FOCUS

ORGANIZED CHAOS

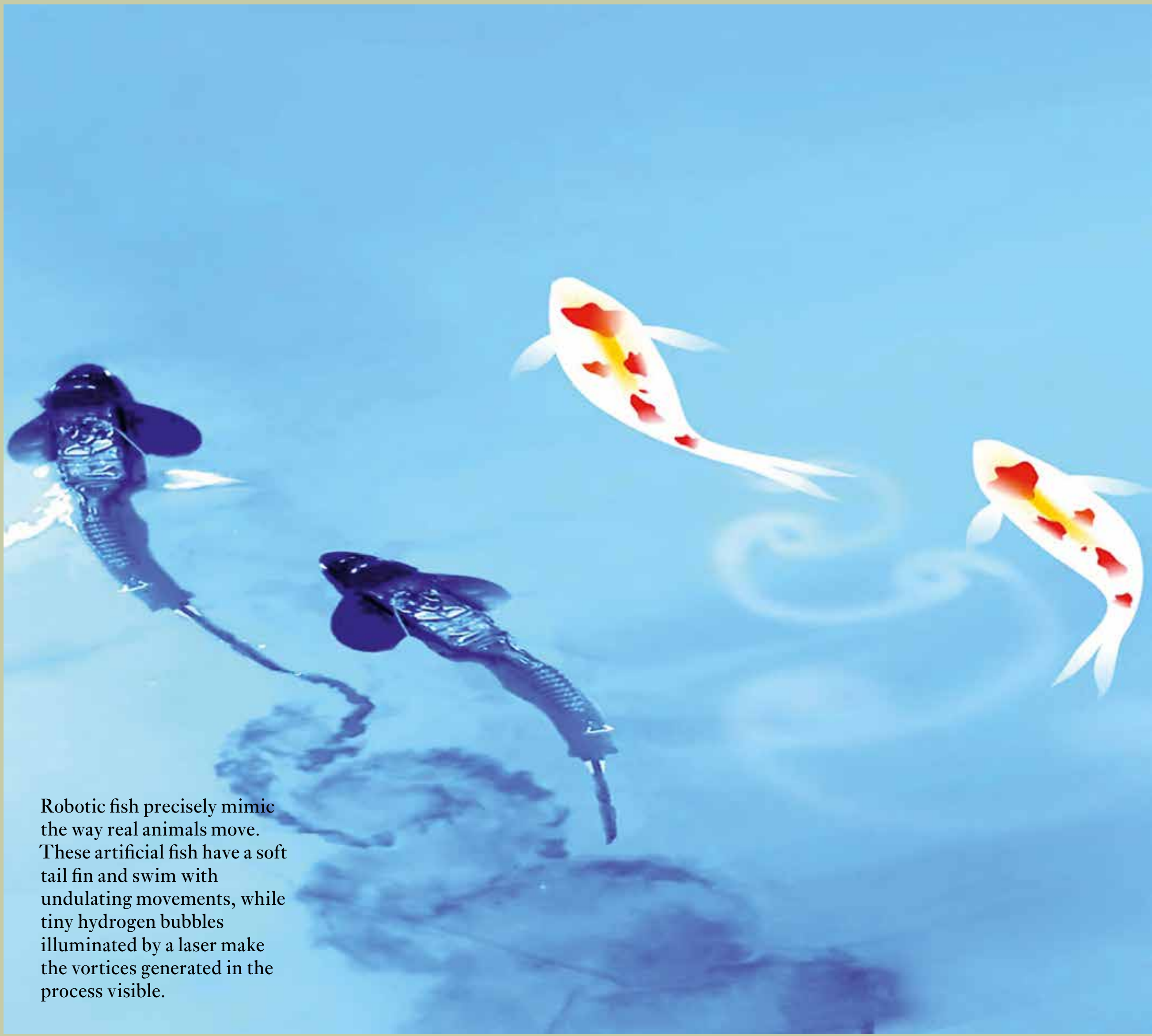


PHOTO: LIANG LI / MPI OF ANIMAL BEHAVIOR

Robotic fish precisely mimic the way real animals move. These artificial fish have a soft tail fin and swim with undulating movements, while tiny hydrogen bubbles illuminated by a laser make the vortices generated in the process visible.

SCHOOL VORTEX

TEXT: HARALD RÖSCH

Iain Couzin, a researcher at the Max Planck Institute of Animal Behavior in Constance, and his team want to discover the rules that schools of fish follow as well as the advantages of life in the collective. Cutting-edge technology is helping the researchers to find order amid the chaos.

