From interactions rules to critical states in schooling fish

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Abstract: Understanding how animal groups achieve coordination remains a fundamental challenge in behavioral biology. Schooling fish provide a model system where collective dynamics can be quantified and linked to precise interaction rules at the individual scale. In our work with rummy-nose tetras (*Hemigrammus rhodostomus*), we show that complex group-level patterns emerge from surprisingly simple mechanisms. By disentangling alignment and attraction behaviors from high-resolution trajectories, we identified the functional forms of individual interactions and showed how they govern swimming coordination. Building on these results we developed an experimentally grounded model that reproduces not only the spontaneous motion of isolated fish but also the coordinated dynamics of pairs. We also showed that in this species, collective patterns such as cohesion and polarization can be reproduced when individuals consider only one or two most influential neighbors. This selective focus reduces cognitive load while maintaining robust group structure. Finally, through experiments combining light-induced stress with computational modeling, we revealed that fish schools tune the strength of social interactions to approach critical states. Near criticality, groups maximize responsiveness and adaptability, ensuring rapid adjustment to environmental challenges. Together, our studies reveal that coordination of collective motion in fish relies on the combination of minimal interaction rules, perceptual filtering, and stress-induced modulation of social forces to produce critical states that enhance group performance. These insights not only

advance our understanding of self-organization in animal societies but also provide inspiration for the design of efficient, bio-inspired algorithms in robotics and distributed artificial systems.

Bio: Guy Theraulaz is a senior research fellow at the CNRS and an expert in the study of collective animal behavior. He is also a leading researcher in the field of swarm intelligence, primarily studying social insects but also distributed algorithms, e.g. for collective robotics, directly inspired by nature. His research focuses on understanding a broad spectrum of collective behaviors in animal societies by quantifying and then modeling individual-level behaviors and interactions, thereby elucidating the mechanisms generating emergent group-level properties. He was one of the main figures in the development of quantitative social ethology and collective intelligence in France. He has published extensively on nest construction in ant and wasp colonies, collective decision-making in ants and cockroaches, and collective motion in fish schools and pedestrian crowds. He has also coauthored five books, among which “Swarm Intelligence: From Natural to Artificial Systems” (Oxford University Press, 1999) and “Self-organization in Biological Systems” (Princeton University Press, 2001), which are now considered reference textbooks.

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