Understanding and Controlling the Collective Behaviour of Zebrafish

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A group of fish can be described as an active matter system, where the fish interaction gives rise to emerging collective behaviour. Here we study the 3D collective behaviour of zebrafish in the laboratory. We found that a large group of zebrafish exhibits typical pattern when they were introduced to a new environment, with decreased speed and cohesion. The changing states can be effectively described by the reduced persistence length of the fish, and these states can be captured by a simple agent–based model. With genetic modification, the fish present different single–fish properties which lead to different collective behaviour.

Introduction

○ When particles are capable of constantly moving themselves, by using environmental or internal energy, they form a class of non-equilibrium system called active matter.[1] The key feature of active matter systems is that they present stunning collective behaviours such as flocking and swarming.[2, 3]

○ Inspired by the pioneering work of Cavagna et al. on the flocking birds [2], we focus on the collective behaviours of a group of zebrafish, by calculating and analysing their 3D trajectories.

○ Understanding the behaviour of zebrafish, we can use the behaviour as a tool to characterise mutant fish, which will enable us to locate genes that affects the fish.

Method

We use 3 synchronised cameras, mounted above the water, to capture videos of the fish. We then calculate the 3D positions of the fish [4], and link these positions into 3D trajectories [5] for further analysis.

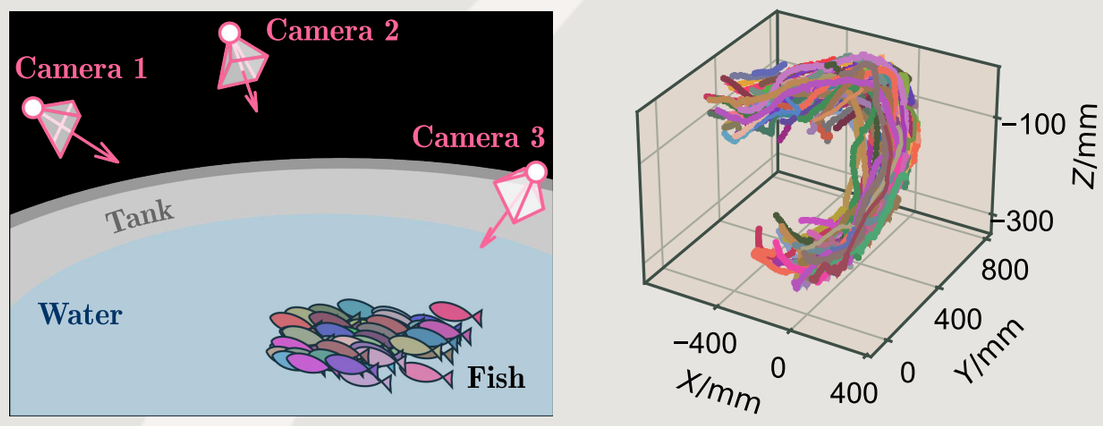

Figure 1. The experimental setup (left) and the 3D trajectories of 50 zebrafish (right).

Zebrafish Adapting to a New Environment

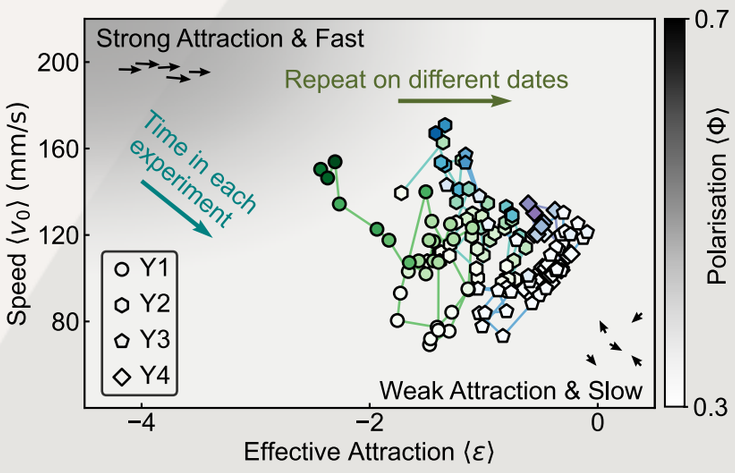

Figure 2. The evolution of states of 50 wildtype fish. The speed were measured directly from the positions and the effective attraction was calculated from the radial distribution function (the g of r).

○ The fish tend to start at a fast & cohesive state, and relax to slow and not attractive states (Fig. 2).

○ The movement of the fish were polarised (most fish swimming towards the same direction) in the fast & cohesive states.

