Avalanche Behavior and Leadership in Schooling Fish

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Behavioral contagion and the presence of behavioral cascades have been observed in groups of animals showing collective motion. Here we examine the collective motion of black neon tetra (*Hyphessobrycon herbertaxelrodi*), a fish species that tend to form highly polarized schools, to categorize size and duration of rearrangement avalanches, sudden individual directional changes that spread through the group during a period of time, and their relation to leadership. Building on the classical Vicsek model, we show how the presence of an effective leader, i.e. any group member with long range behavioral influence over the rest of the group, is capable to induce a heterogeneous response in the movement of the other individuals in response to a perturbation in the leader's direction of motion, and replicate avalanche features of our experimental results. Avalanches size and duration in black neon tetra and in the modified Vicsek Model show scale-free signatures, reminiscent of self-organized critical behavior. The application of a finite-size scaling analysis allows to compute scaling exponents associated to such distributions, which hint towards partial universality.

INTRODUCTION

Collective motion

Collective motion is observed in a wide variety of living systems.

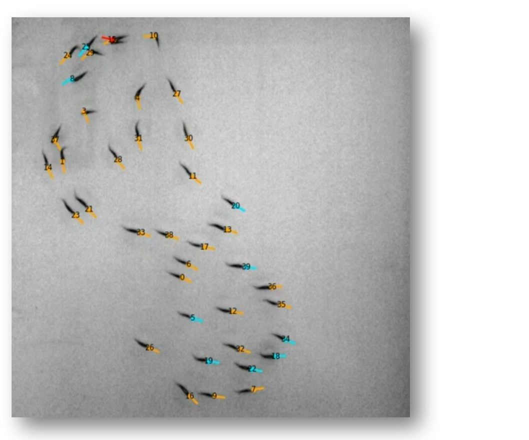
Social animals tend to group and travel together as an adaptive mechanism for reasons as varied as protection from predators, better foraging or navigation accuracy.

This phenomenon requires an efficient transfer of information among individuals.

LEADERSHIP

Leadership is relevant in the emergence of cooperation and conflict:

a) Permanent hierarchical leadership
b) Context-dependent switching leadership
c) **Effective leadership: spontaneous individual behavioral variations that are transmitted to the group.**



AVALANCHE

An avalanche, or a behavioral cascade, is interpreted as a sudden local rearrangement of individual headings during a period of time.

Animal studies have found evidence of avalanche-like responses: rearrangements in response to local perturbation or individual scale changes that can spread throughout the group or extinguish rapidly.

OBJECTIVES

Characterize the interplay between effective leadership and avalanche behavior in the collective motion of schooling fish (black neon tetra).

Model experimental observations in a modified version of the Vicsek Model of self-propelled particles:

Global leader with a long range orientational contagion effect: run-and-tumble.

EXPERIMENTAL SETTING AND NUMERICAL ANALYSIS

Experiments with schooling fish

SUBJECTS

Black neon tetra (*Hyphessobrycon herbertaxelrodi*).

Tendency to form highly polarized schools.

Body length of ~2.5cm

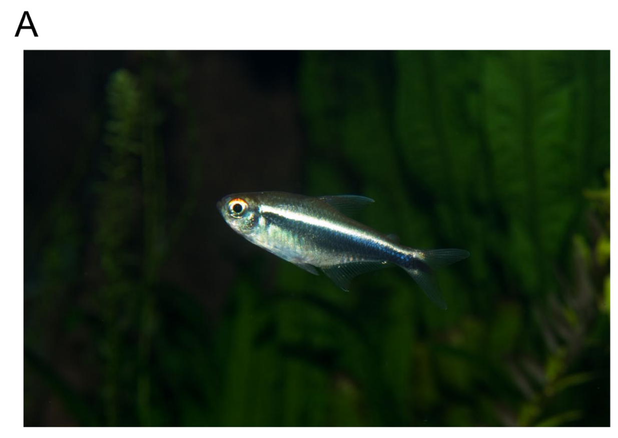
RECORDINGS

100 x 93 cm square tank with 5 cm of water depth.