PHOTO: IMAGO IMAGES/IMAGEBROKER/H.XREINHARD

In Iain Couzin's laboratory, schools of sunbleak fish swim around tanks of several thousand liters. In the dense, seething mass of fish bodies flitting back and forth, the human eye struggles to follow any individual fish for longer than a few seconds, but thanks to modern, high-performance cameras, automatic image-based tracking, and motion analysis, the researchers working with Iain Couzin are nevertheless able to observe, and even identify, each fish. The apparent chaos within the school is confusing not only to the human eye; for predators, too, it is hard to focus on one specific animal. Although a school like this is easier to find than one single fish, and therefore draws the attention of predators more readily, the sheer quantity of fish offers safety.

Seeing, smelling, and feeling more

Protection is one of the reasons why fish travel through the ocean in often enormous schools. The school not only confuses attackers, but is also more reactive to their environment because thousands of eyes, noses, and pressure sensors can see, smell, and feel more! The first fish in the school to perceive a predator alerts its neighbors by fleeing, setting off a chain reaction. The information travels at lightning speed, and this informational advantage means a school can react up to 15 times faster to an attack than an individual. Large predatory fish aim to prevent this, and the researchers have discovered that some of these animals swim into the school in a row, one behind the other, when they attack in order to divide it up. Prey is then easier to catch in the resulting small groups.

Living in a school also helps with the perception of local differences or gradual changes in salinity, light, or temperature. By living together in a group, the school acquires collective knowledge about its environment and can react to this – knowledge that individual animals do not have. Furthermore, the scientists have discovered that by schooling, an individual can save energy, compared to when swimming alone, because they can recover energy from the water vortices created by the

In good company: sunbleak perfectly demonstrate the advantages of living in a school. The fish, which are around five centimeters long, usually live in still or gently flowing water – for example, in ponds, flooded gravel pits, or swampy ditches.

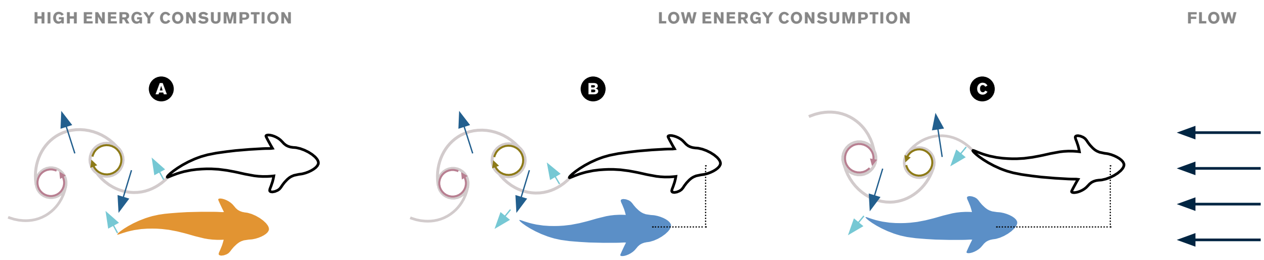
fin strokes of their neighbors, thus making collective swimming more efficient. Researchers had long suspected as much, but Couzin and his team provided the most conclusive evidence to date in 2020. To do so, they engineered biomimetic artificial fish and measured their energy consumption as they swam collectively in a countercurrent pool. Tiny hydrogen bubbles that lit up under laser light revealed the vortices that each fish creates as it swims and that spread backward. The secret to saving energy lies in the synchronization of the tail beats: "The fish swimming behind has to coordinate the beat of its tail fin with that of the animal swimming in front, and this – depending on the distance to the fish in front – results in an optimal phase shift. If the robotic fish swim side-by-side, for example, then their tail fins ideally need to beat synchronously," explains Couzin.

But do real fish behave that way too? The researchers developed a hydrodynamic model that predicts precisely, for example, how two fish swimming together should coordinate their tail beats to do so. And indeed, the animals swim in such a way that they optimally utilize the vortex of their partner, allowing them to save around five percent of the energy they put into swimming. "That's a big deal when you think that locomotion requires a large proportion of the fish's energy," says Couzin. But not only that: if necessary, the animals can then also decide not to save energy, but rather utilize the energy of the vortex to increase their propulsion. This allows trailing fish to speed up more quickly. However, a fish should not be too small if it wishes to benefit energetically from its neighbors. For very small fish, the viscosity of the water is too high. "For them, the water is like honey – they can't make any lasting vortices in it."

