology Letters, 16(9), 20200436. https://doi.org/10.1098/rsbl.2020.0436

K

Kirtay, M., Wudarczyk, O. A., Pischedda, D., Kuhlen, A. K., Abdel Rahman, R., Haynes, J.-D., Hafner, V. V. (2020). **Modeling robot co-representation: state-of-the-art, open issues, and predictive learning as a possible framework**. 2020 Joint IEEE 10th International Conference on Development and Learning and Epigenetic Robotics (ICDL-EpiRob), 1–8. https://doi.org/10.1109/ICDL-EpiRob48136.2020.9278031

L

Landgraf, T., Gebhardt, G. H. W., Bierbach, D., Romanczuk, P., Musiolek, L., Hafner, V. V., Krause, J. (2020). **Animal-in-the-Loop: Using interactive robotic conspecifics to study social behavior in animal groups**. Annual Review of Control, Robotics, and Autonomous Systems. https://doi.org/10.1146/annurev-control-061920-103228

L

Landgraf, T., Moenck, H. J., Gebhardt, G. H. W., Weimar, N., Hocke, M., Maxeiner, M., Musiolek, L., Krause, J., Bierbach, D. (2020). **Socially competent robots: adaptation improves leadership performance in groups of live fish**. arXiv:2009.06633 [cs]. https://doi.org/10.48550/arXiv.2009.06633

Lupyan, G., Abdel Rahman, R., Boroditsky, L., Clark, A. (2020). **Effects of language on visual perception**. Trends in Cognitive Sciences, 24(11), 930–944. https://doi.org/10.1016/j.tics.2020.08.005

M

Meindl, M., Molinari, F., Raisch, J., Seel, T. (2020)**. Overcoming output constraints in iterative learning control systems by reference adaptation.** 21st IFAC World Congress, 53, 1480–1486. https://doi.org/10.1016/j.ifacol.2020.12.1938

Mellmann, H., Schlotter, B., Musiolek, L., Hafner, V. V. (2020). **Anticipation as a mechanism for complex behavior in artificial agents**. Artificial Life Conference Proceedings, 32, 157–159. https://doi.org/10.1162/isal_a_00314

Mühlhoff, R. (2020). **Automatisierte Ungleichheit: Ethik der Künstlichen Intelligenz in der biopolitische Wende des Digitalen Kapitalismus**. Deutsche Zeitschrift Für Philosophie, 6(68). https://doi.org/10.1515/dzph-2020-0059

Mühlhoff, R. (2020). **Prädiktive Privatheit: Warum wir alle „etwas zu verbergen haben". VerantwortungKI – Künstliche Intelligenz und gesellschaftliche Folgen, herausgegeben von Christoph Markschies und Isabella Hermann. Bd. 3/2020.** Berlin-Brandenburgische Akademie der Wissenschaften.

Musiolek, L., Hafner, V. V., Krause, J., Landgraf, T., Bierbach, D. (2020). **Robofish as social partner for live guppies**. Biomimetic and Biohybrid Systems, 270–274. https://doi.org/10.1007/978-3-030-64313-3_26

P

Pischedda, D., Palminteri, S., Coricelli, G. (2020). **The effect of counterfactual information on outcome value coding in medial prefrontal and cingulate cortex: From an absolute to a relative neural code**. The Journal of Neuroscience, 40(16), 3268–3277. https://doi.org/10.1523/JNEUROSCI.1712-19.2020

R

Rahmani, P., Peruani, F., Romanczuk, P. (2020). **Flocking in complex environments–Attention trade-offs in collective information processing**. PLOS Computational Biology, 16(4), e1007697. https://doi.org/10.1371/journal.pcbi.1007697

S

Spatola, N., Wudarczyk, O. A. (2020). **Implicit attitudes towards robots predict explicit attitudes, semantic distance between robots and humans, anthropomorphism, and prosocial behavior: From attitudes to human–robot interaction**. International Journal of Social Robotics.

T

Tump, A. N., Pleskac, T. J., Kurvers, R. H. J. M. (2020). **Wise or mad crowds? The cognitive mechanisms underlying information cascades**. Science Advances, 6(29), eabb0266. https://doi.org/10.1126/sciadv.abb0266

W

Winklmayr, C., Kao, A. B., Bak-Coleman, J. B., Romanczuk, P. (2020). **The wisdom of stalemates: consensus and clustering as filtering mechanisms for improving collective accuracy**. Proceedings of the Royal Society B: Biological Sciences, 287(1938), 20201802. https://doi.org/10.1098/rspb.2020.1802

Y

Yun, H. S., Karl, M., Fortenbacher, A. (2020). **Designing an interactive second language learning scenario: a case study of Cozmo**. Proceedings of HCI Korea, 384–387.

Yun, H. S., Fortenbacher, A., Geißler, S., Heumos, T. (2020). **Towards external regulation of emotions using sensors: Two case studies**. INTED2020, 9313–9320. https://doi.org/10.21125/inted.2020.2576

Z

Zöller, G., Wall, V., Brock, O. (2020). **Active acoustic contact sensing for soft pneumatic actuators**. 2020 IEEE International Conference on Robotics and Automation (ICRA), 7966–7972. https://doi.org/10.1109/ICRA40945.2020.9196916

2019

G

Galbusera, L., Finn, M. T. M., Tschacher, W., Kyselo, M. (2019). **Interpersonal synchrony feels good but impedes self-regulation of affect**. Scientific Reports, 9(1), 14691. https://doi.org/10.1038/s41598-019-50960-0

K

Kurvers, R. H. J. M., Herzog, S. M., Hertwig, R., Krause, J., Moussaid, M., Argenziano, G., Zalaudek, I., Carney, P. A., Wolf, M. (2019). **How to detect high-performing individuals and groups: Decision similarity predicts accuracy**. Science Advances, 5(11), eaaw9011. https://doi.org/10.1126/sciadv.aaw9011

M

Morik, M., Rastogi, D., Jonschkowski, R., Brock, O. (2019). **State representation learning with robotic priors for partially observable environments**. 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 6693–6699. https://doi.org/10.1109/IROS40897.2019.8967938

S

Sosna, M. M. G., Twomey, C. R., Bak-Coleman, J., Poel, W., Daniels, B. C., Romanczuk, P., Couzin, I. D. (2019). **Individual and collective encoding of risk in animal groups**. Proceedings of the National Academy of Sciences, 116(41), 20556–20561. https://doi.org/10.1073/pnas.1905585116

W

Wall, V., Brock, O. (2019). **Multi-task sensorization of soft actuators using prior knowledge**. 2019 International Conference on Robotics and Automation (ICRA), 9416–9421. https://doi.org/10.1109/ICRA.2019.8793697

Y

Yun, H. S., Fortenbacher, A. (2019). **Listen to your body: Making learners aware of their cognitive and affective state.** ICER2019.

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