N = 40 individuals

Three 10-minute videos of fish moving freely

A



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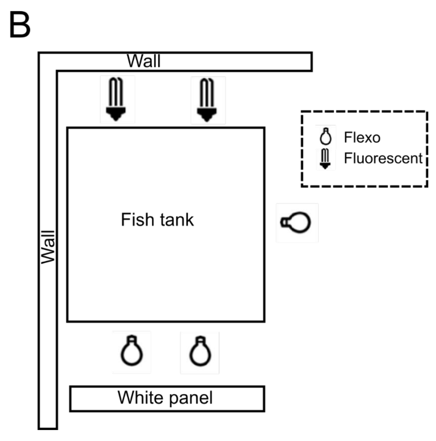


Vicsek Model (Vicsek et al. 1995)

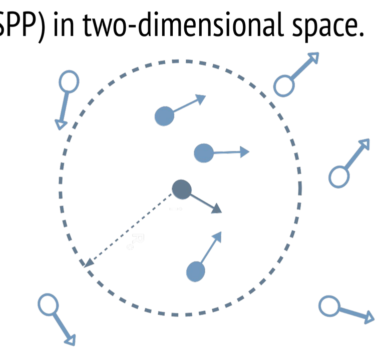
Model of self-propelled particles (SPP) in two-dimensional space.

Update orientation:

$$\theta_{(t+\Delta t)} = \langle \theta_{(t)} \rangle R_0 + \xi_{i(t)}$$

Update position:

$$\vec{x}_i(t+\Delta t) = \vec{x}_i(t) + \vec{v}_i(t)\Delta t$$



PARAMETERS

- **Density ρ**: Number of particles *N* in a volume unit.
- **Velocity v_0 :** individual velocity module, constant.
- **Noise ξ :** random variable uniformly distributed in $[-\pi\eta, \pi\eta]$

OBSERVABLES

- **Order parameter Φ**: Average normalized velocity,

$$\Phi = \frac{1}{N v_0}\left|\sum_{i=1}^{N} \vec{v_i}\right|$$

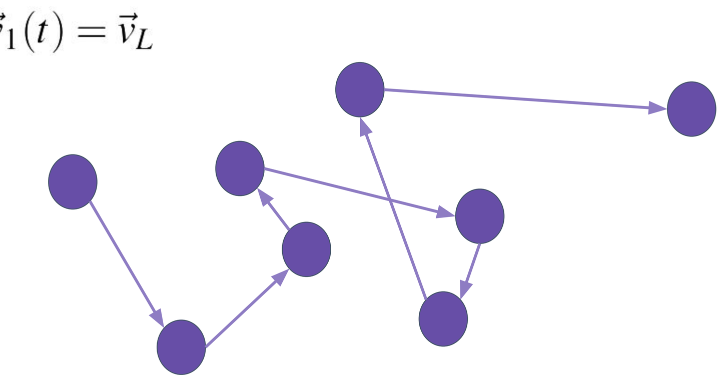
Effective leader in modified Vicsek model

The velocity of the leader is not affected by the behavior of its neighbors: $\vec{v}_1(t) = \vec{v}_L$

Leader heading is constant: $\theta_0(t) = \theta_L$

Random reorientation of the leader's heading by an angle $\Delta\theta_L$

The rest of particles feel the effect of their local neighborhood and of the leader, independently of their relative distance.



RUN-AND-TUMBLE

RESULTS

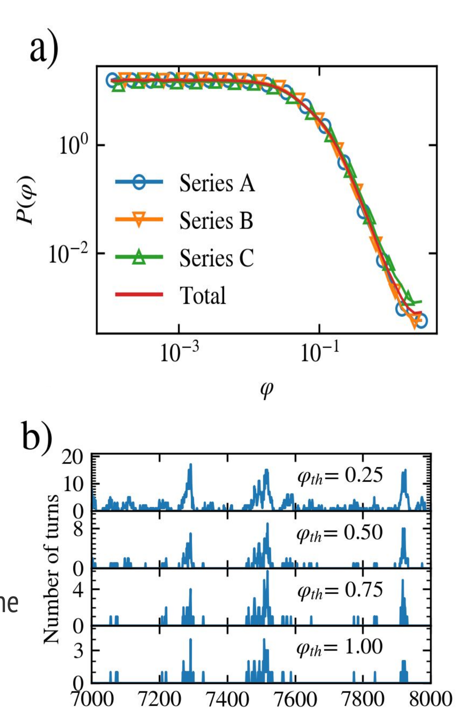
AVALANCHES IN BLACK NEON TETRA

Avalanche statistics

To quantify avalanches we examined the **turning angle distribution** (P(φ)) and define turning thresholds (φ_{th}):

