One algorithm to rule spatial decision-making

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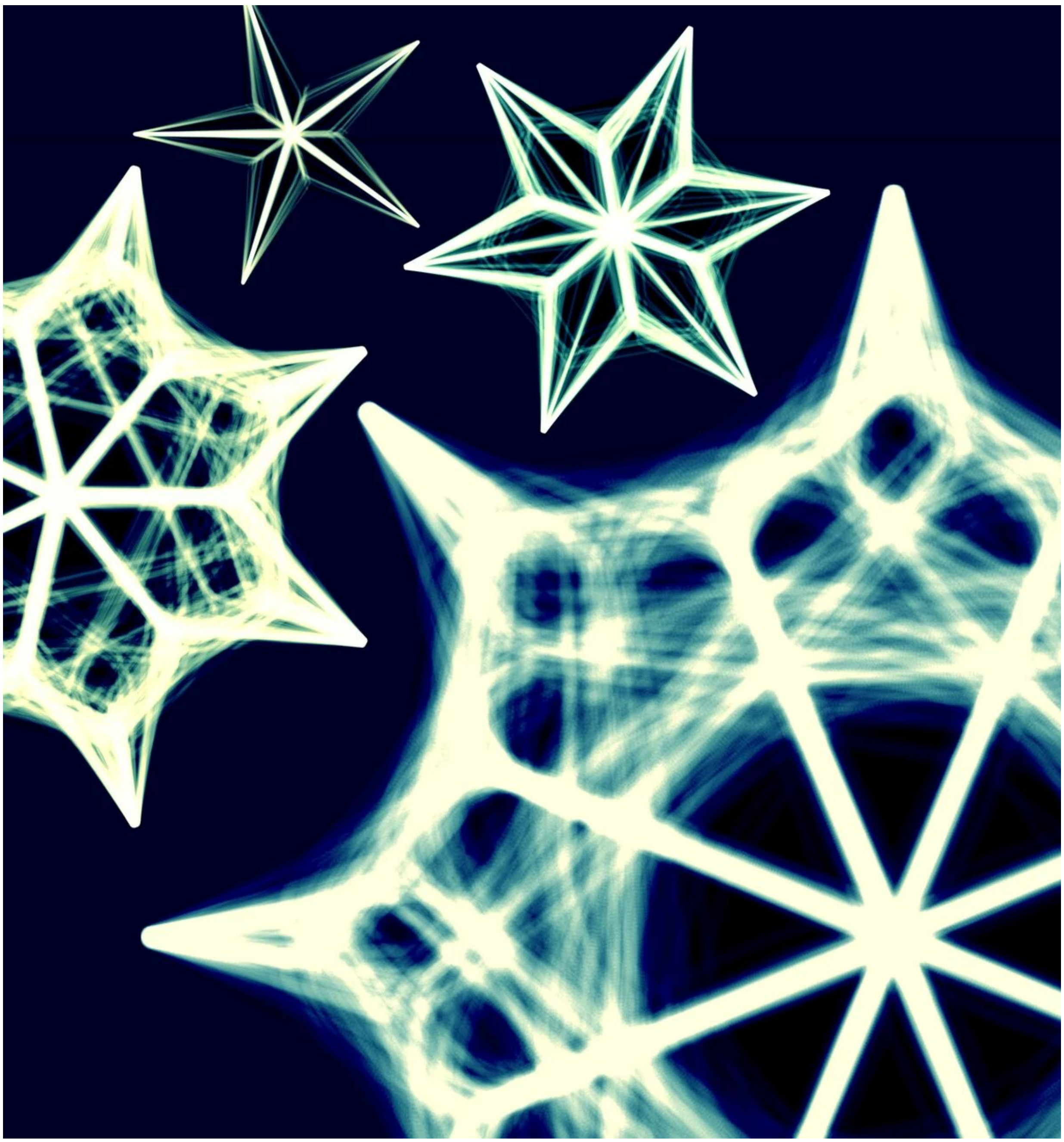

Computer simulations show that the same geometric principals govern spatial decision-making in animals as diverse as insects and fish. Credit: MPI of Animal Behavior/ Vivek Sridhar

An international team led by researchers from the University of Konstanz and Max Planck Institute of Animal Behavior in Germany have employed virtual reality to decode the algorithm that animals use when deciding where to go among many options. The study reveals that animals cope with environmental complexity by reducing the world into a series of sequential two-choice (binary) decisions—a strategy that results in highly effective decision-making no matter how many options there are. The study offers the first evidence yet of a common algorithm that governs decision-making across species and suggests that fundamental geometric principles can explain how, and why, animals move the way they do.

