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Effects of burst-and-coast duty cycle on collective behavior in a fish school model

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Collective behaviour course research seminar report

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Burst-and-coast swimming is a common mode of locomotion among fish. Its asynchronous decision making process significantly affects interactions between fish and collective behavior within a school. Our project expands upon a paper that modeled burst-and-coast swimming and studied its long-term collective behaviour, but modeled the burst phase as an instantaneous impulse. We intend to investigate the effects of this simplification on collective behavior as well as the effects of intermittent movement and asynchronous decision making in general by varying the duty cycle and number of decisions per burst.

Collective behavior | Burst-and-coast | Fish school model

Introduction

The behavior of individual fish in a group is strongly influenced by social interaction, resulting in collective behaviors such as swarming, schooling and milling. These behaviors have been extensively studied [1, 2] and reproduced using continuous motion models.

However, continuous motion is not the typical mode of locomotion for many species of fish. Instead, many species use burst-and-coast swimming [3] where movement is composed of two cyclical phases: the burst phase, during which the fish decides on a direction (based on the aforementioned social interactions) and rapidly accelerates towards it; and the coast phase, during which the fish passively glides and does not actively attempt to change its speed or heading outside of deceleration due to drag. The ratio between the duration of the burst phase and the total durations of both phases is known as the duty cycle [4].

We build upon a paper by Wang et al. [5] which models the behavior of *Hemigrammus rhodostomus* using agents that implement burst-and-coast swimming and analyzes the long-term collective behavior of large groups of such agents. One of the simplifications made by the model is to treat the burst phase as an instantaneous event due to its short duration compared to the coast phase [6], which is equivalent to a duty cycle of 0%. We will introduce additional parameters to model a non-zero duty cycle and study its effects on the collective behavior.

Related work. Lin et al. [7] researched the effect of perturbations on the behavior of schools of fish based on the burst-and-coast model. The perturbations were modeled as a slight modification of the attraction and alignment strength of a subset of fish in the population. Their findings showed that larger groups of fish (N = 100) are much more sensitive to perturbations than smaller groups (N = 25 or N = 50) across most combinations of attraction and alignment strength.

The paper we're expanding upon is based on work by Calovi et al. [6] that also implements a burst-and-coast model for the same species of fish. This paper used raw data obtained by capturing the movement of fish in enclosed tanks using a camera, along with domain knowledge about the specific species of fish, to model the movement of fish during the kick and glide phases. They also separated the drives of avoiding the wall of the tank and interacting with another (neighboring) fish.

Methods

We re-implemented the model from the original paper [5] in Python. We then extended it with two additional parameters that model a non-zero duty cycle.

Base model. The original burst–coast model consists of a repeated cycle:

1. **Heading selection:** Before each burst, the fish computes a new heading based on random noise, attraction and alignment to its $k = 1$ or $k = 2$ most influential neighbors.
2. **Burst phase (kick):** The fish updates its heading and samples a random kick time and length.
3. **Coast phase:** The fish now moves along a straight path for the duration and length of its kick, with an exponentially decreasing velocity.

4. **Repeat:** Once the fish reaches the end of its coast phase, it immediately selects a new heading and begins a new burst.

Extended model. The extended model introduces two new key parameters: the duty cycle ω and the number of decision steps n_ω. This transforms the motion from discrete jumps to continuous velocity integration, which is a more realistic representation of fish locomotion.

Duty cycle. When a new swimming cycle beings, its total duration τ, is split into burst and a coast phase:

$$\tau_{\text{burst}} = \omega \cdot \tau \quad \text{and} \quad \tau_{\text{coast}} = (1 - \omega) \cdot \tau$$

At low duty cycles ($\omega \approx 0$), we expect the behavior of the extended model should resemble the behavior of the base model. At higher duty cycles, the velocity will not immediately begin to decrease when a new heading is selected.

Number of decision steps. The parameters n_ω controls the granularity of decision making during the burst phase. It dictates how many times a fish re-evaluates social forces and adjusts its direction within a single burst.

Determining groups. In order to study the effects of different parameters on the collective behaviour of fish in more detail, each fish is assigned to a group of (one or more) fish based on its position (proximity to other fish) on every kick. Initially, we just implemented the same algorithm for group assignment as the original authors, but that proved to be computationally inefficient. This prompted us to add *path compression* to initial group assignment and to tackle group merging using a *union-find data structure* instead of a naive full traversal of the group array for a given pair of fish.

