

Bio-inspired model for auto-organized motion of a swarm of UAVs

Matthieu Verdoucq

*Ecole Nationale de l'Aviation Civile
Université de Toulouse, 31400 Toulouse, France*

*Centre de Recherches sur la Cognition Animale
Centre de Biologie Intégrative
CNRS, UMR 5169, Toulouse, France*



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Intelligent Robots and Systems (IROS 2023)
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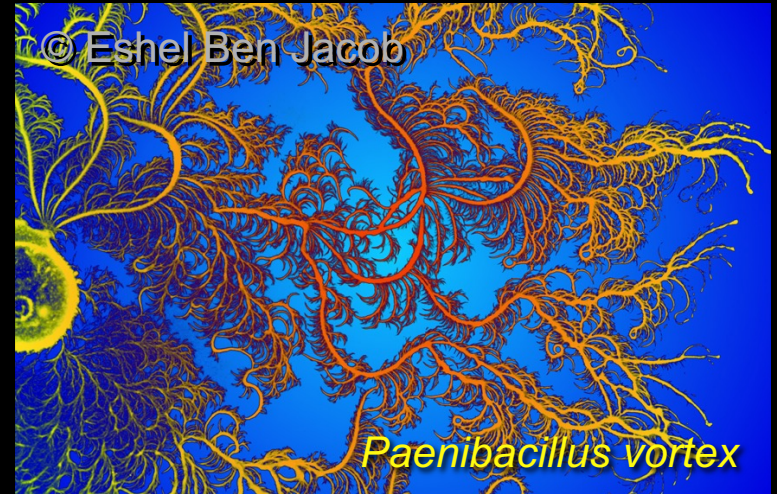


Collective motion in groups of organisms

How do individuals coordinate their movements?



Sturnus vulgaris



Paenibacillus vortex



Caranx sexfasciatus



Collective motion in fish schools

Collective states emerging from social interactions between fish



*Océans, (2010)
Directed by
Jacques Perrin,
Pathé Distribution*



Milling

Sphyraena barracuda

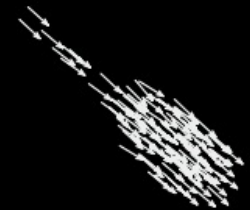
swarm



mill



school

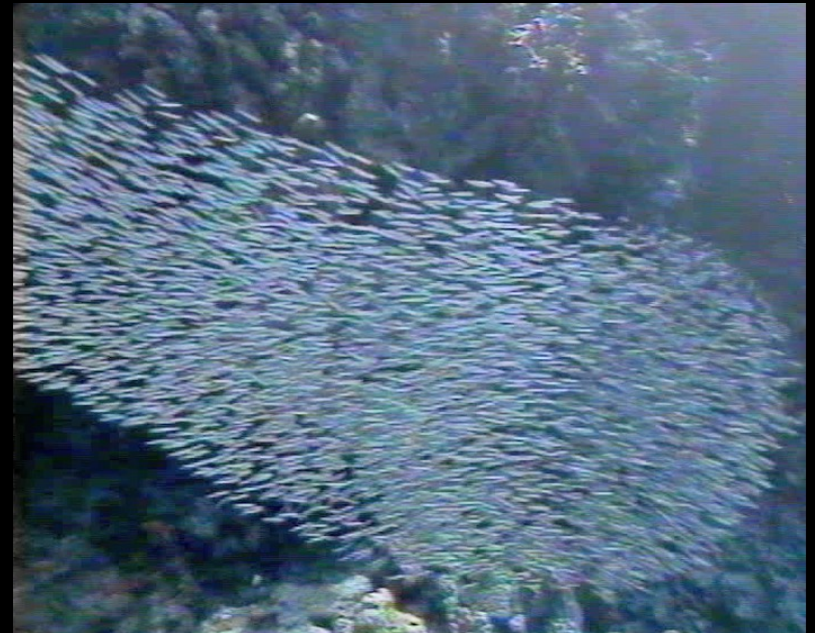


Gautrais, J. et al., *Ann. Zool. Fennici* (2008)

Lopez, U. et al., *Interface Focus* (2012)

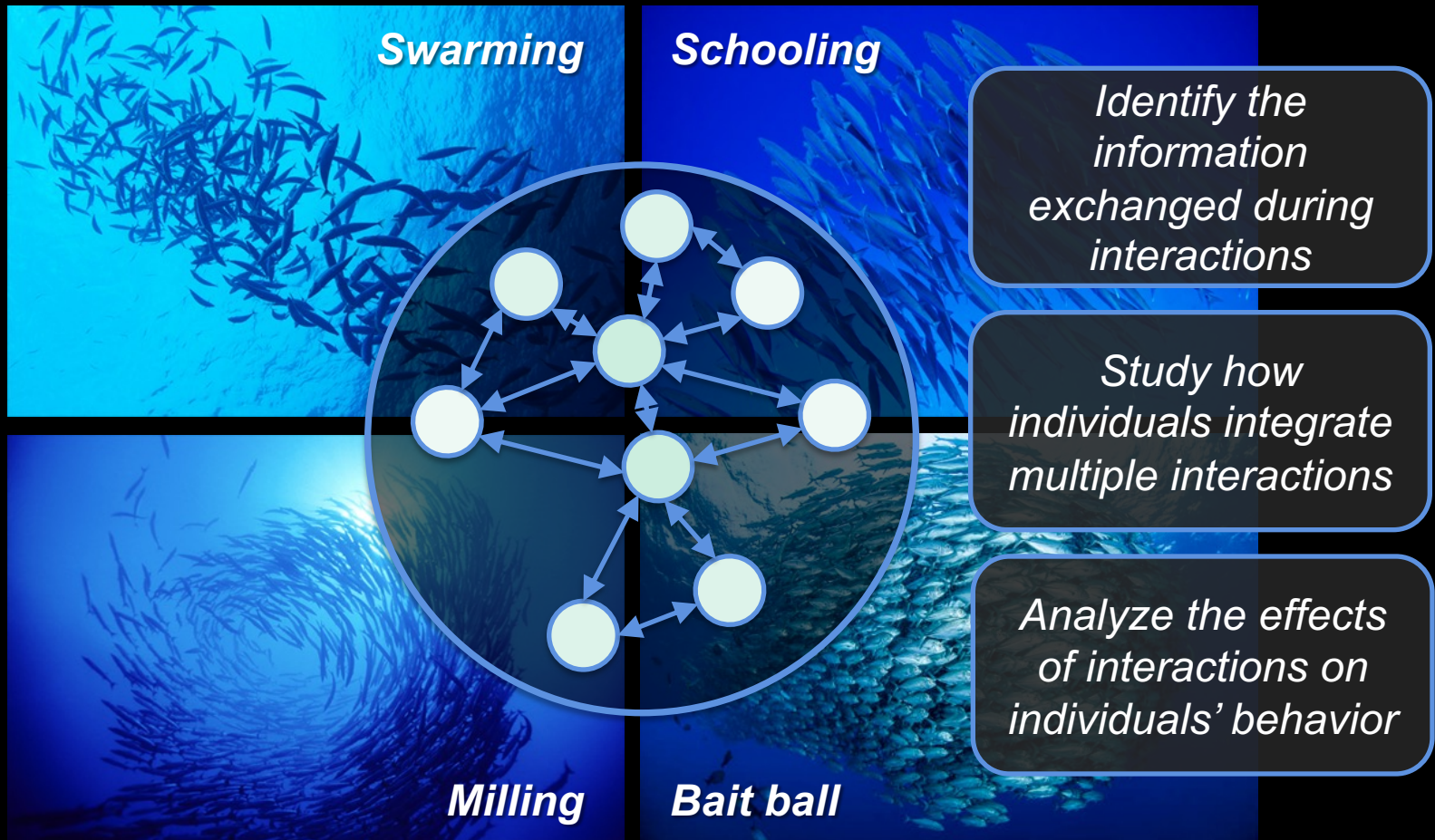
Collective motion in fish schools

Schooling manoeuvres in response to predator attacks



Collective motion in fish schools

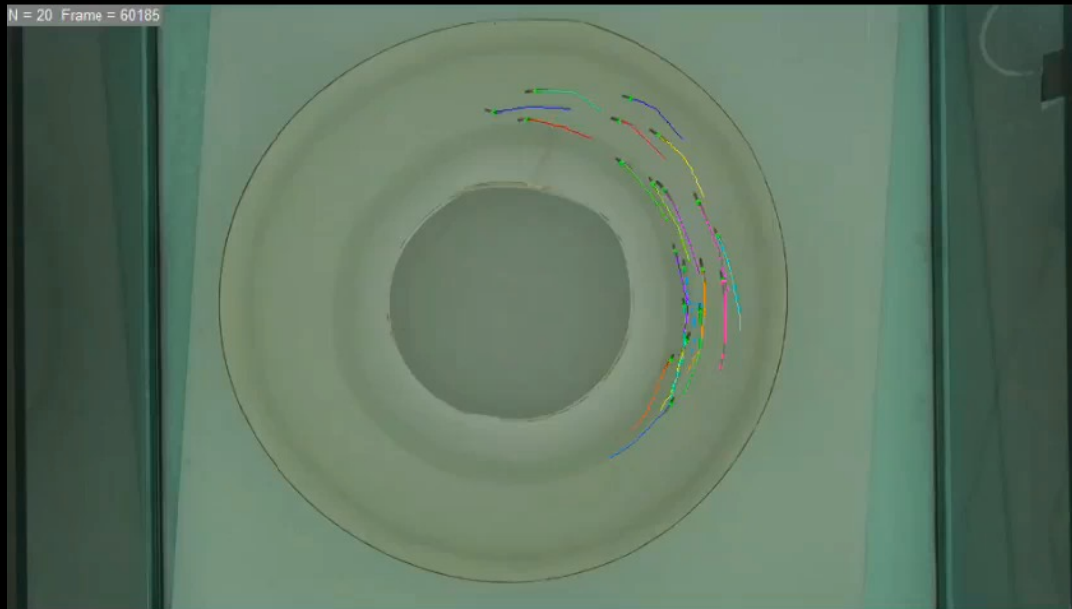
Collective patterns emerging from interactions between fish



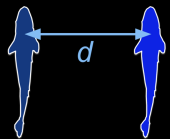
What are the interactions rules and behavioral mechanisms involved in the coordination of collective motion?

How do group-level properties emerge?

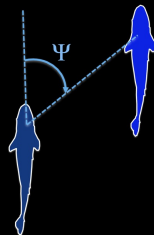
Automated tracking of animal movement and behaviour



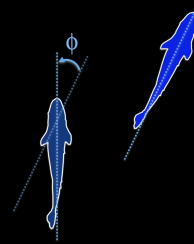
Hemigrammus rhodostomus



Distance



Angular
position

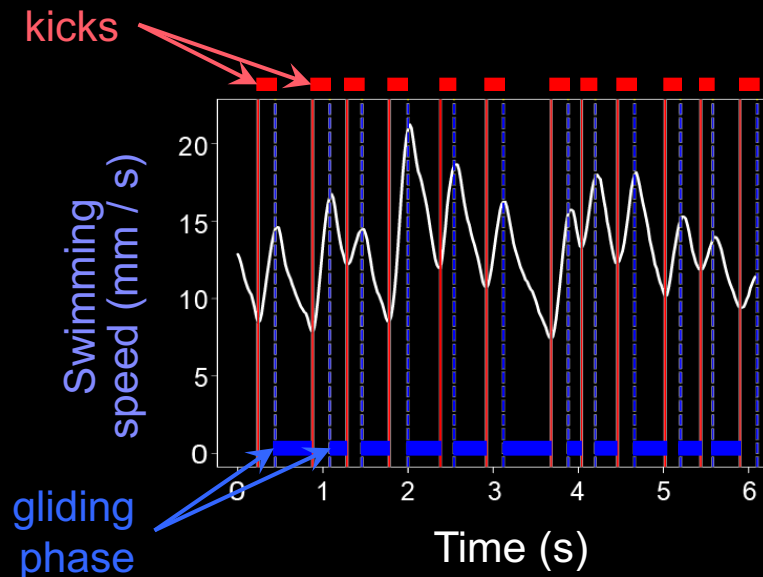
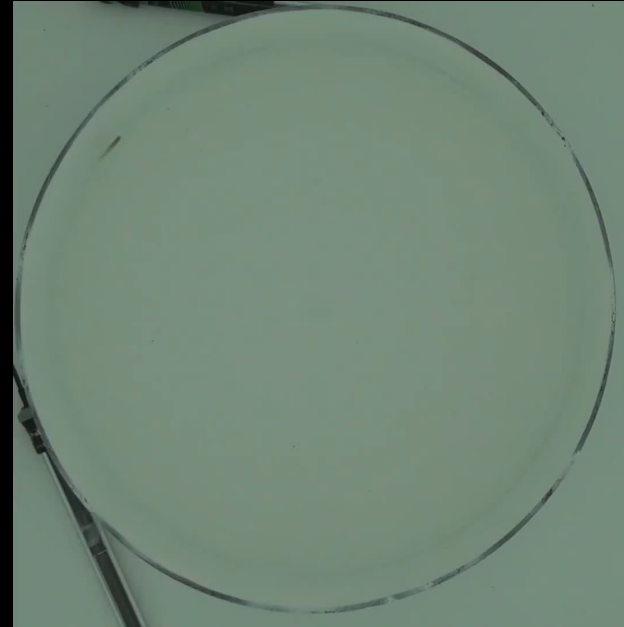
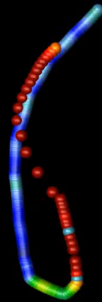