With the technologies available today, it has so far only been possible to analyze the interaction of two individuals. Things start to get extremely complicated as soon as a third one is added – let alone a whole school. It is therefore also not yet clear how efficient swimming and defensive behavior against predators influence each other. Does one of the two predominate, or do fish compromise between the two requirements? The behavior of animals in a school appears so perfectly coordinated that you cannot help but suspect there are highly complicated rules that keep the school together, but Couzin and his team have dispelled this misconception. "Animals that live in large groups like this follow relatively simple and effective rules; they don't need to exchange information actively with each other at all. It is enough to react to the movements of their neighbors." Fish swimming very close together, there-

"A school can remember things that a particular animal may never have experienced itself."

IAIN COUZIN



If the force arrows of swimming movements (light blue) and vortices (dark blue) point in different directions, swimming together consumes more energy (A). To save energy, therefore, a fish needs to synchronize its movements with the animal swimming in front so that its vortices assist its own movements (B). If the distance is greater, the tail fin must beat with a greater time lag (C).

GRAPHIC: LI, L., NAGY, M., GRAVING, J.M. ET AL. VORTEX PHASE MATCHING AS A STRATEGY FOR SCHOOLING IN ROBOTS AND IN FISH. NAT COMMUN 11, 5408 (2020)

fore, repel each other and thus avoid collisions, while individuals located further away are drawn towards the others. These are the rules that govern the direction the fish swim in. "Always stay close to the other members of the school, but don't get too close to them – then you automatically swim in the same direction as them."

Couzin and his team have also discovered that, contrary to conventional wisdom, the middle of a school is often not the best position to have at all. The animals swimming at the front and the sides get information from other members of the school on the one hand, but at the same time, they have direct access to information about occurrences outside of the group, such as the appearance of a predator. The worst place is at the back, which leads to the animals there constantly attempting to leave this risky position and therefore remaining permanently on the move.

The researchers have also found out that fish follow the majority principle – even though they themselves cannot count. If ten fish swim to the right and eight to the left, then the school generally opts to go right. Surprisingly, some mammals behave in a similar way. Together with Couzin's colleagues Meg Crofoot and Ariana Strandburg-Peshkin, the researchers have equipped a herd of free-ranging baboons in Kenya with GPS transmitters and used them to determine the position of each individual animal over a period of weeks. Evaluation of the data revealed that the direction the animals choose to travel depends on the angle at which two leading baboons move away from each other. If the angle is less than 90 degrees, then the following animals compromise and head for the middle. If, however, the angle is greater than 90 degrees, the baboons take the direction preferred by the majority of group members. The dominant animal can only follow suit *(Max Planck Research 02/21)*.

The individuals in many fish schools do not know each other; they are usually not related and do not form lasting relationships. Previously, it was assumed that fish within a school are entirely anonymous and egalitarian. However, the findings of Iain Couzin and his team challenge these notions. The researchers have developed machine learning algorithms that can identify individual fish even when they look completely the same to us humans. The research shows that, surprisingly, schools are not uniform in structure, but exhibit previously unknown internal structures. The fact that a school is a self-organizing system does not, therefore, mean that all individuals have the same influence on its behavior. Despite a lack of any obvious hierarchy, the analysis reveals some individuals are more important than others. Fish at the edge of the school are the first to react to changes, for example, to an attacker, and thus dictate the group's direction of motion for several seconds. Some individuals, meanwhile, swim faster than others and, as a result, can lead the school for longer periods, for example, when searching for food. Such individual differences have hardly been studied so far, yet they give structure to a seemingly uniform group and have a massive influence on its behavior.

SUMMARY

Life in a school offers a host of benefits for fish: it protects them from predators, among other things, saves energy as they swim, and improves perception.

Schools of fish form according to simple rules: individuals who seek proximity to one another but simultaneously always maintain a minimum distance all swim in the same direction and therefore stay together. They thus form a school.

A school is more than the sum of its individuals. It can acquire collective intelligence that the individual animal does not have.

The wisdom of the many: Angela Albi, Eduardo Sampaio, Kajal Kumari, Iain Couzin, and Lior Lebovich (left to right) enjoy discussing their ideas on school behavior collectively.

PHOTO: INES JANAS FOR MPG

Making better decisions together

Together with colleagues from the Universities of Konstanz and Cambridge, Couzin used sticklebacks to study the influence of individual differences on group behavior. The researchers analyzed the behavioral patterns of multiple individuals in various environments. Then they placed the fish together in groups and observed how the animals found and utilized sources of food. The results show that the individuals that spent more time close to members of the same species were slower, more likely to stay in the center of the group, and also tended to follow other fish. A group consisting primarily of such individuals held together more closely but moved about less and with poorer coordination. Meanwhile, groups of individuals less concerned with proximity to members of the same species held together more poorly but swam faster. This raises the question of "personalities" in fish. Why do some swim faster than others? Are they braver? Are some of them perhaps more altruistic, while others are clearly more concerned with their own advantage and exploit their neighbors in the school? "Personally, I'm less inclined to talk about 'personalities' in fish, because I think this kind of term is not very helpful for describing relatively simple differences. Ultimately, we still don't know whether an individual swims faster because it is braver or because it is simply bigger or stronger," says Couzin. Regardless of how one might describe the differences among the members of the school, a few small variations are enough to influence decision-making, both of an individual and an entire school.