Evaluation Metrics. We use three metrics to evaluate collective behavior. These will also be used to compare our results with the original model. The first one is **dispersion**, representing the average square of distance from the barycenter (i.e. how much the fish are spread out in space). The second one is **polarization**, which is the measure of how aligned the headings of different fish are (higher polarization corresponds to higher degree of alignment). Lastly, the **milling index** quantifies the degree of how much the fish are swimming around a barycenter in a circular fashion. We will use the exact same metrics as the original paper with the goal of producing comparable results. These metrics allow for classification of ordered schooling, milling, swarming, and disordered phases. For exact formulas and their explanations, see [5].

Experiments. We first verified that our implementation of the base model matches that of the original paper. We varied the attraction strength ($[0, 0.6]$, discrete step 0.05) and alignment strength ($[0, 1.2]$, discrete step 0.1), collecting the averages of all three key metrics over 20 simulations for each set of parameters. Each simulation had $N = 100$ fish and stopped at $200000 = 2000 \times N$ kicks. We performed this experiment for both $k = 1$ and $k = 2$.

An analogous experiment was performed for the extended model. To study the effects of the new duty cycle (ω) and decision steps (n_ω) parameters, we collected the three key metrics while varying ω and n_ω. For the purposes of brevity, we performed the experiment for only four combinations of the new parameters (low/high ω with low/high n_ω). The results are provided in the appendix (5-8).

Results

Base model. Figure 1 shows the results of the experiment we performed to verify the correctness of our base model. The values are nearly identical to those in the original paper, although our experiment was performed with a lower resolution in terms of attraction and alignment strength.

Figure 2 depicts how the number of groups in the whole population evolved through time for different types of emergences. However, this experiment yielded somewhat different results than the original paper.

Extended model.

Duty cycle (ω).

- Low ω (≤ 0.3): These states show moderate polarization and relatively high dispersion, which aligns with expectations. Short bursts and long coasts reduce opportunities for coordinated corrections within the group. The agents have fewer chances to align or stay cohesive, so schooling is less compact and more fragmented.

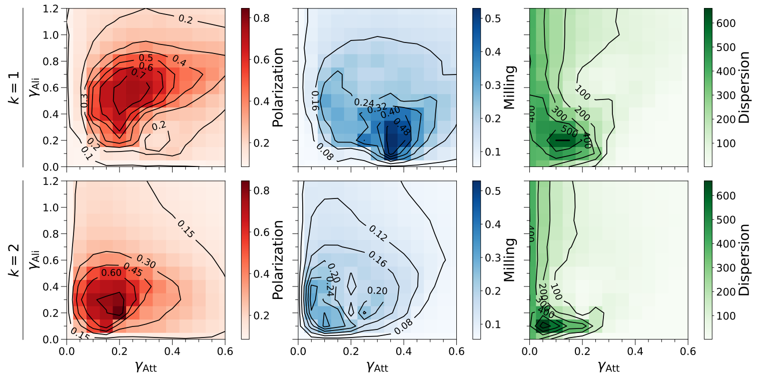


Figure 1. Polarization (red), milling (blue) and dispersion (green) values for different combinations of attraction strength (γ_{Att}), alignment strength (γ_{Ali}) and number of neighbors that influence heading selection (k). Each value is an average of 20 runs with different seeds, with each run lasting $2000 \times N = 200000$ kicks. Metrics are only collected after $1000 \times N$ kicks to reduce the influence of initial conditions.

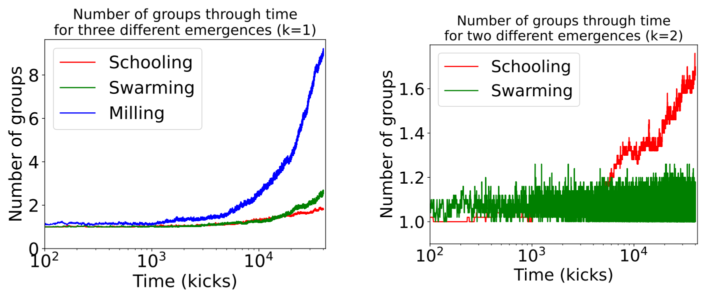
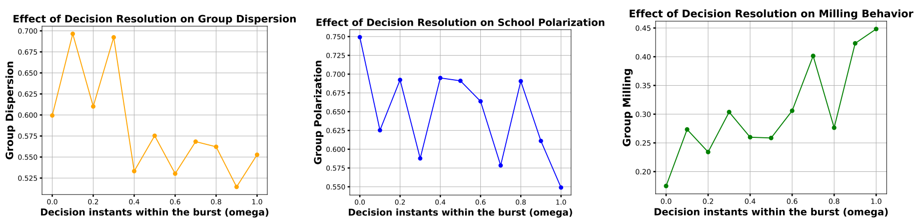


Figure 2. Number of groups with respect to time for two different types of emergences. Each fish was influenced by $k = 1$ (left) or $k = 2$ (right) fish at every kick. This time, we got more mixed results compared to the original paper. These discrepancies may be explained by the lower number of runs per configuration and slight differences between the behaviour and/or assignment of groups in the two implementations.