Relative
heading

Pérez-Escudero, A. et al., *Nat. Methods* (2014)
Lecheval, V. et al., *Proc. R. Soc. B* (2018)

Characterization of individual swimming behavior

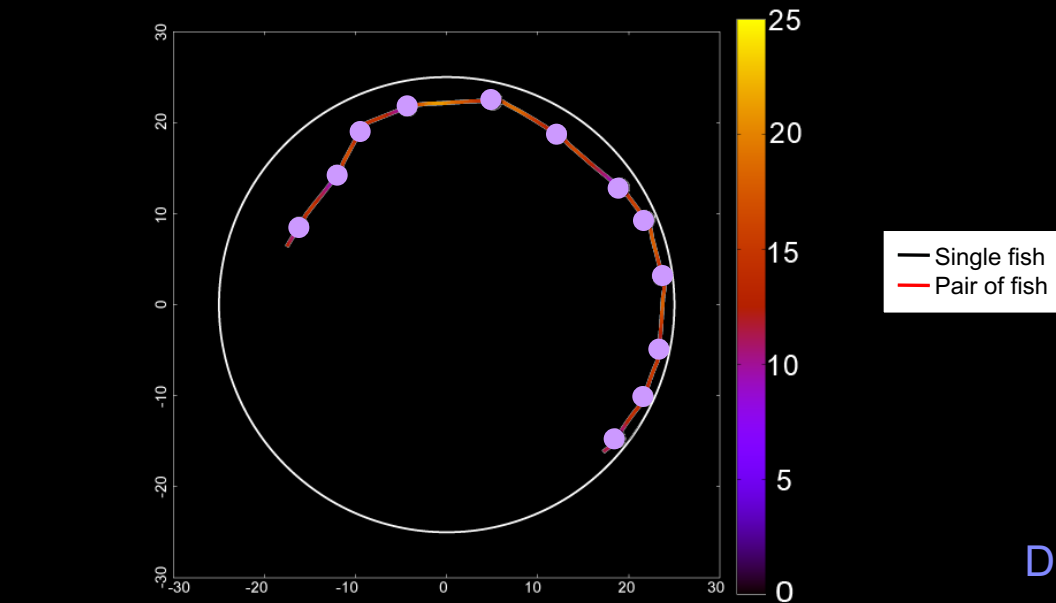
Burst-and-coast swimming



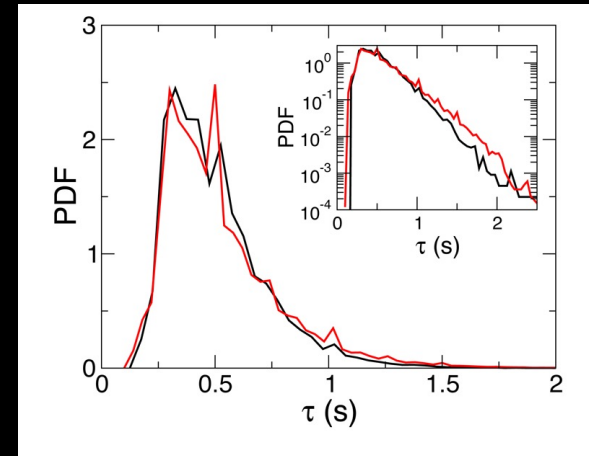
- *Hemigrammus rhodostomus* performs burst and coast swimming
- Each monotonous increase of velocity higher than 1cm/s is identified as a « kick »

Characterization of individual swimming behavior

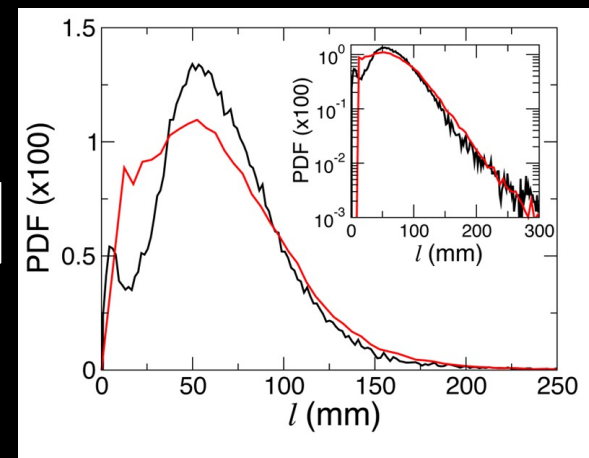
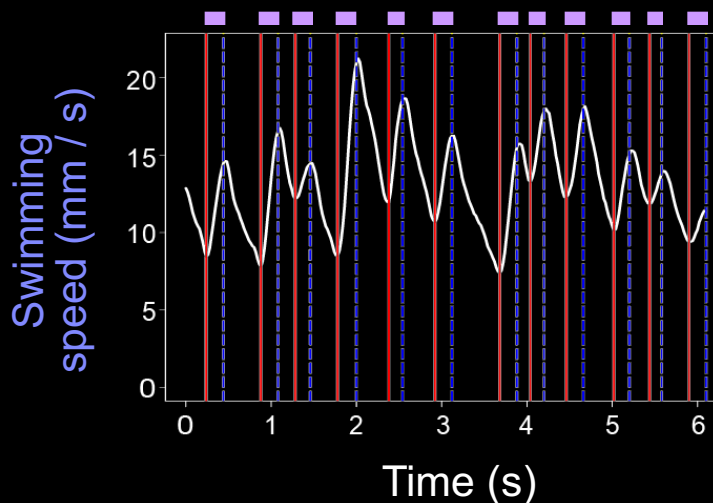
Duration and distance traveled by a fish between two kicks



Duration between two kicks



Distance travelled between two kicks



Measuring and modeling fish interaction with the wall

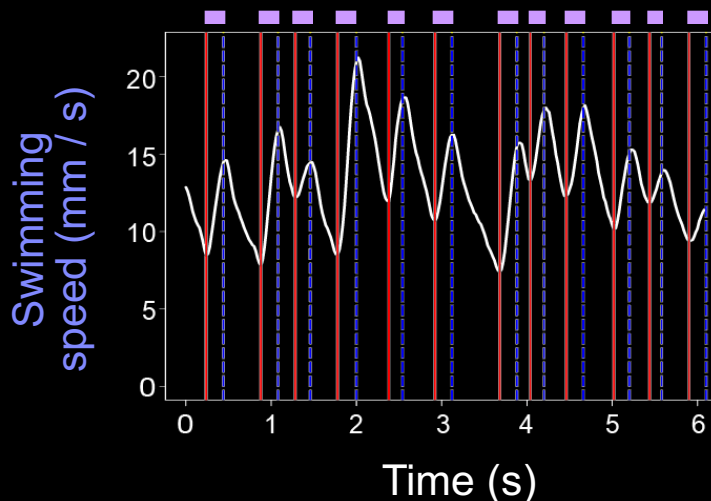
Reconstructing the stimulus-response functions

PHILOSOPHICAL
TRANSACTIONS B

royalsocietypublishing.org/journal/rstb

A data-driven method for reconstructing and modelling social interactions in moving animal groups

R. Escobedo¹, V. Lecheval³, V. Papaspyros⁴, F. Bonnet⁴, F. Mondada⁴, C. Sire² and G. Theraulaz^{1,5}



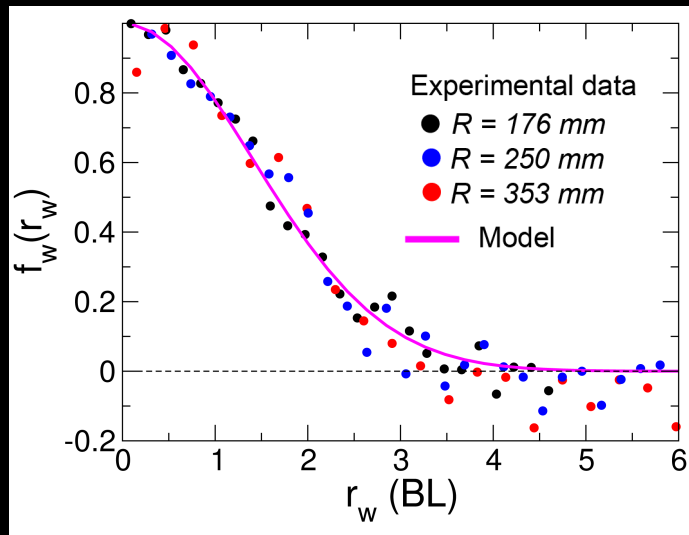
$$\delta\phi_w(r_w, \theta_w) = f(r_w) g(\theta_w)$$

- The heading variations of a fish result from the product of two decoupled functions of θ_w et r_w

Measuring and modeling fish interaction with the wall

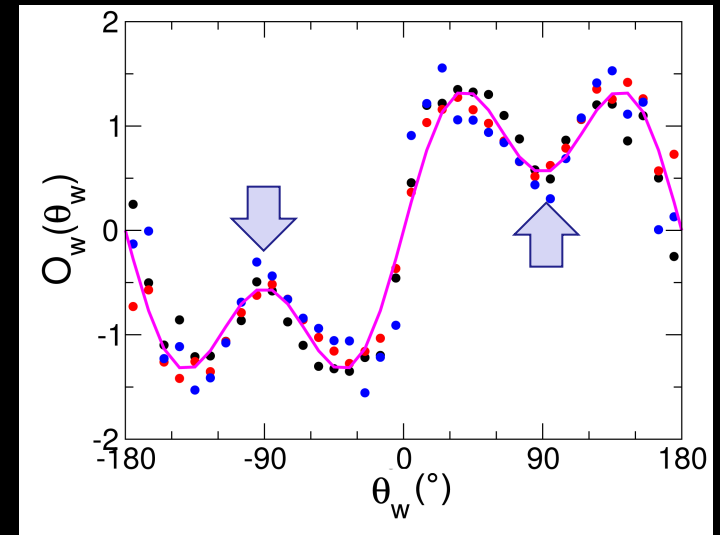
Extraction of interactions functions from trajectory data

Reaction of fish as a function of the distance to the wall



$$f_w(r_w) \propto \exp[-(r_w / l_w)^2]$$
$$l_w \approx 2 \text{ BL} \sim 60 \text{ mm}$$

Reaction of fish as a function of its relative orientation to the wall



$$O_w(\theta_w) \propto \sin \theta_w [1 + \epsilon_2 \cos 2\theta_w]$$
$$\epsilon_2 \approx 0.7$$

Modeling single fish behavior and wall avoidance

Model description

- **1.** Fish randomly select an initial velocity and gliding time from the experimental distribution and define

$$l = v\tau_0 \left[1 - \exp(-\tau/\tau_0) \right] \quad (\tau_0 \approx 0.7s)$$

- **2.** Change the direction of the fish by an angle $\delta\phi$ with

$$\delta\phi = \delta\phi_R + \delta\phi_w$$

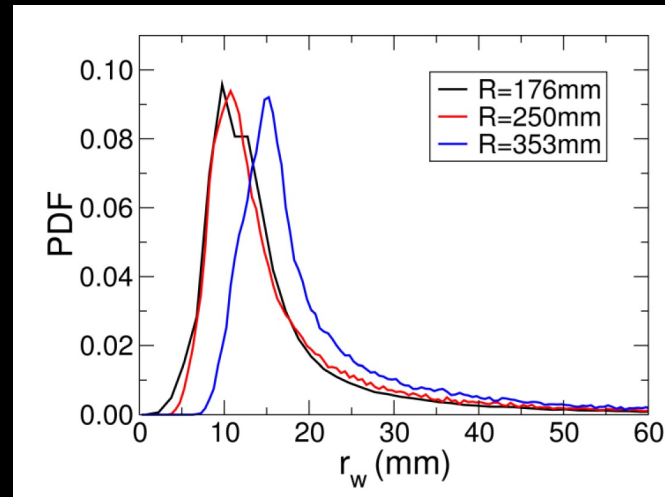
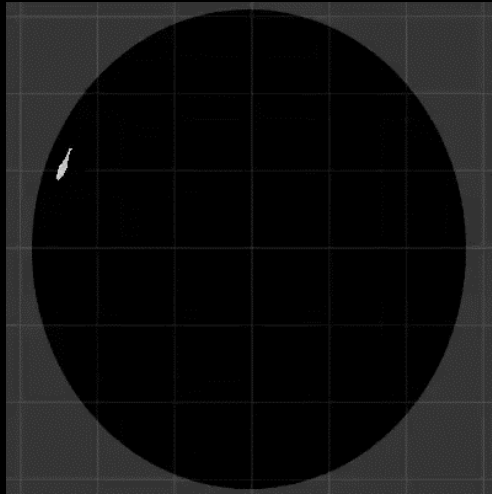
- **3.** Move over a distance of length l in the new direction
- **4.** Accept the move if the fish is still in the tank
- **5.** If not redraw $\delta\phi_R, v, \tau$