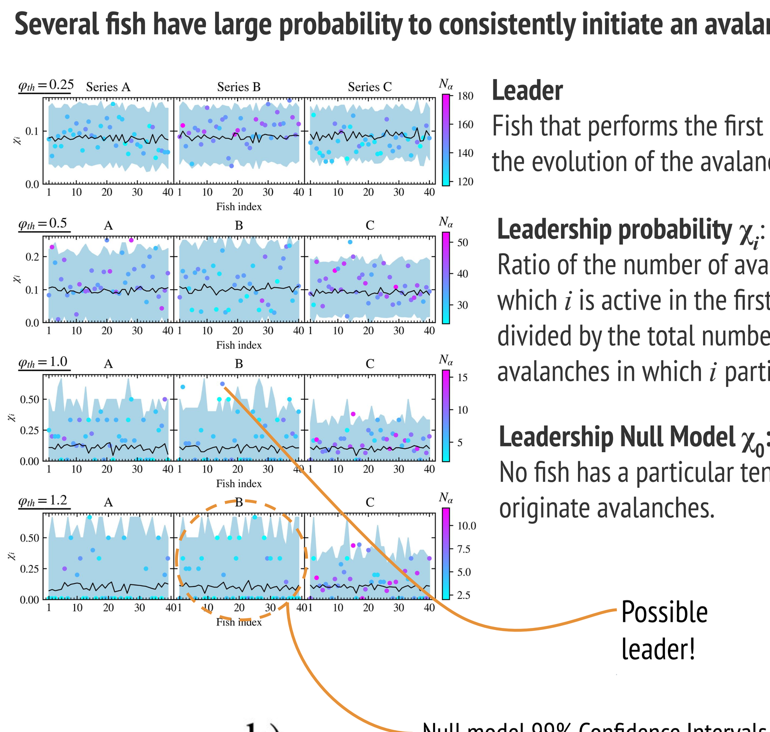
For each **turning threshold**, we counted the number of fish in a given frame turning an angle greater than φ_{th} as a function of time.

An avalanche occurs when more than one fish is active in a train of consecutive frames.



Fish leadership and avalanche behavior

Several fish have large probability to consistently initiate an avalanche



Leader
Fish that performs the first large turn in the evolution of the avalanche.

Leadership probability χ_i:
Ratio of the number of avalanches in which i is active in the first frame, divided by the total number of avalanches in which i participates.

Leadership Null Model χ_0:
No fish has a particular tendency to originate avalanches.

Avalanche size (*s*) and duration (*t*)

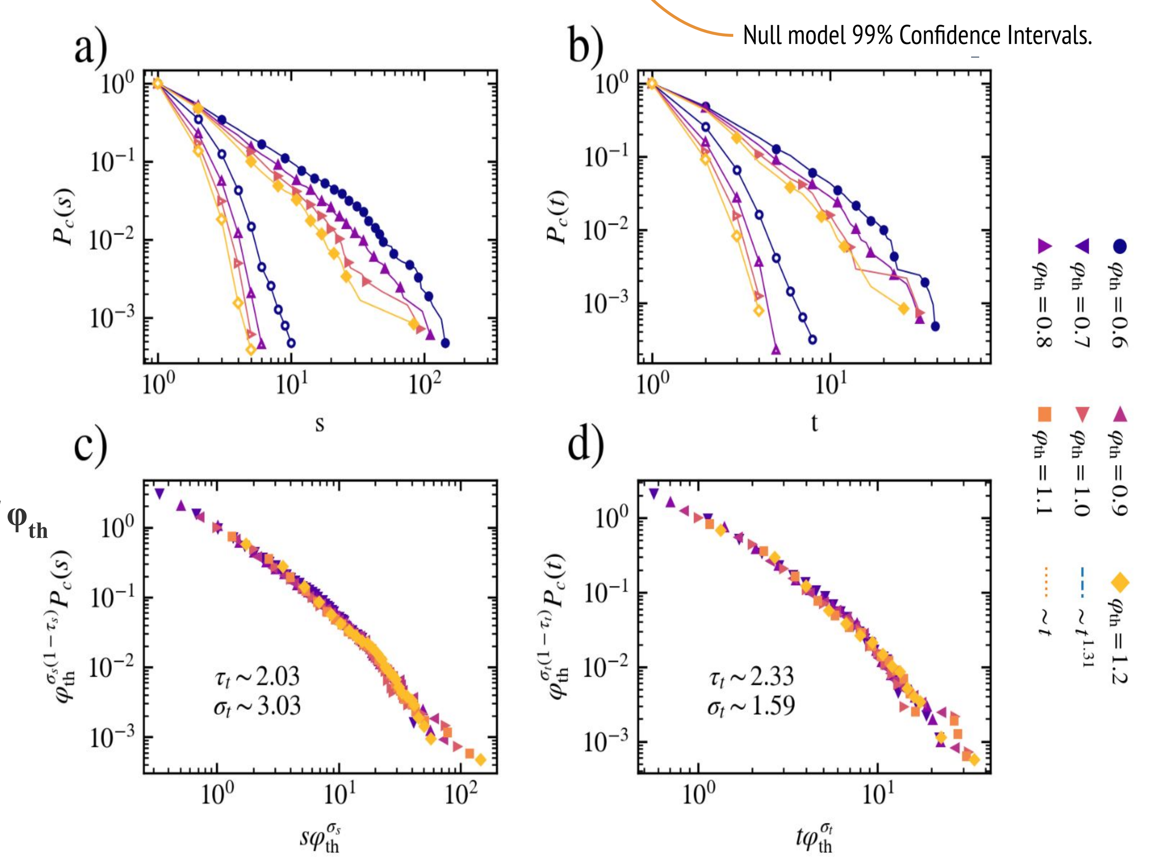
The turn dynamics of the fish is correlated:

- Both $P_c(s)$ and $P_c(t)$ show **long tails**, a power-law of the form $P(s) \sim s^{-\tau s}$ and $P(t) \sim t^{-\tau t}$, respectively.
- Randomizing the sequence of turning angles of each fish shows an exponential decay (hollow symbols)

After scaling, distributions for different values of φ_{th} collapse onto a universal function $F'_s(z)$:

$$\varphi_{th}^{\sigma_s(1-\tau_s)} P_c(s) = F'_s\left(s\varphi_{th}^{\sigma_s}\right)$$

where $F'_s(z) = z^{-\tau_s+1} F_s(z)$



AVALANCHES IN MODIFIED VICSEK MODEL

Avalanche duration (t):
Number of consecutive time steps with at least one active individual.

Avalanche size (s) :
Sum of the number of active individuals at each time step.

Avalanche statistics

Avalanches can be induced by the presence of effective leaders that have long-range interactions.

Only turning angles larger than a threshold can be attributed to leader perturbations.

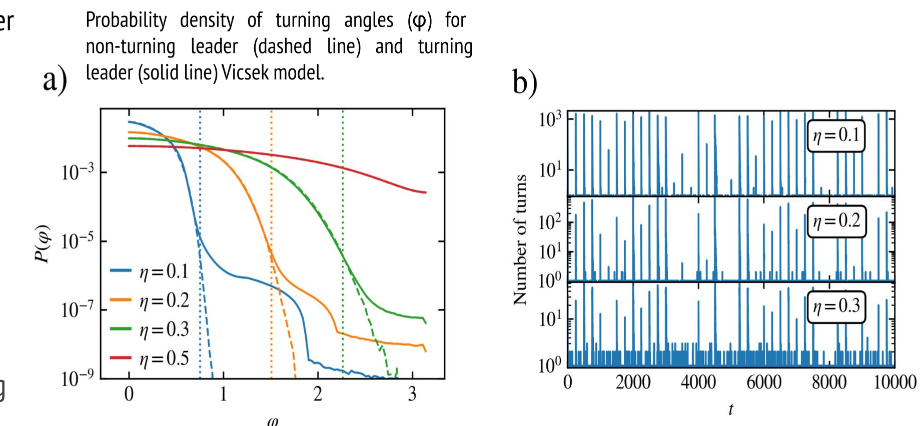
$$\varphi_{th} \geq \varphi_c(\eta)$$

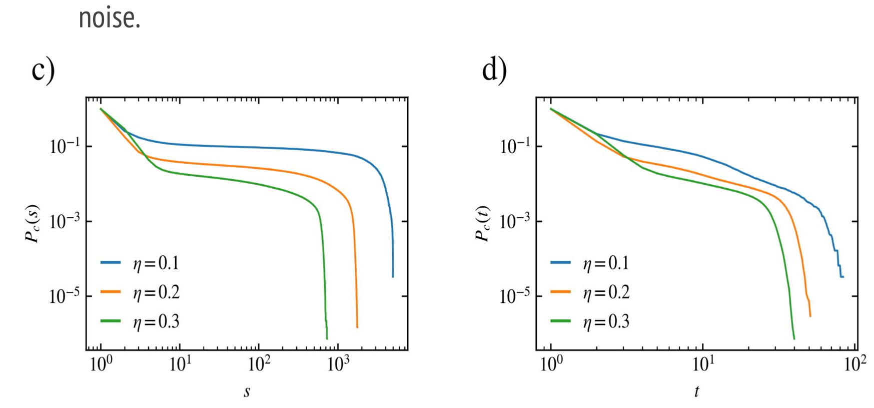
Turns in time have a similar behavior than fish:

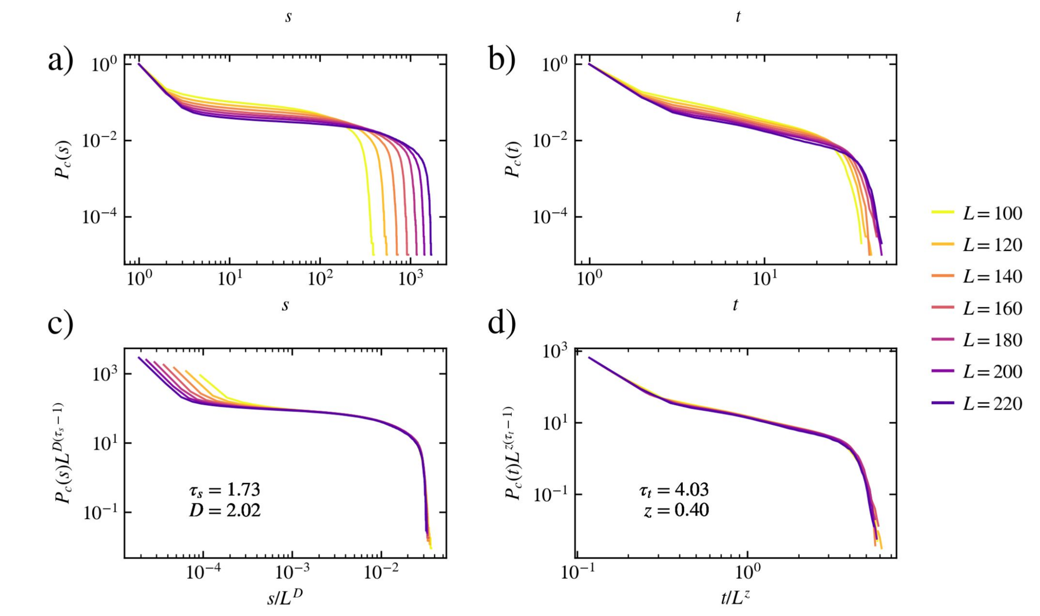
Variable avalanche sizes in response of leader's changes of direction.

The strength of the effect of the leader decreases with increasing noise.

Probability density of turning angles (φ) for non-turning leader (dashed line) and turning leader (solid line) Vicsek model.







Avalanche size (*s*) and duration (*t*)

Avalanches defined with turning threshold $\varphi_{th} = \varphi(\eta)$.

S and t distributions similar to fish:
Power-law behavior followed by a sharp decrease for large s and t.

Avalanche size distributions are independent of the noise intensity but avalanche duration dynamics is affected by the level of noise of the system.

Finite-size scaling (FSS) moments analysis on system of different sizes L shows similar exponents for different η.

$_t$ exponents are particularly different.

Data collapse analisis hints partial univerality:

Fixing η = 0.2 and rescaling s and t, and their probability distributions, by system size (L) results in a perfect collapse with the same universal function.

CONCLUSIONS

- We examined avalanche behavioral features in groups of schooling fish and compared the results with a modified version of the Vicsek model.
- Our numerical results show that avalanches can be induced by the presence of effective leaders that have long-range interactions.
- The model replicated avalanche features of the fish collectives. Avalanches in fish could be initiated by few individuals acting as effective leaders.
- Avalanche size and duration distributions in both our experimental and numerical analysis share traits with physical avalanching systems: power-law tail truncated by a cut-off due to system size.
- Through finite-size scaling analysis, we found scaling exponents for avalanche size and duration, which hint towards partial universality.
- Leadership probability analysis in fish indicate the existence of fish that consistently initiate rearrangement avalanches.

Further work

- Explore the relationship between individuals speed and turning rate in fish avalanches.
- Study in depth the presence of individuals that consistently initiate an avalanche and how the process of switching effective leadership occurs in fish collective motion.
- Disentangle the relationship of avalanche duration with microscopic properties, such as noise intensity

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