- Intermediate ω $(0.4 \leq \omega \leq 0.7)$: Group polarization remains relatively high and stable while dispersion shows modest fluctuations. This suggests that an intermediate duty cycle allows the school to maintain both alignment and cohesion effectively, balancing active swimming and coasting.
- High ω (≥ 0.8): At high duty cycles, fish swim almost continuously. Our results show that dispersion slightly decreases compared to low ω, indicating a more cohesive school. Polarization, however, does not monotonically increase and exhibits some fluctuations, reflecting that continuous swimming promotes cohesion but may also amplify local fluctuations in alignment.



(a) Dispersion **(b)** Polarization **(c)** Milling

Figure 3. Side-by-side comparison of dispersion, polarization, and milling for different values of ω. Results are obtained from long simulations of $200{,}000$ kicks and multiple independent realizations per parameter setting, providing statistically robust estimates.

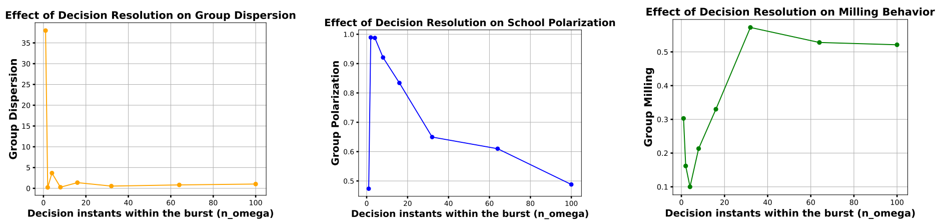
These results indicate a nuanced relationship between duty cycle ω and collective behavior. Polarization peaks around intermediate values of ω ($\omega \sim 0.4$–0.7), suggesting an optimal balance between burst and coast for maintaining alignment. Dispersion is generally highest at very low ω due to infrequent heading updates, while it slightly decreases at high ω, reflecting a more cohesive school without extreme compression.

Number of decision steps (n_ω). We also explored the effect of the number of decision steps n_ω within a fixed duty cycle ($\omega = 0.5$) on school stability.

- $n_\omega = 1$: This corresponds to a single heading decision per burst, representing the discrete burst–coast baseline. At this resolution, the school is highly unstable:

polarization is low and dispersion is extremely high (unbounded in some runs), indicating that the agents are unable to perform corrective maneuvers and the group fragments easily. This confirms that a single burst decision is insufficient for maintaining cohesion.

- $n_\omega = 2$–4: Adding even a few decision steps per burst strongly stabilizes the school. Polarization rises sharply and dispersion drops dramatically, indicating more cohesive and aligned group motion. Even a small number of intra-burst corrections significantly improves schooling stability.
- $n_\omega \geq 8$: Beyond moderate n_ω, polarization and dispersion begin to fluctuate in a stable range and converge, suggesting that the system approaches a quasi-continuous-time limit. Further increasing n_ω results in very frequent updates, so small angular corrections are applied continuously, which accumulates into persistent turning, which promotes milling-like trajectories.



(a) Dispersion **(b)** Polarization **(c)** Milling

Figure 4. Side-by-side comparison of dispersion, polarization, and milling for different values of n_ω. Results are obtained from long simulations of $200{,}000$ steps and multiple independent realizations per parameter setting, providing statistically robust estimates.

These results confirm that increasing the number of decision steps per burst strongly enhances school cohesion and alignment, especially when moving from the extreme discrete case $n_\omega = 1$ to $n_\omega \geq 2$. Polarization quickly rises while dispersion drops to realistic values. For larger n_ω, the metrics stabilize, supporting the idea that continuous intra-burst heading updates are critical for maintaining cohesive and aligned schooling in this extended model. Too much control allows rotational modes (milling) to emerge and compete with alignment (polarization).

Discussion

We have (re-)implemented a burst-and-coast model and extended it with both a simulation framework and a generalization of the duty cycle. The results we obtained are consistent with those of the original model ([5], see figure 1), with the exception of the number of groups.