Simulations of the model

Spatial distribution and motion of a fish swimming alone

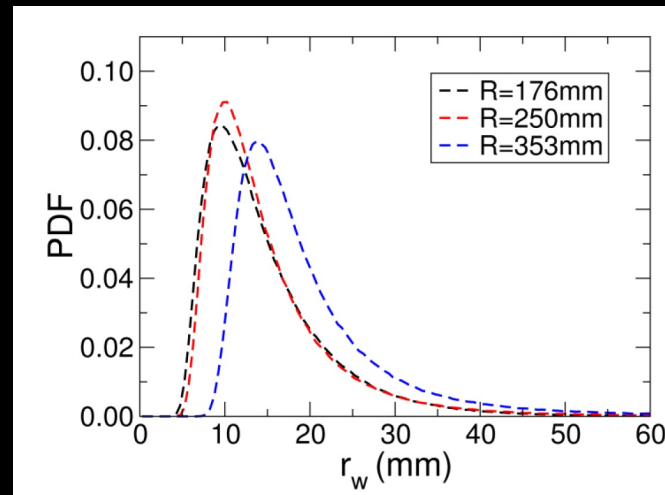
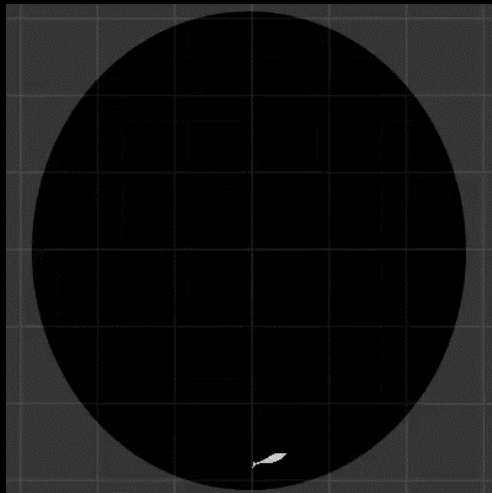
Distances of fish to the wall

Experiment



30 experiments
($3 \cdot 10^5$ kicks)

Model

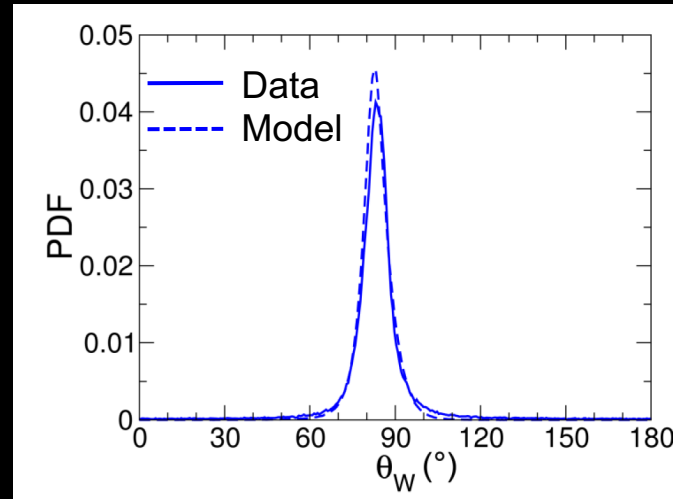
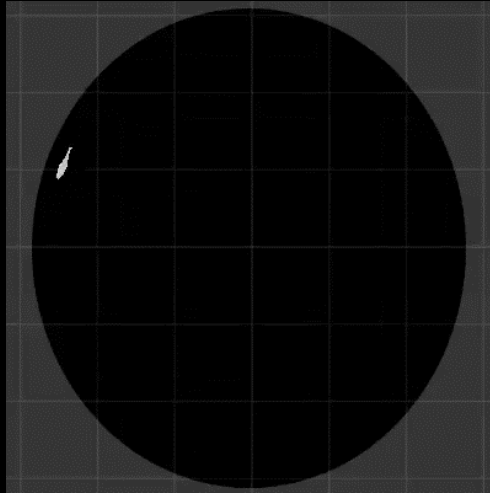


100 simulations
(10^6 kicks each)

Simulations of the model

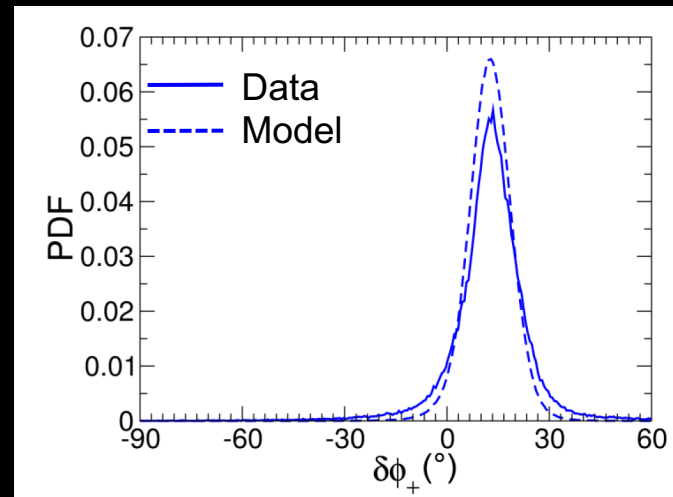
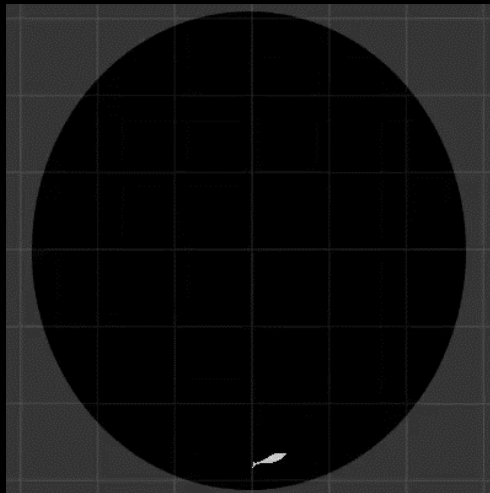
Spatial distribution and motion of a fish swimming alone

Experiment



Relative orientation of the fish to the wall

Model

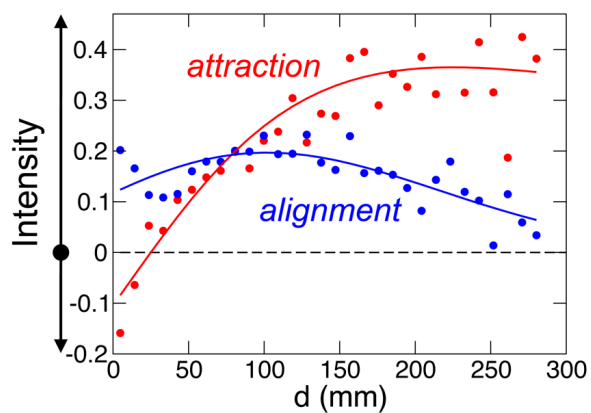


Heading changes of fish in the 353 mm diameter arena

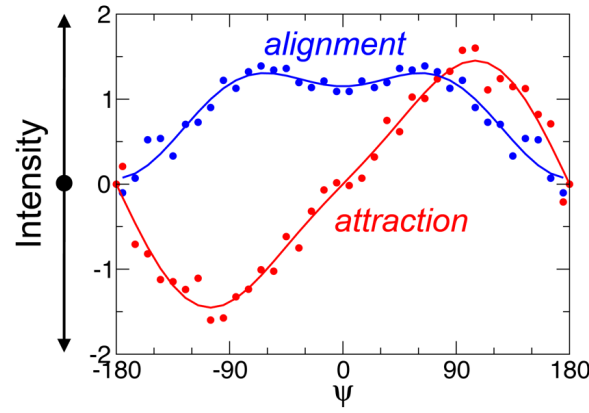
Measuring and modeling social interactions

Attraction and alignment between two fish

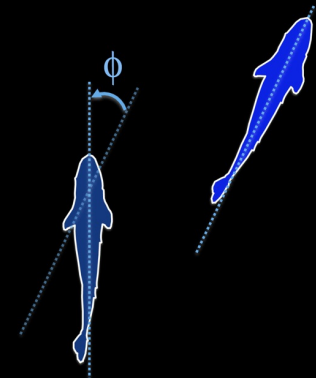
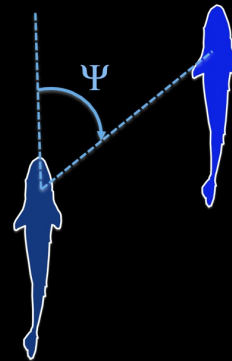
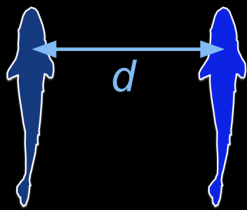
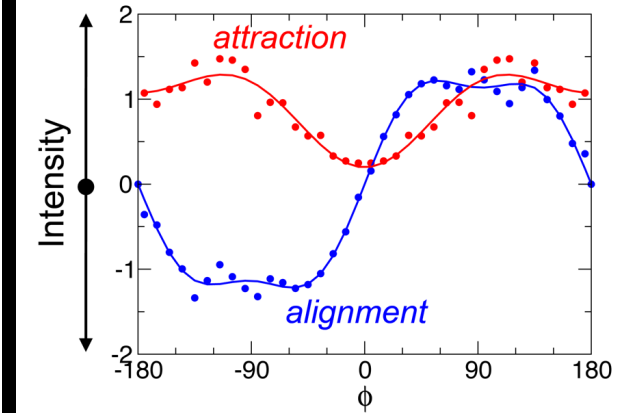
Distance



Angular position



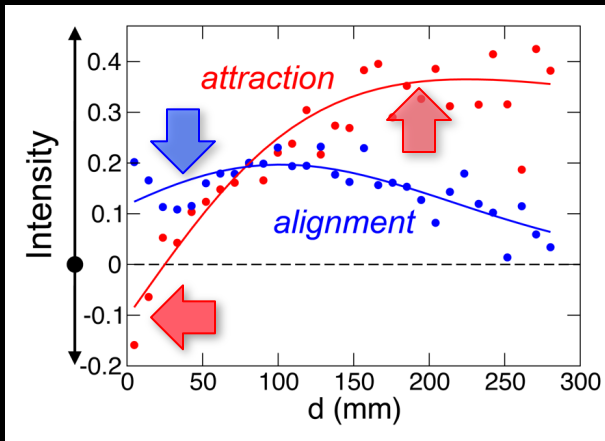
Relative heading



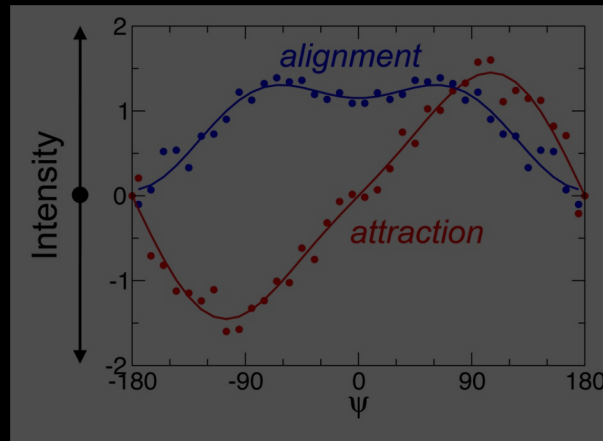
Measuring and modeling social interactions