For most animals, life is about deciding where to go. Running, swimming, or flying through the world, animals are constantly making decisions while on the move—decisions that allow them to choose where to eat, where to hide, and with whom to associate. Breakthroughs in neurobiology over the past decades, including those awarded the 2014 Nobel Prize in Medicine, have pieced together a picture of how animals represent spatially-distributed options. Now, an international team of researchers have applied this neurobiological knowledge to understand how animals choose among options scattered in space. "Animals' neural representations of options inevitably change as they move through space," says Vivek Hari Sridhar, first author on the study and a post-doc at the Max Planck Institute of Animal Behavior in Konstanz. "We show that considering this in our understanding of spatial decision-making reveals new and fundamental geometric principles that were, until now, overlooked."

Biologists, engineers, and physicists from Germany, the Weizmann Institute of Science in Israel, and Eötvös Loránd University in Hungary collaborated on the study. Drawing inspiration from neurobiology, physics and animal behavior, the interdisciplinary team constructed a computational model of decision-making in the brain. The model took features of how the brain represents options in "space"—in this case direction to potential destinations—in order to understand how decisions are made on the move. "Taking into account the interplay between movement and the neural dynamics was key," says Sridhar, who conducted his work as a Ph.D. student in the Department of Collective Behavior at the University of Konstanz and the Max Planck Institute of Animal Behavior. "It allowed us to gain a new perspective about how the brain makes decisions."

Spontaneous bifurcations

The resulting model predicted that the brain spontaneously breaks down decisions among multiple options to a series of two-choice decisions until only one option—the one ultimately selected—remains. This was found to result in animals exhibiting a series of abrupt changes in direction, each associated with the exclusion of one of the remaining options. Each change of direction was a result of sudden changes in neural dynamics—a property scientists call a "bifurcation"—at very specific geometrical relationships between the animal and the remaining options.

The algorithm was found to be so robust that the researchers predicted, not only would this "bifurcation" process result in highly accurate decisions, but also that it could be 'universal." By overlaying many trajectories of their simulated animals, they found a branching structure that should, they expected, also be apparent if they overlaid many trajectories taken by real animals making spatial decisions.

Validating their theory

The team used immersive virtual reality to test their theoretical predictions in flying, walking, and swimming animals—the fruit fly, desert locust, and zebrafish, respectively. This technology allowed the scientists to place the animals in open, photorealistic, environments while simultaneously having precise measurements of the animals' movements during decision-making. All species were found to exhibit exactly the same bifurcations as had been predicted.

"It is often thought that animals first decide where to go and then they move to the target," says Sridhar. "But our findings show that the interplay between movement and the changing neural representation of options considerably impacts how decisions are made. What is so exciting about these findings is that this response yields extremely effective decision-making in complex and diverse ecological contexts."

From individuals to collectives

The scientists also found that the same geometric principles likely apply to spatial decision-making by animal collectives, such as mobile herds or flocks. Iain Couzin, senior author and co-Director of the Cluster of Excellence "Centre for the Advanced Study of Collective Behavior' at the University of Konstanz and Director at the Max Planck Institute of Animal Behavior says: "It is remarkable to see such a beautiful process underlying decision-making across vast scales of biological organization, from neural dynamics to individual decisions, and from individual decisions to collective movement. This is transforming our understanding of how animals make sense of their rich and complex world."

More information: Vivek H. Sridhar et al, The geometry of decision-making in individuals and collectives, *Proceedings of the National Academy of Sciences* (2021). DOI: 10.1073/pnas.2102157118

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