With the extended model, we first verified that it reproduces the base burst–and-coast dynamics exactly in the familiar case, where $\omega = 0$ and $n_\omega = 1$. Varying the duty cycle ω then leads to gradual changes in all metrics, with intermediate values supporting stable and cohesive schooling. In contrast, the number of decision steps n_ω has a dominant effect on stability: a single decision per burst results in fragmented and weakly aligned groups, while even a small number of intra-burst decisions dramatically improves cohesion and alignment. For sufficiently large n_ω, the collective metrics converge, indicating that the model approaches a continuous-decision regime. These results highlight the importance of intra-burst temporal resolution for maintaining stable collective motion.

CONTRIBUTIONS. JA implemented the base model. MP implemented the simulation framework. AH implemented the extended model. All authors contributed to the report.

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Appendix

Table 1. Mean and standard deviation of polarization, dispersion, and milling as a function of ω.

ω	Polarization	Dispersion	Milling
0.00	0.7492 ± 0.2252	0.5994 ± 0.1895	0.1750 ± 0.1174
0.10	0.6252 ± 0.2208	0.6965 ± 0.1878	0.2734 ± 0.1585
0.20	0.6923 ± 0.2053	0.6101 ± 0.1753	0.2341 ± 0.1391
0.30	0.5878 ± 0.2317	0.6923 ± 0.1747	0.3037 ± 0.1627
0.40	0.6949 ± 0.2694	0.5332 ± 0.1787	0.2599 ± 0.2221
0.50	0.6911 ± 0.2380	0.5753 ± 0.1882	0.2586 ± 0.1878
0.60	0.6638 ± 0.2652	0.5302 ± 0.1551	0.3059 ± 0.2313
0.70	0.5784 ± 0.2908	0.5683 ± 0.1721	0.4014 ± 0.2185
0.80	0.6906 ± 0.2147	0.5622 ± 0.1580	0.2764 ± 0.1566
0.90	0.6110 ± 0.3283	0.5145 ± 0.1692	0.4233 ± 0.2286
1.00	0.5490 ± 0.3125	0.5527 ± 0.1622	0.4482 ± 0.2281

Table 2. Mean and standard deviation of polarization, dispersion, and milling as a function of n_ω.

n_ω	Polarization	Dispersion	Milling
1	0.4736 ± 0.0313	37.9653 ± 13.7558	0.3028 ± 0.0334
2	0.9891 ± 0.0001	0.2215 ± 0.0066	0.1619 ± 0.0027
4	0.9875 ± 0.0401	3.6712 ± 18.6655	0.0999 ± 0.0603
8	0.9209 ± 0.1220	0.2705 ± 0.1947	0.2133 ± 0.1735
16	0.8340 ± 0.1834	1.3743 ± 4.6047	0.3300 ± 0.2348
32	0.6496 ± 0.2446	0.5445 ± 0.1847	0.5725 ± 0.2833
64	0.6099 ± 0.1882	0.8251 ± 0.3290	0.5279 ± 0.1905
100	0.4880 ± 0.1501	1.0343 ± 0.4150	0.5211 ± 0.1638