Attraction and alignment between two fish

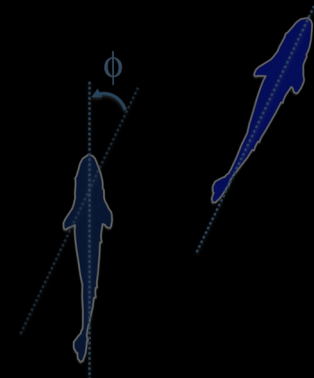
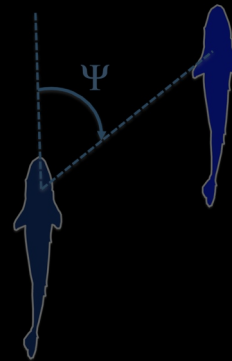
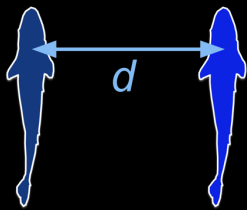
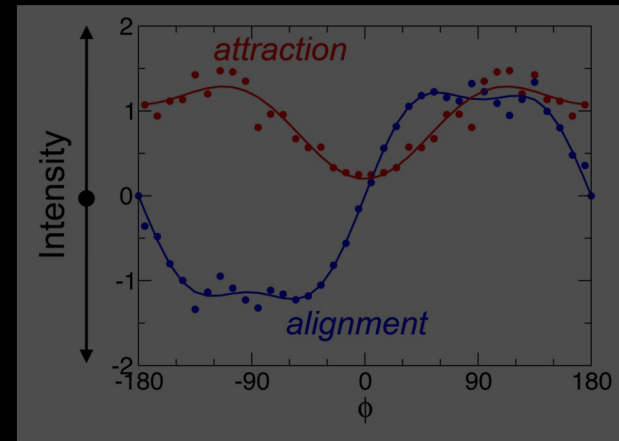
Distance



Angular position



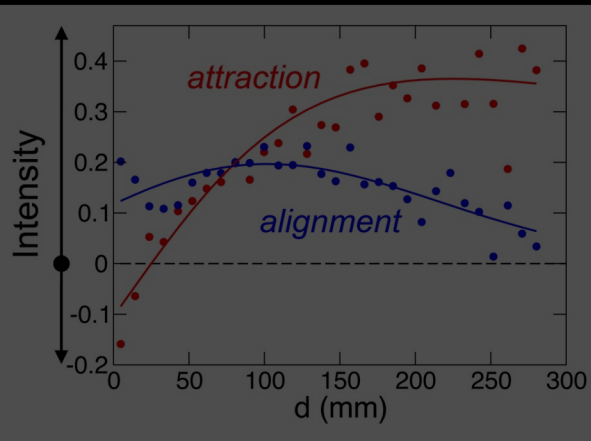
Relative heading



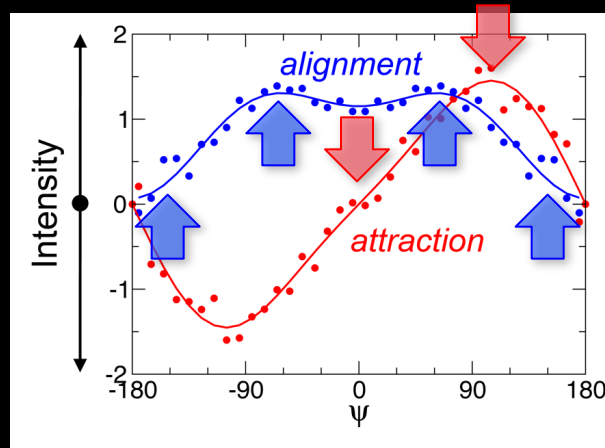
Measuring and modeling social interactions

Attraction and alignment between two fish

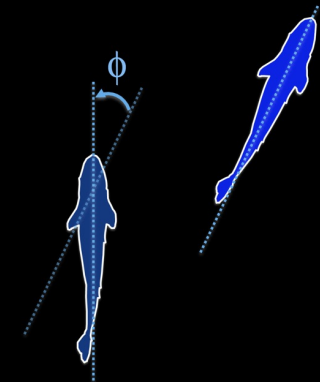
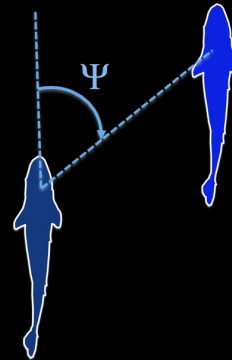
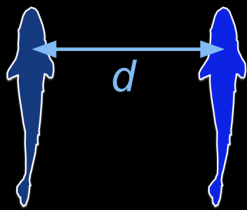
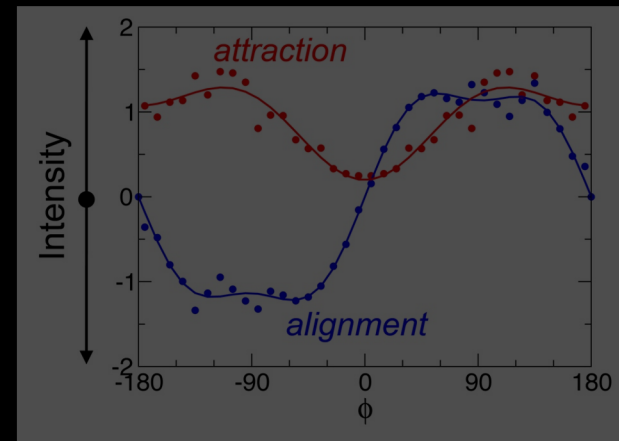
Distance



Angular position



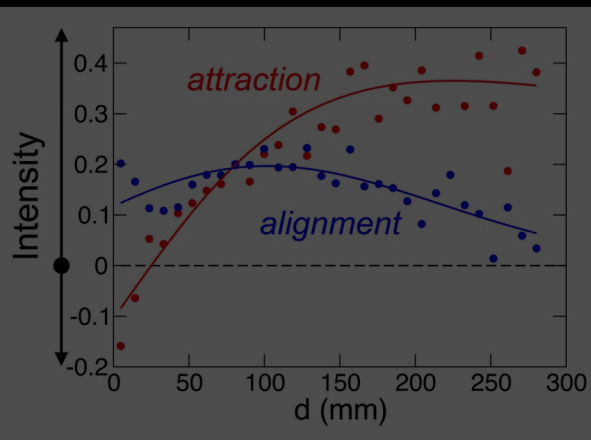
Relative heading



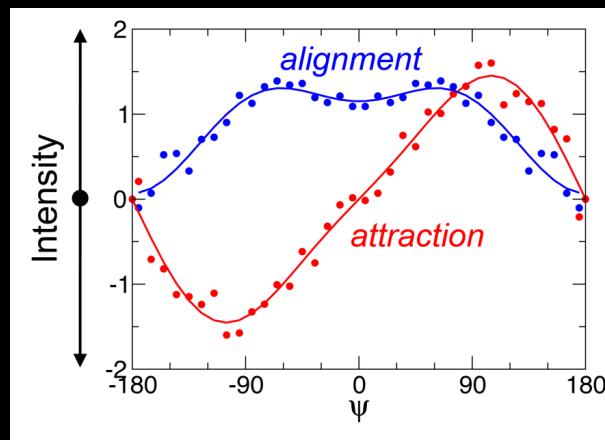
Measuring and modeling social interactions

Attraction and alignment between two fish

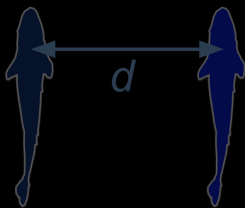
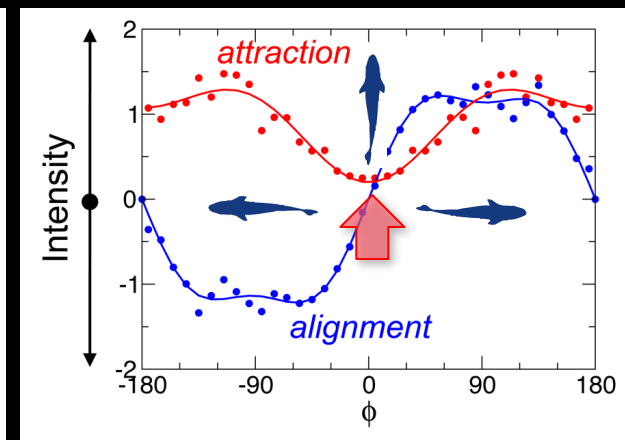
Distance



Angular position



Relative heading

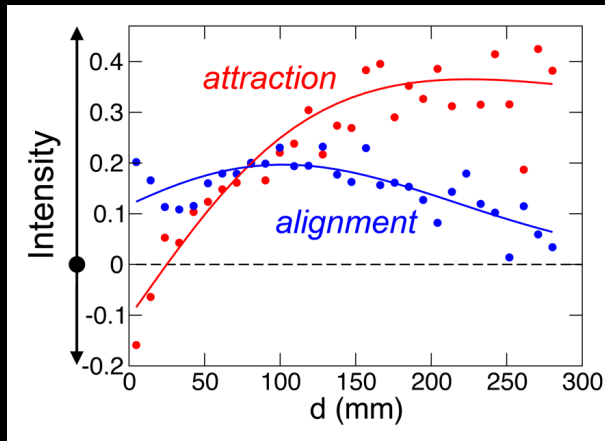


- The fish aligns its heading to that its neighbor
- The intensity of attraction increases with the relative size of the neighbor

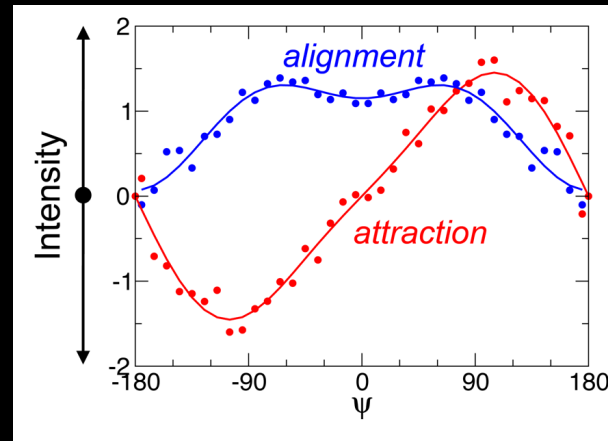
Measuring and modeling social interactions

Modeling the interactions between two fish

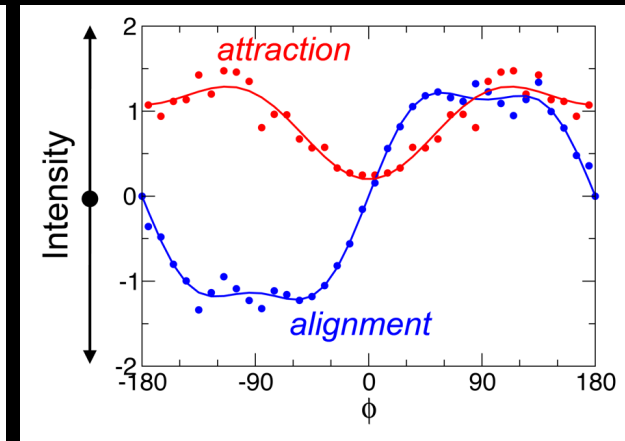
Distance



Angular position



Relative heading



$$F_{\text{Att}}(d) \propto \frac{(d - a) / l_{\text{Att}}}{1 + (d / l_{\text{Att}})^2}$$

$$O_{\text{Att}}(\psi) \propto \sin(\psi)[1 - 0.33 \cos(\psi)]$$

$$E_{\text{Att}}(\Delta\phi) \propto 1 + 0.48 \cos(\Delta\phi) - 0.31 \cos(2\Delta\phi)$$

$$F_{\text{Ali}}(d) \propto \left(\frac{d}{l_{\text{Ali}}} + c \right) \exp[-(d / l_{\text{Ali}})^2]$$

$$E_{\text{Ali}}(\psi) \propto 1 + 0.60 \cos(\psi) - 0.32 \cos(2\psi)$$

$$O_{\text{Ali}}(\Delta\phi) \propto \sin(\Delta\phi)[1 + 0.30 \cos(2\Delta\phi)]$$

Measuring and modeling social interactions

Modeling the interactions between two fish

- In the presence of another fish, the total heading angle change is the sum of the variations induced by the environment of the focal fish

$$\delta\phi = \delta\phi_R(r_w) + \delta\phi_W(r_w, \theta_w) + \delta\phi_{Att}(d, \psi, \Delta\phi) + \delta\phi_{Ali}(d, \psi, \Delta\phi)$$

- The angle change due to the social interactions is expressed in terms of decoupled functions of the instantaneous state of the fish: the distance (d), relative orientation (ψ) and alignment (ϕ) with its neighbor