A large number of interconnected units that share information with each other and can thus make better decisions as a collective – isn't that reminiscent of how the brain works? "That's right. Our experiments with schooling fish have shown that it is not only the brain of the fish that processes information but also the school as a whole. How reliably the school reacts to an attacker, for example, depends not on the sensitivity of the individual fishes but rather on their position in relation to, and distance from, one another: they need to see each other as well as possible to be able to pass on information optimally. Nerve cells in our brains follow the same principle," says Iain Couzin. If the connection between the individuals or the nerve cells changes, then this also affects the flow of information between them, and this can lead to changes in the behavior of the entire system. According to the researchers, fish in a school can thus react earlier to dangers without increasing the risk of false alarms. In contrast, overly sensitive fish or neurons that react to even the smallest sign of danger would trigger mass false alarms.

In this way, schools of fish and other groups of animals develop abilities not possessed by individual animals. The school is therefore more than the sum of its parts

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– and this, too, is an analogy to the brain and likewise constitutes the basis of the "wisdom of the many" often cited in connection with the internet. The knowledge of the individuals – some of which is subject to errors – all adds up to a fairly accurate reflection of reality. "This means a school can develop a collective memory and remember things that a particular animal may not have experienced itself," explains Couzin. This kind of "collective mind" is also known from state-forming animals such as ants and bees, but unlike these insects, the fish in a school are only rarely related to each other. Therefore, evolution cannot optimize the school itself, but only its individuals.

It is well known, however, that the wisdom of the many is not infinite. Iain Couzin and his former doctoral researcher Albert Kao, who has recently started leading his own research team in Boston, have demonstrated that the informational advantage brought by life in a school declines again above a group size of fifteen to twenty individuals. Why, then, do some species form schools of many thousands of individuals? "Contrary to how it may seem at first glance, many large groups are not uniformly structured, but are rather heterogeneous, meaning that they include subgroups. Large herds of elephants, for example, consist of different families and clans," says Couzin. These kinds of group structures can prevent the flow of information from breaking down.

School code cracked

Thanks to the analytical tools they developed, the researchers are able to reveal piece by piece how fish coordinate their behavior in the school. This also provides indications of how humans might apply these rules to effectively coordinate swarms of autonomous vehicles such as drones. "I believe we have finally cracked the code, and it tells us that the rules developed by nature are probably just as good as those created by humans, but much simpler and more robust.

PHOTO: INES JANAS FOR MPG

The way to save: flow experiments with robotic fish show that energy consumption drops when they swim together.

PHOTO: INES JANAS FOR MPG

Our studies of fish could therefore soon have an impact on our day-to-day lives." What is not yet clear is whether schools of fish also exhibit such structures. Couzin and his team aim to close this knowledge gap and hope their latest development will help: software based on artificial intelligence that is able to track the movements of each individual fish in a school. "We don't have to mark the animals in advance. Our algorithm can identify each individual and measure its route – something that will revolutionize research into collective animal behavior," says Couzin. Schools of fish have been roaming the world's oceans for millions of years – defying predators and environmental changes. Recently, however, a new player has appeared on the scene that doesn't play by the rules: Homo sapiens. In the face of fishing trawlers with nets that are often kilometers long, even huge schools offer no protection – quite the contrary, as they attract the fishing fleets all the more. Many fish stocks have therefore collapsed.

What holds the school together at its core: Project Leader Liang Li uses sophisticated technology to reveal the rules according to which fish coordinate their collective behavior.

The numbers of other animals that form groups have also plummeted: birds, large mammals, insects. What this means for the survival of these species cannot yet be foreseen. There may, for example, be a threshold value below which there are no longer enough individuals to form a school, meaning a species could then become extinct, even though there are still many thousand individuals remaining. "Research into animal collectives thus helps with species conservation," says Iain Couzin. Whether schools of fish will still be swimming through the world's oceans in the future is therefore highly uncertain. It is certainly to be desired – and not only because, in coming together, they perfectly symbolize the power of the small and defenseless.

www.mpg.de/podcasts/schwarm (in German)