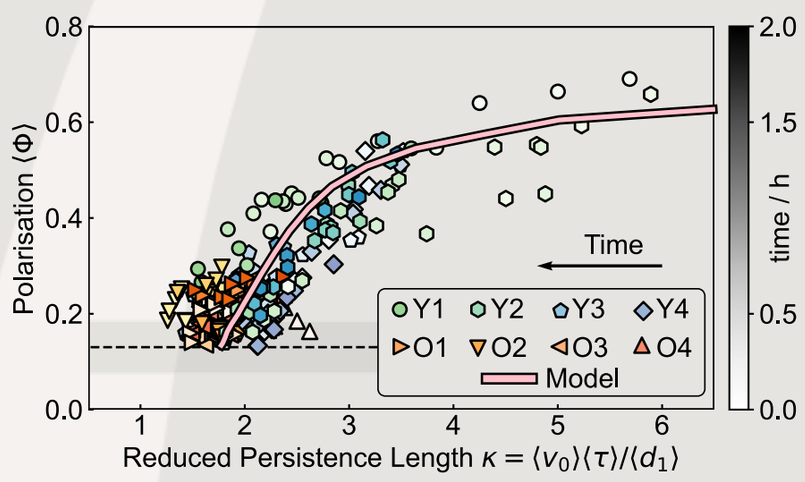

Figure 3. The polarisation of 50 wildtype zebrafish as a function of the reduced persistence length, which is the product of the speed (v_0) and orientational relaxation time (τ), scaled by the nearest neighbour distance (d_1). The relationship can be captured by simulating the Vicsek model with an extra inertia term.

○ Robust & characteristic relationship between the polarisation and the reduced persistence length (Fig. 3).

○ This relationship can be captured by simple variation of the Vicsek model [6], with an extra inertia term.

$$\mathbf{v}_i(t+1) = v_0\Theta\left[(1-\alpha)\ \underbrace{v_0\mathcal{R}_\eta\left[\Theta\left(\sum_{j\in S_i}\mathbf{v}_j(t)\right)\right]}_{\text{Vicsek Model}} + \alpha\mathbf{v}_i(t)\right]$$

velocity updating rule for the model fish

Changing the Fish Behaviour by Genetic Modification

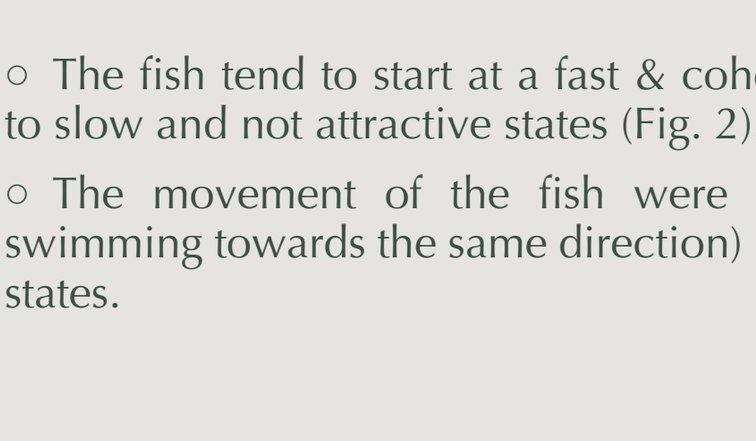

Figure 4. The auto correlation function (ACF) of the fish orientation, calculated with trajectories where only 1 fish was in the tank. The relaxation time (τ) values were obtained by an exponential fit.

○ Zebrafish can be genetically modified. The *col11a2* mutant fish exhibit compromised bond development [7].

○ The mutant fish took longer time to change their moving directions (Fig. 4), being effectively less noisy.

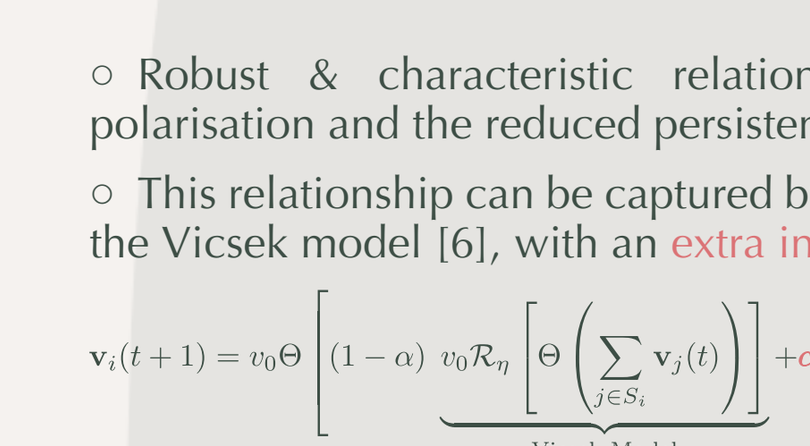

Figure 5. The polarisation of 25 mutant (col11a2) and wildtype (wt) fish as a function of the reduced persistence length. The experiments were repeated as the fish grew, and the data were fitted to the inertial Vicsek model.

○ The longer relaxation time of col11a2 fish yields larger reduced persistence length, yielding more polarised movements.

○ The growth of fish = increase speed & decreased inertia.

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