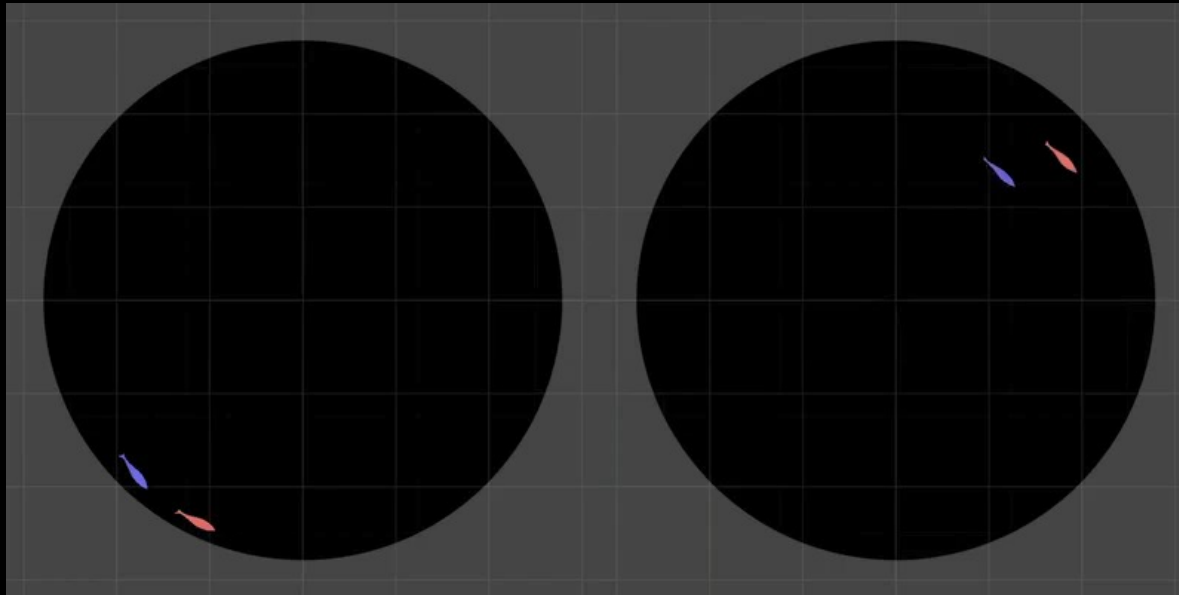
$$\delta\phi_{Att}(d, \psi, \Delta\phi) = F_{Att}(d)O_{Att}(\psi)E_{Att}(\Delta\phi)$$

$$\delta\phi_{Ali}(d, \psi, \Delta\phi) = F_{Ali}(d)O_{Ali}(\Delta\phi)E_{Ali}(\psi)$$

Modeling interactions between pairs of fish

Comparison between experiments and simulations

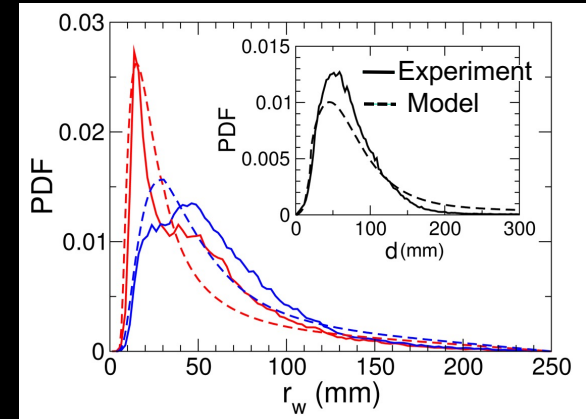
Experiment



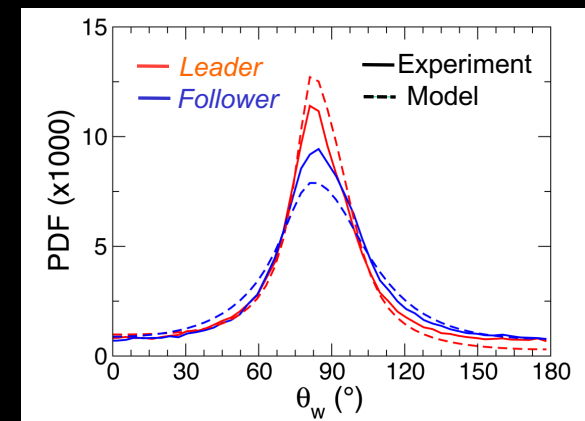
Model

- The model qualitatively and quantitatively reproduces the key features of the motion and spatial distributions of fish observed in experiments

Distance of fish to the wall and distance between fish

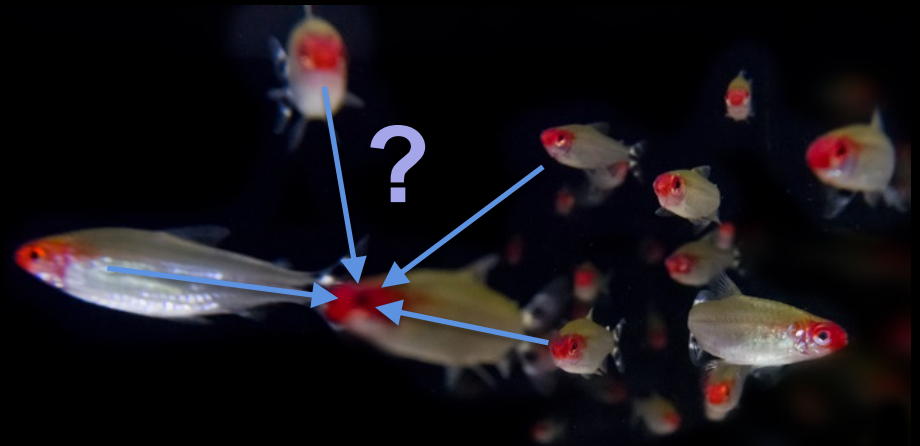


Relative angle to the wall



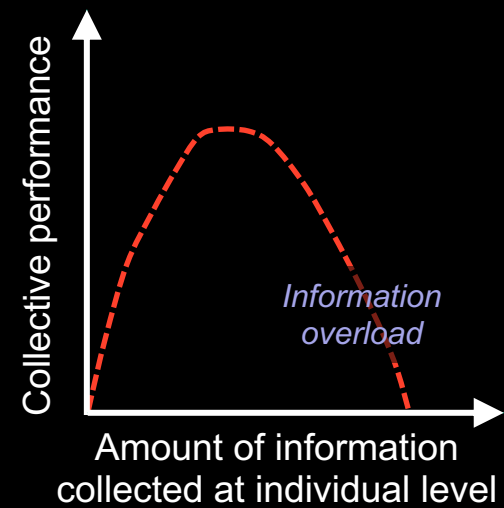
Combining interactions with multiple neighbors

Determining the influential neighbors



- How do fish combine the interactions with multiple neighbors when swimming in a school?
- What is the amount of information needed by fish about their environment to coordinate their motion?

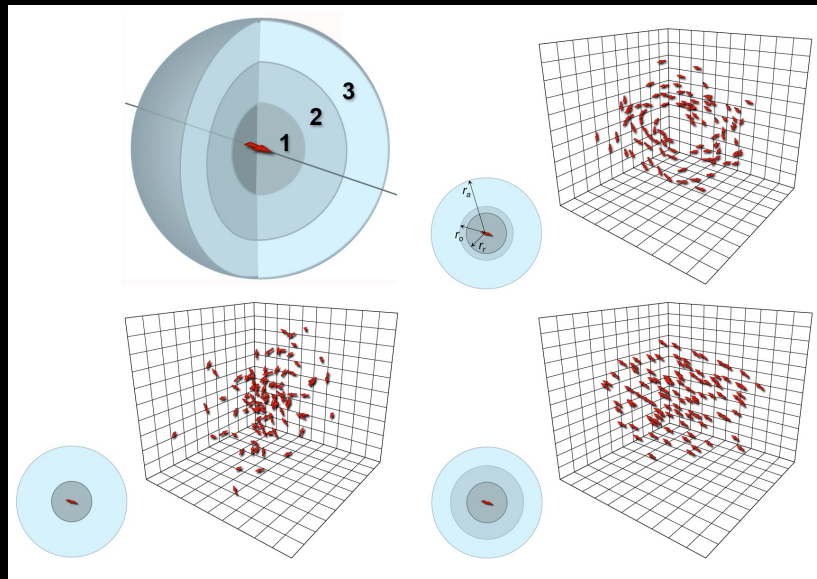
Hemigrammus rhodostomus



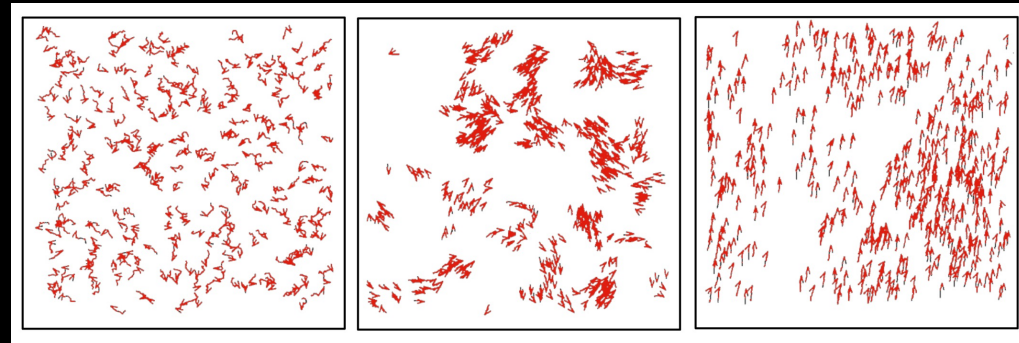
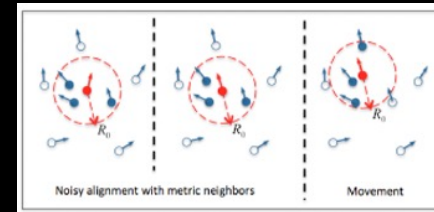
Combining interactions with multiple neighbors

Phenomenological models of schooling and flocking

Aoki-Couzin Model
Repulsion, orientation
and attraction zones



Vicsek Model
Alignment interaction with
neighbors inside a metric range R_0



Aoki I. *Bull Japan Soc Sci Fish.* (1982)
Vicsek T. et al. *Phys. Rev. Lett.* (1995)
Couzin, I. et al., *J. theor. Biol.* (2002)

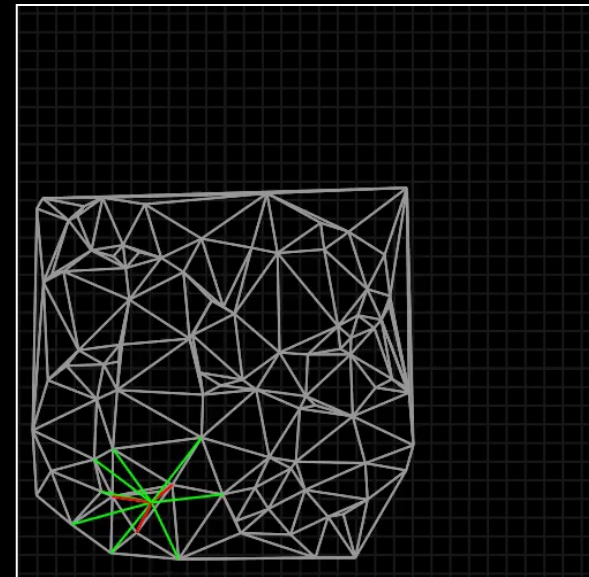
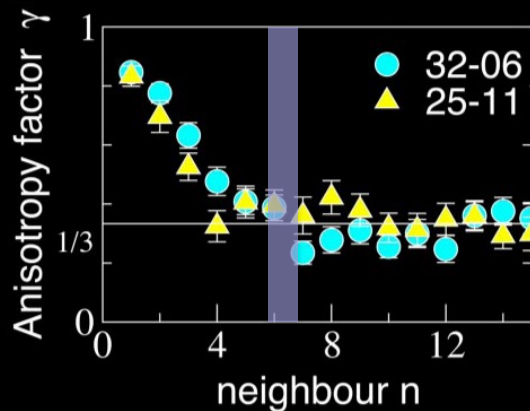
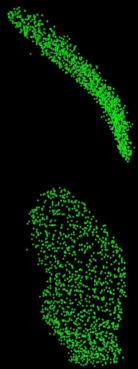
Combining interactions with multiple neighbors

Data-driven flocking and schooling models



Interaction ruling animal collective behavior depends on topological rather than metric distance: Evidence from a field study

M. Ballerini^{*†}, N. Cabibbo[§], R. Candelier[¶], A. Cavagna^{*†**}, E. Cisbani[†], I. Giardina[¶], V. Lecomte^{†††}, A. Orlandi^{*}, G. Parisi^{*†§**}, A. Procaccini[‡], and M. Viale^{§§}, and V. Zdravkovic^{*}



Each bird interacts on average with a fixed number of neighbors (6 – 7)

Ballerini, M. et al., PNAS (2008)
Gautrais, J. et al., PloS Comput. Biol (2012)

Combining interactions with multiple neighbors

The selective attention of fish to their neighbors

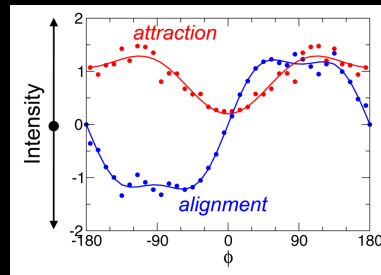
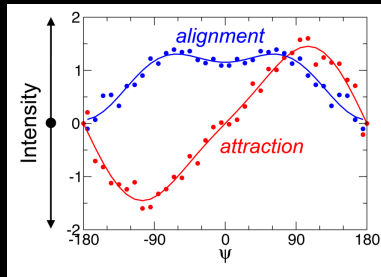
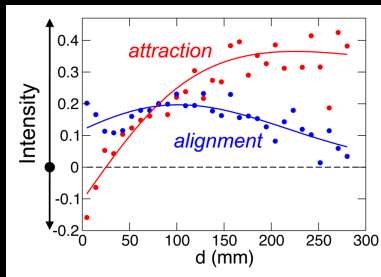


- To coordinate their movements rummy nose tetras only interact with the most or the two most influential neighbors
- These most influential neighbors are those that have the strongest contribution to the heading variation of the focal fish

Combining interactions with multiple neighbors

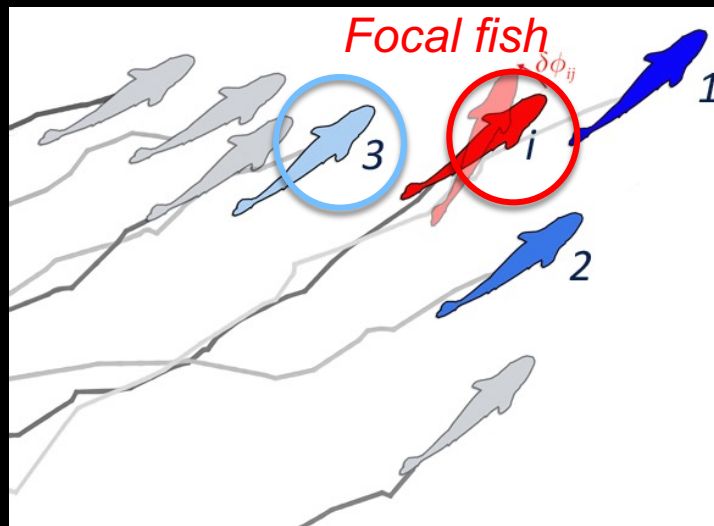
Identifying influential neighbors

Pairwise interaction functions



Ranking of neighbors according to their influence on a focal fish

$$\delta\phi_{i1} > \delta\phi_{i2} > \delta\phi_{i3}$$



- The influence exerted by one neighbor on a focal fish is calculated from the analytical expression of the pairwise interaction functions derived from experiments in groups of two fish

Combining interactions with multiple neighbors

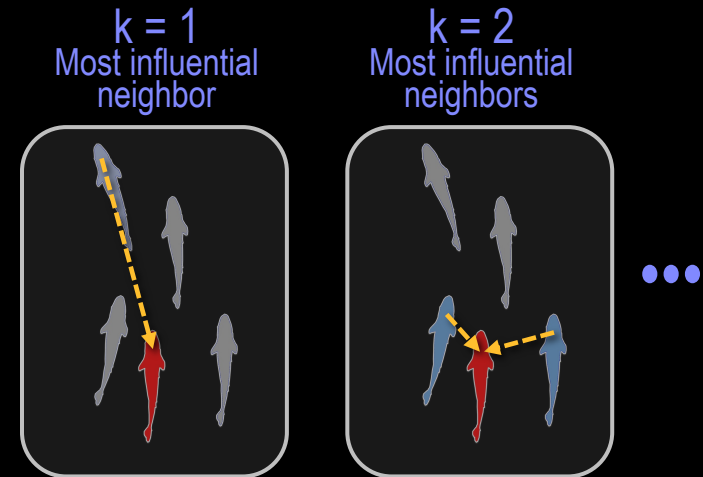
Local interactions strategies

- Experiments with groups of 5 fish moving freely in a circular tank
- Modeling different strategies for combining pairwise interactions between fish and analyze their impact on collective motion



$$\delta\phi_i^n = \delta\phi_{W,i}^n + \delta\phi_{R,i}^n + \sum_{j=1, j \neq i}^N \delta\phi_{ij}^n$$

Combination of pairwise interactions



Collective states in the fish school model

Impact of the intensity of the attraction and alignment interactions on collective states

Attraction intensity

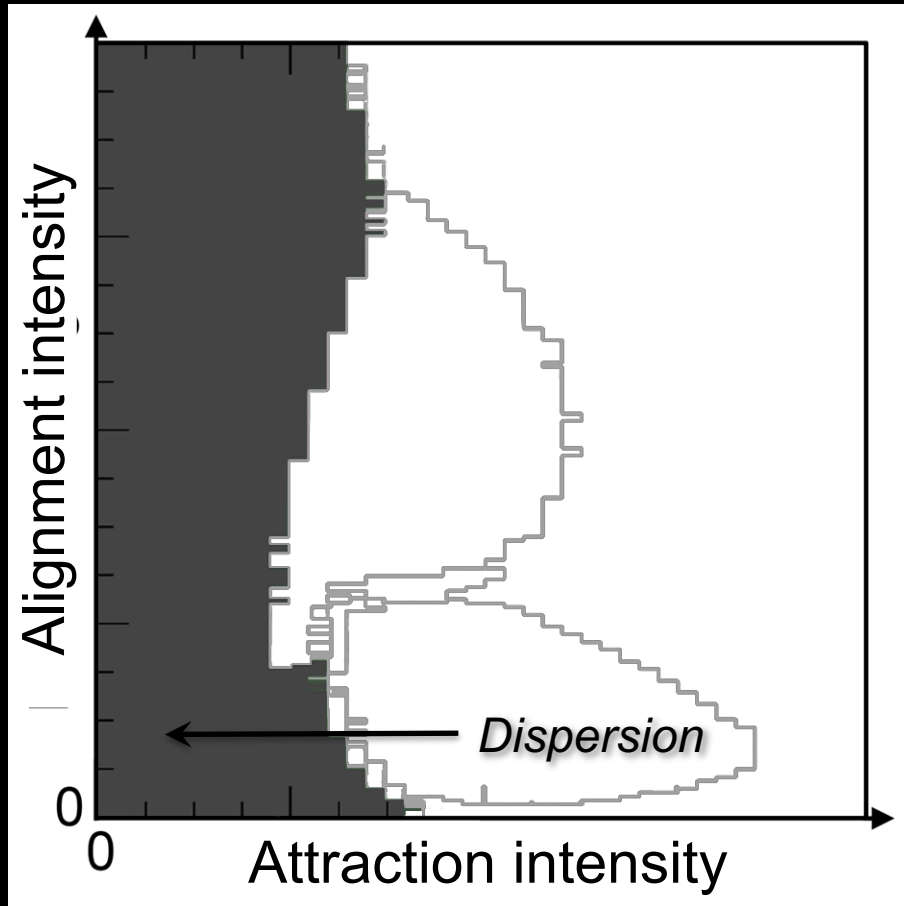
$$F_{\text{Att}}(d) = \gamma_{\text{Att}} \frac{d/d_{\text{Att}} - 1}{1 + (d/l_{\text{Att}})^2}$$

$$F_{\text{Ali}}(d) = \gamma_{\text{Ali}} \left(\frac{d}{d_{\text{Ali}}} + 1 \right) \exp \left[- \left(\frac{d}{l_{\text{Ali}}} \right)^2 \right]$$

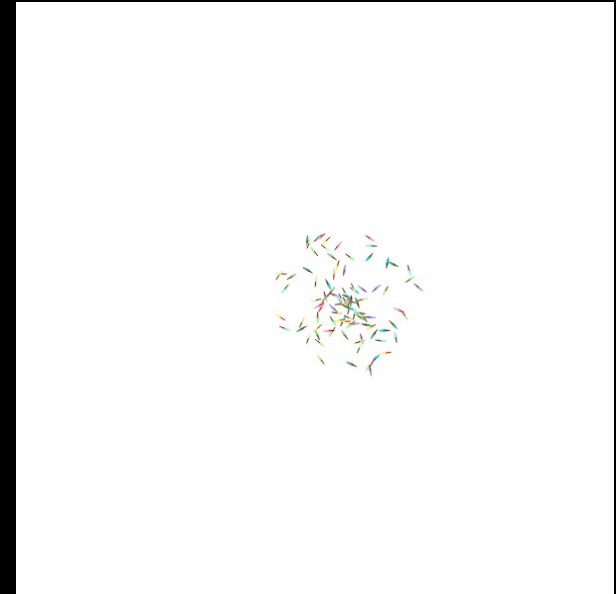
Alignment intensity

Collective states in the fish school model

Impact of the intensity of the attraction and alignment interactions on collective states



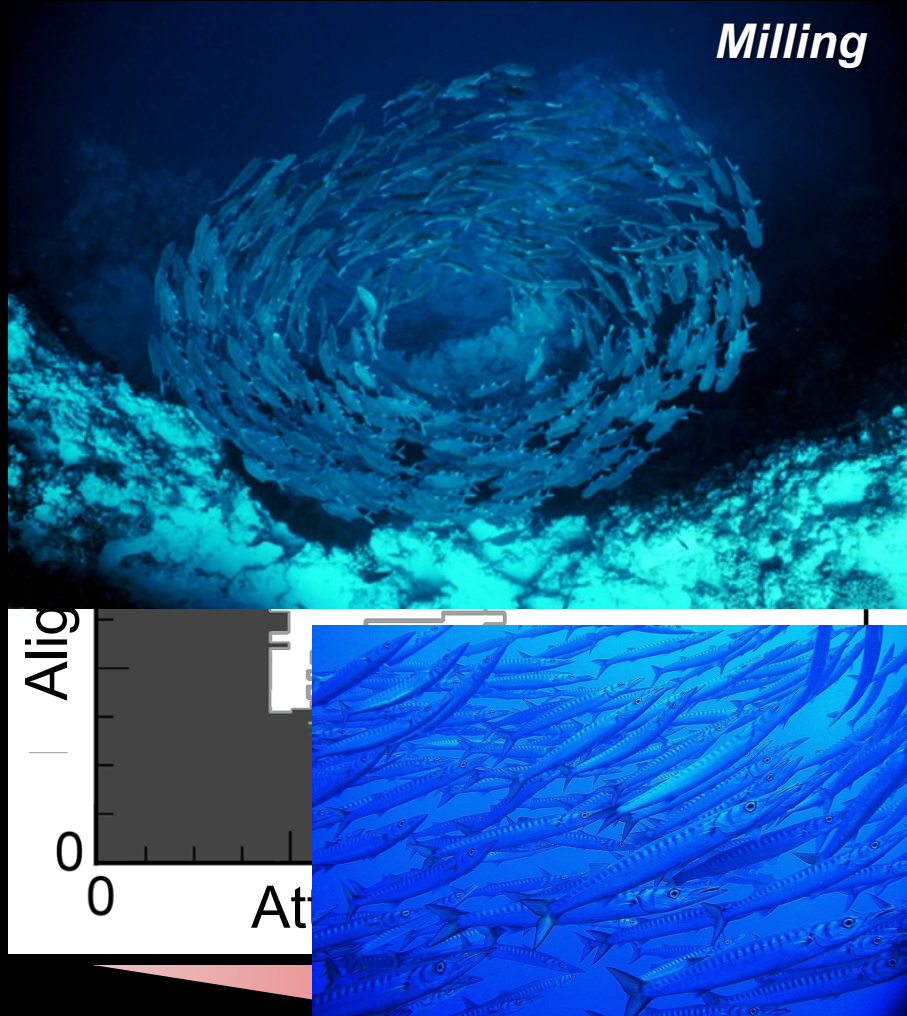
Collective movement in a school of 100 fish



Each fish interacts with its most influential neighbor

Collective states in the fish school model

Impact of the intensity of the attraction and alignment interactions on collective states



Collective movement in a school of 100 fish



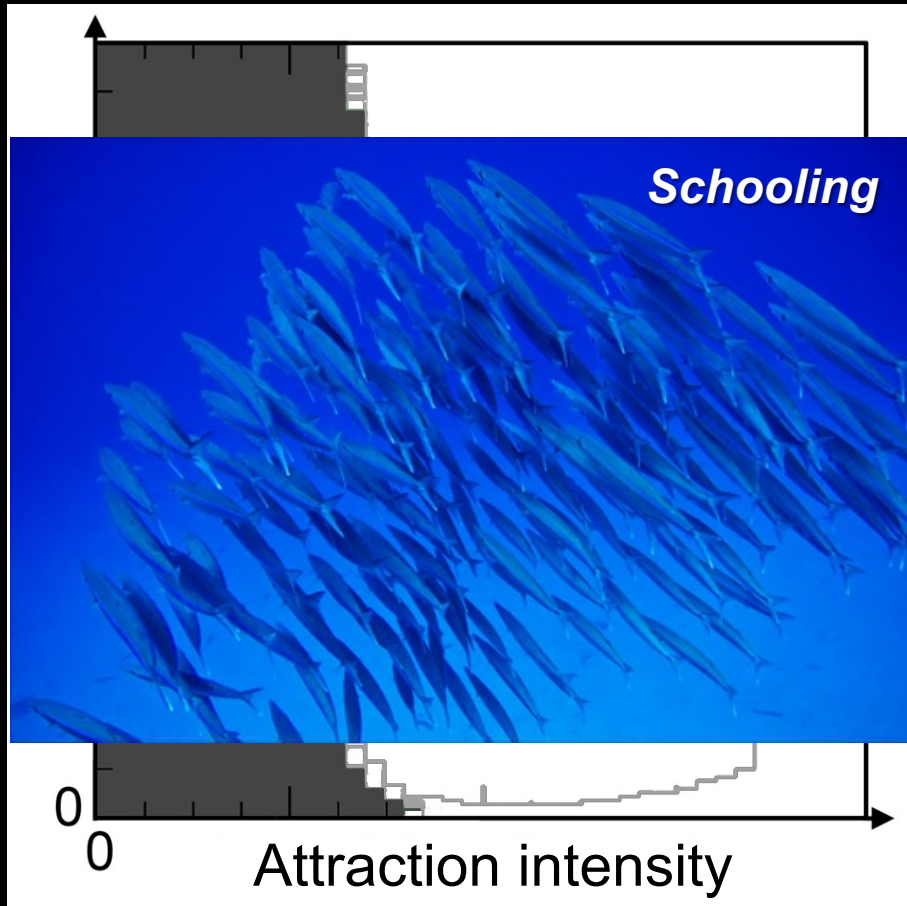
Each fish interacts with its most influential neighbor

Sphyraena barracuda

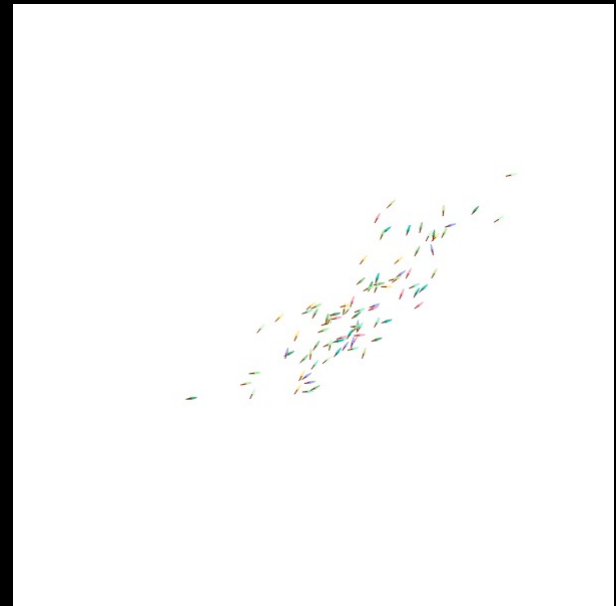
Wang, W. et al., *PloS Comp. Biol.* (2022)

Collective states in the fish school model

Impact of the intensity of the attraction and alignment interactions on collective states



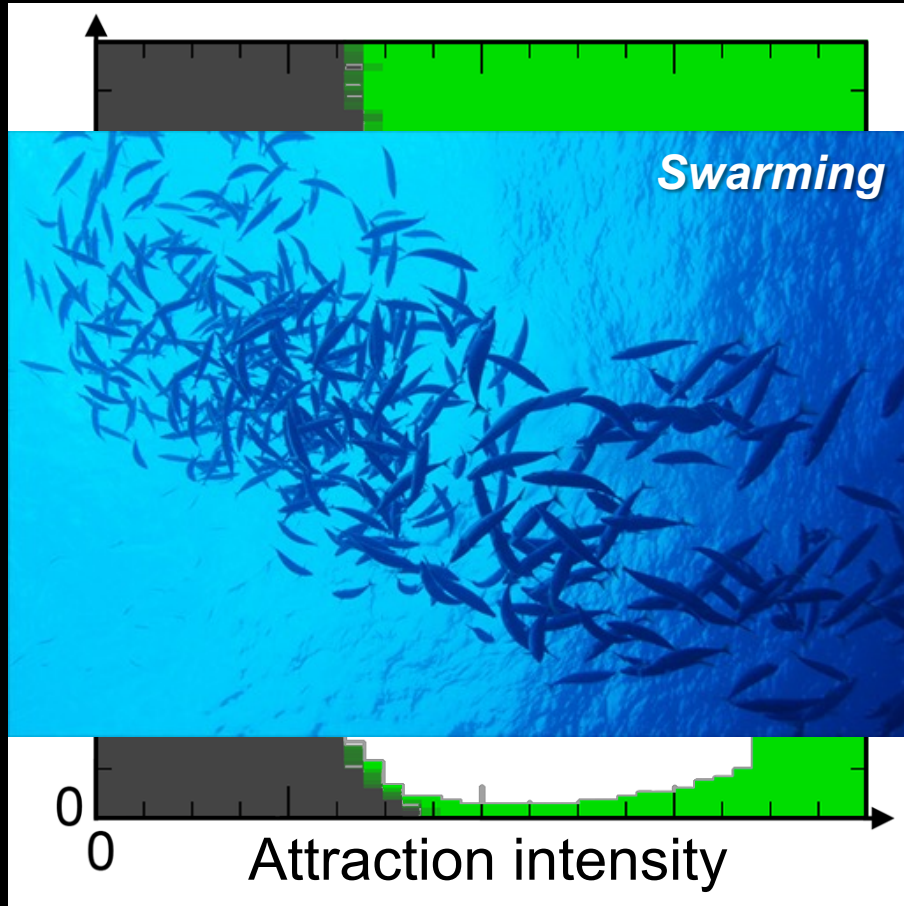
Collective movement in a school of 100 fish



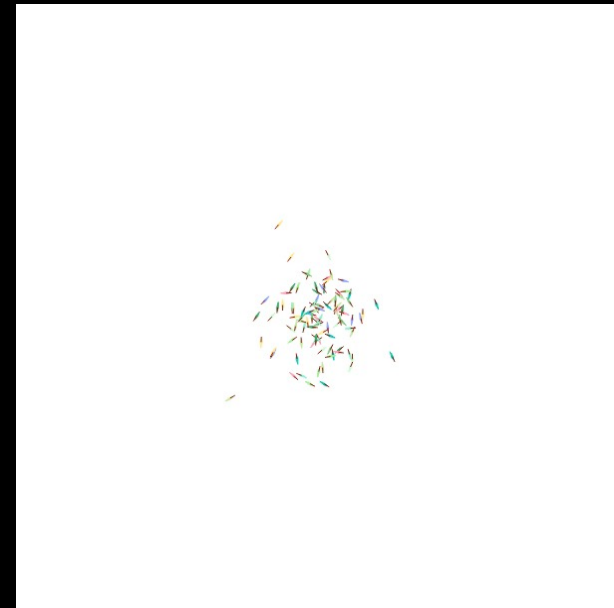
Each fish interacts with its most influential neighbor

Collective states in the fish school model

Impact of the intensity of the attraction and alignment interactions on collective states



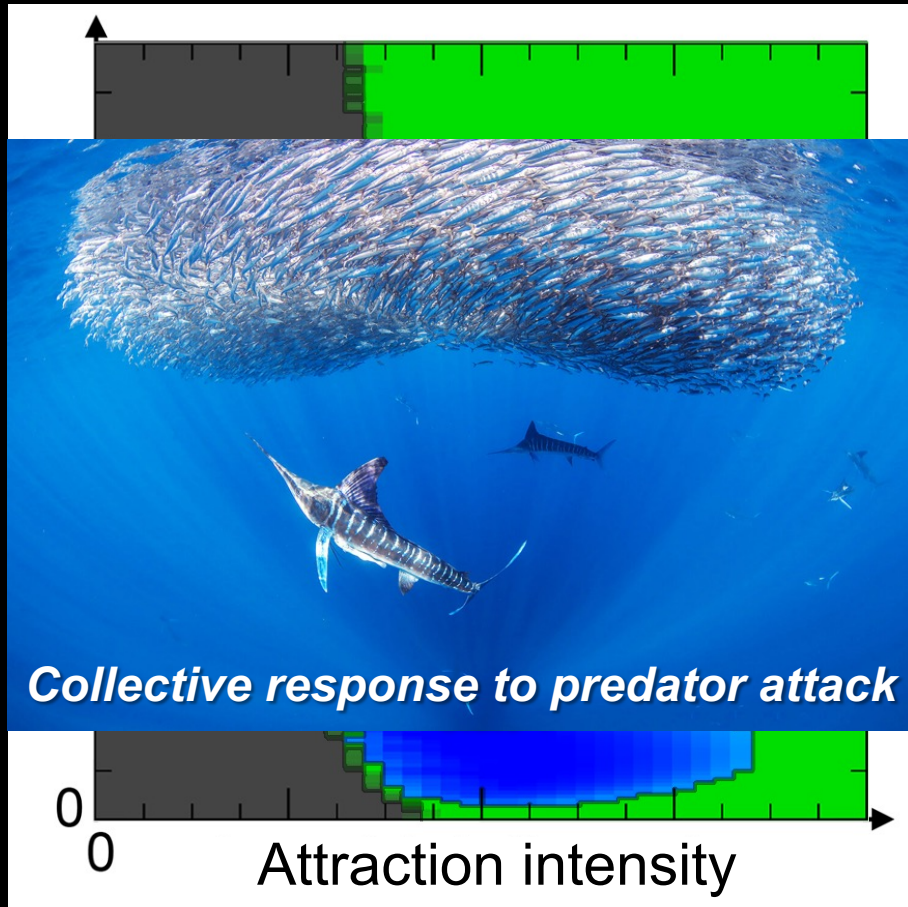
Collective movement in a school of 100 fish



Each fish interacts with its most influential neighbor

Collective states in the fish school model

Impact of the intensity of the attraction and alignment interactions on collective states



Collective movement in a school of 100 fish



Each fish interacts with its most influential neighbor

Collective motion in groups of organisms

Swarms, schools, flocks and herds are in « critical state »

- In many species, the interactions between individuals lead the group to a state that is neither too disorderly nor too rigidly organized, while being endowed with extreme sensitivity.
- Being in a critical state enhances the collective adaptive capacity of a group



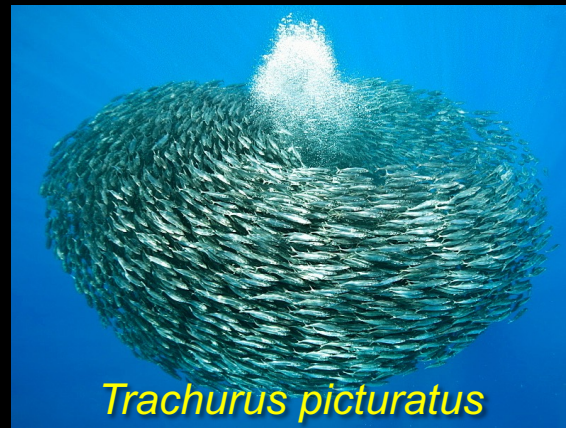
Corynoneura scutellata

© Andrea Cavagna



Sturnus vulgaris

© Walerian Walawski



Trachurus picturatus

© Christopher Swann



Ovis aries

© Tim Whittaker

Coordination mechanisms in fish schools

Conclusions

- An incremental approach to build a fish behavior model **completely based on interactions with the physical environment and neighboring fish**
- A continuous balancing between attraction and alignment behavior **as a function of the distance between fish and their relative positions and orientations**

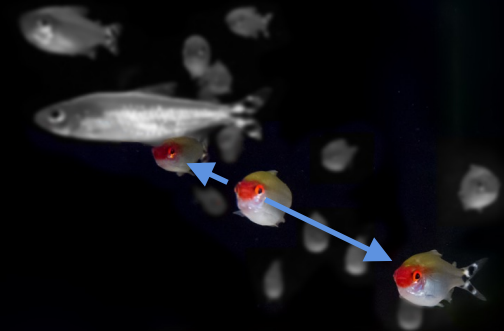


Hemigrammus rhodostomus

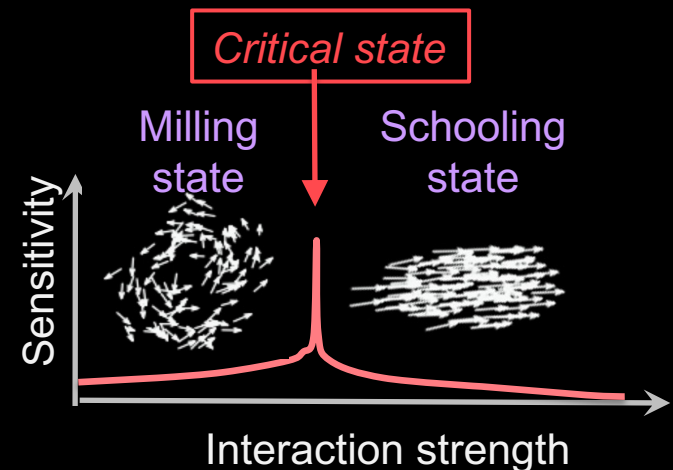
Coordination mechanisms in fish schools

Conclusions

- Each fish must acquire only a minimal amount of information about the behavior of its neighbors for coordination to emerge at the group level
- In vertebrates the midbrain continuously monitors the environment for the relevant stimuli and the forebrain selects those stimuli on which the fish focuses its attention
- Fish do not have to pay attention to all their neighbors to ensure the coordination of swimming
- In the frontier state between milling and schooling, the state of the fish school becomes critical and the responsiveness of the school to perturbations is maximum

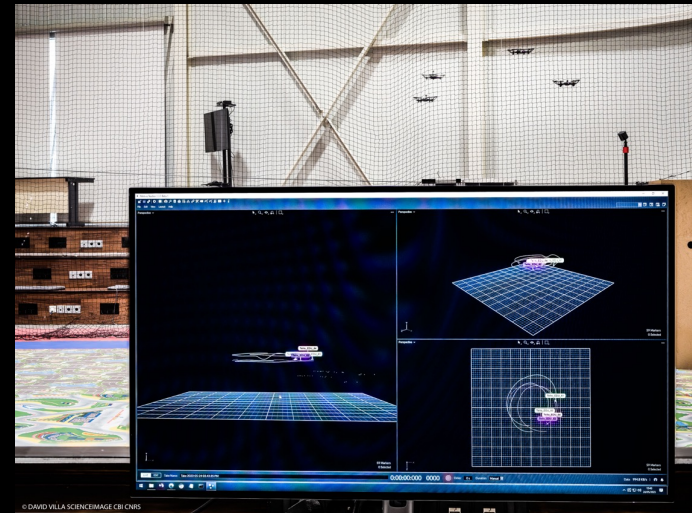


Hemigrammus rhodostomus



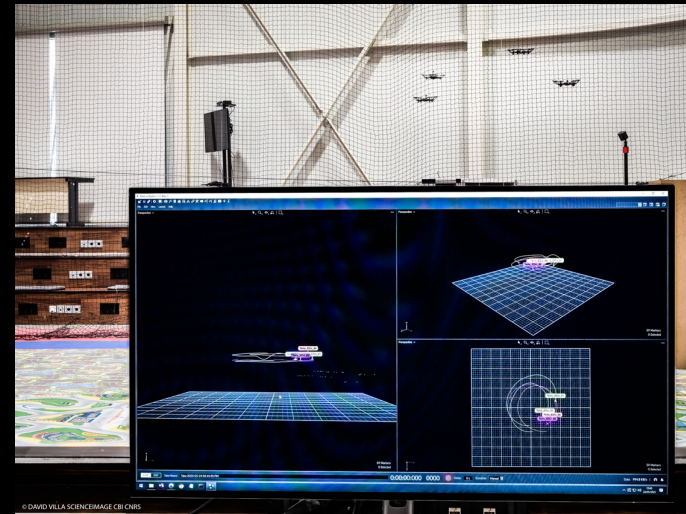
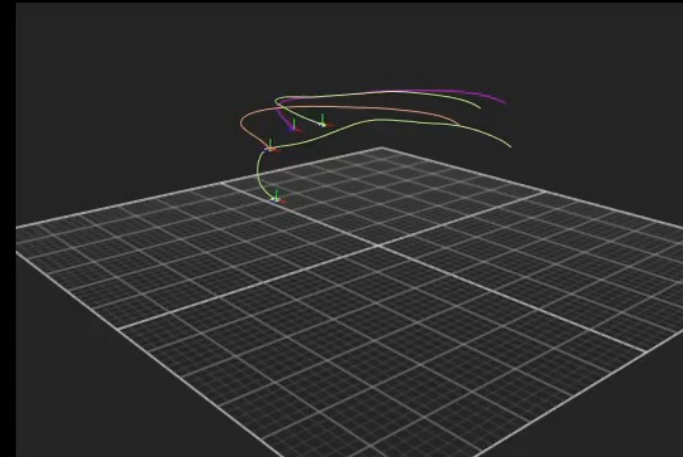
Application to UAV Control Model

- This model was adapted into a **3D UAV flocking model**.
- A lot of modifications for **safety**, **continuity**, and **3D motion** were made.
- Agents interact with:
 - Their most influential agent
 - The arena wall and vertical border
 - Operational orders



Application to UAV Control Model

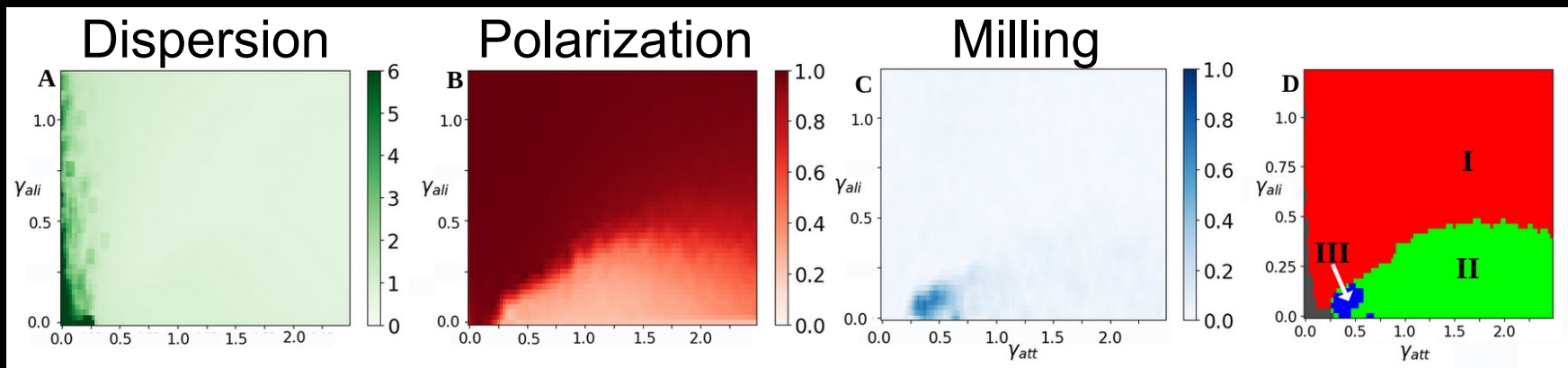
- Two interactions were added:
 - A longitudinal speed interaction
 - A vertical speed interaction
- The agent then calculates a **speed vector**, and a **yaw rotation speed**
- A **function of influence** is used to designate the **most influential agent** regarding every **interactions**.



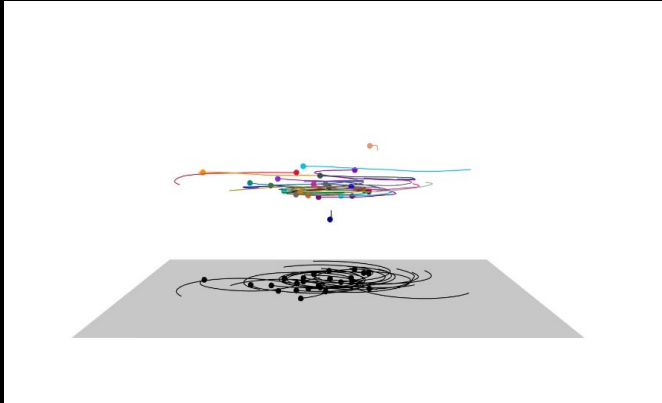
Application to UAV Control Model

■ As made with the fish model, we can plot a **phase diagram**, depicting the **collective patterns** issued from the tuning of the **two main interactions intensities**.

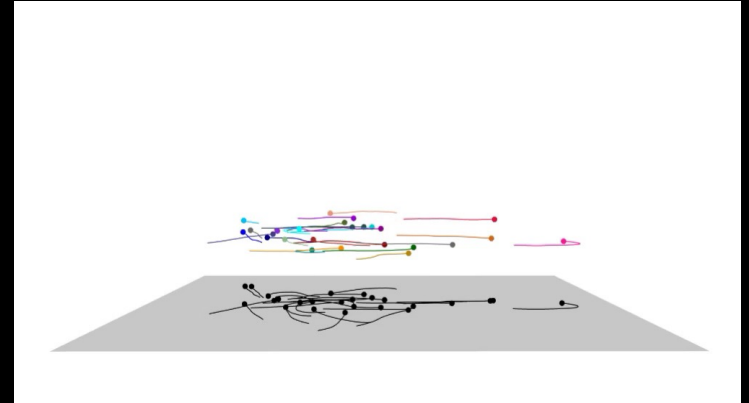
■ Three patterns emerge in 3D, being the **schooling state (I)**, the **swarming state (II)**, and the **milling state (III)**. When envisioning operational applications of the model, each phase can be useful.



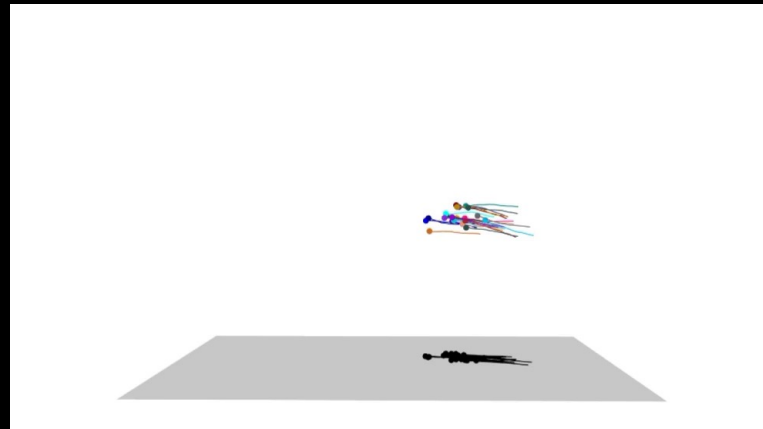
Application to UAV Control Model



Milling



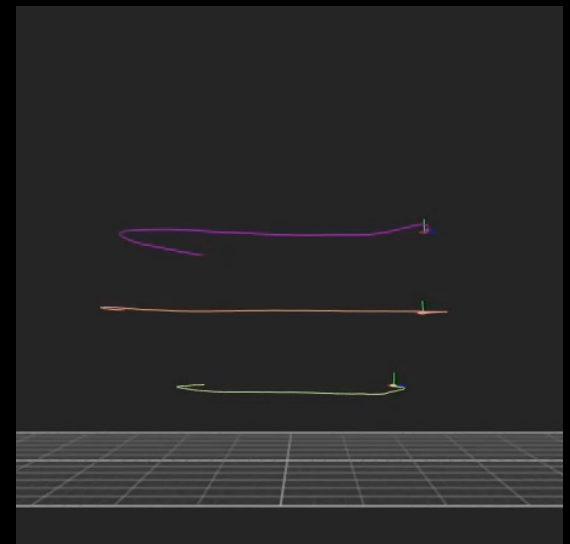
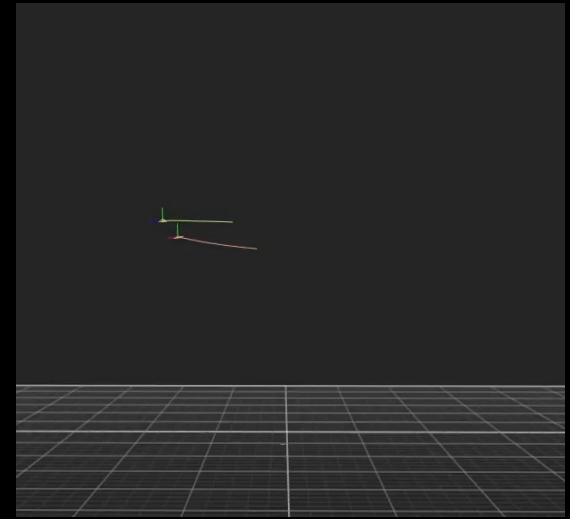
Swarming



Schooling

Application to UAV Control Model

- When focusing about **operational purposes**, alignment to a **direction** and attraction to a desired **altitude** is implemented
- **Equilibrium** is found with and without a specified **altitude**. Phases are **enhanced to 3D**, allowing the operator to **shape the fleet** to any needs.
- Recent results show that when faced to **perturbations** (repulsion with an enemy), the fleet is more **efficient**, **separate less**, and **follow a direction** better when the state is close to the **critical state**.



Application to UAV Control Model

Conclusions

- The adapted **model** is capable of displaying **collective patterns** without losing **fleet integrity**
- It can be adapted to **fixed-wing UAVs** and enhance their **coordination capabilities**
- The collective patterns obtainable are useful and their **transition is quick**, allowing their switch by an **operator** or an **operational scenario**.
- The **critical state** between **schooling** and **swarming state** is also very useful when dealing with **perturbations**.



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