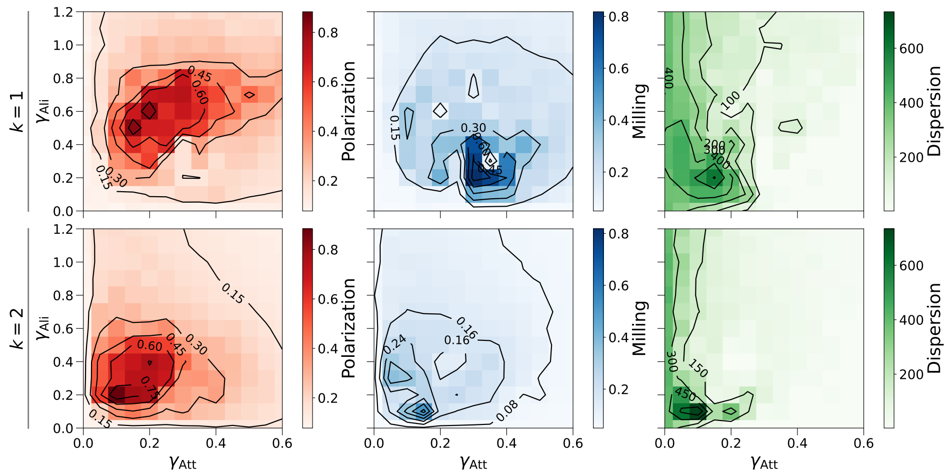

Figure 5. Extended model with $\omega = 0$ and $n_\omega = 1$, which reproduces the base implementation. The dispersion color bar spans values up to 600, indicating that the school is highly spread out and frequently fragmented. Shown are polarization (red), milling (blue), and dispersion (green) for different combinations of attraction strength (γ_{Att}), alignment strength (γ_{Ali}), and number of influential neighbors (k). Each data point is averaged over 20 independent runs with different random seeds, where each run lasts $2000 \times N = 200{,}000$ kicks. Metrics are collected only after the first $1000 \times N$ kicks to reduce the influence of initial conditions.

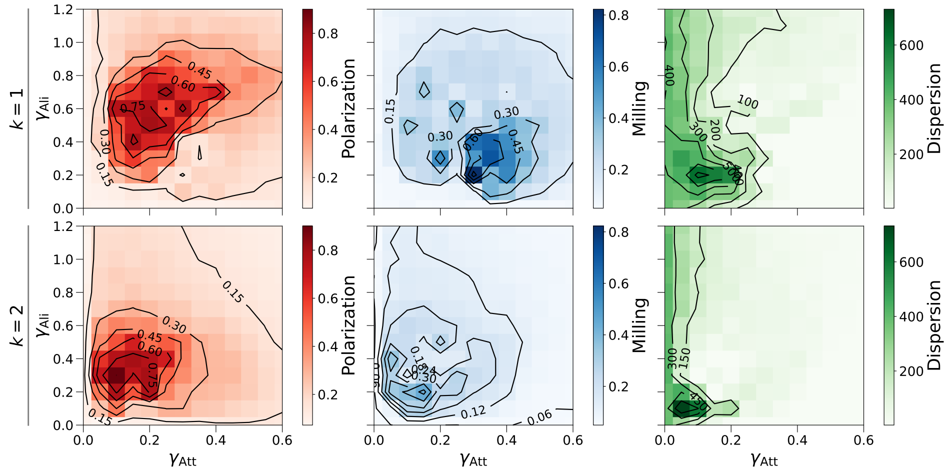

Figure 6. Extended model with $\omega = 0.5$ and $n_\omega = 1$. Polarization is slightly higher compared to the base implementation, as indicated by the emergence of a 0.75 polarization contour. The central milling region is marginally more spread out. However, due to the low decision resolution ($n_\omega = 1$), these differences remain minor, and the school overall remains unstable and prone to fragmentation.

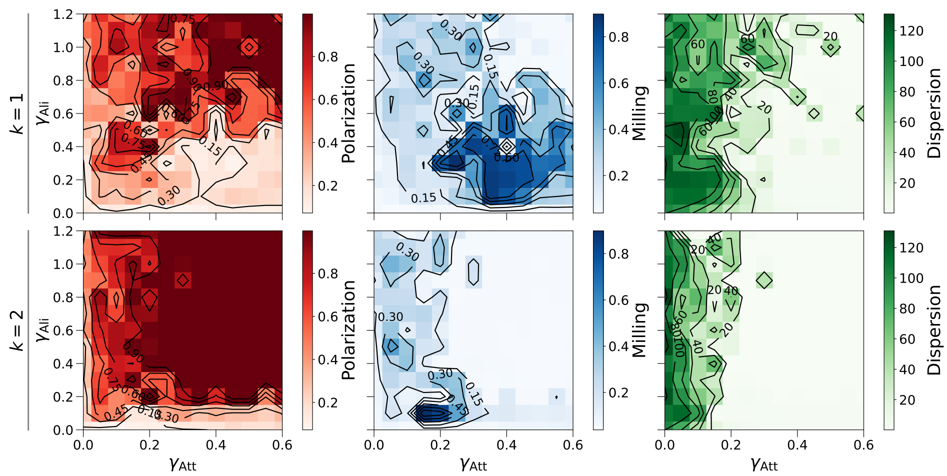

Figure 7. Extended model with $\omega = 0$ and $n_\omega = 10$. Increasing the number of decision steps leads to a significantly more compact and cohesive school, with dispersion values reaching approximately 120 instead of 600. The increased presence of dark green regions reflects the rescaled color bar rather than higher absolute dispersion. Polarization is markedly stronger, as indicated by extended dark red regions, showing that fish are nearly parallel. Strong milling states (dark blue) emerge, demonstrating the ability of the school to maintain stable circular motion without tangential escape.

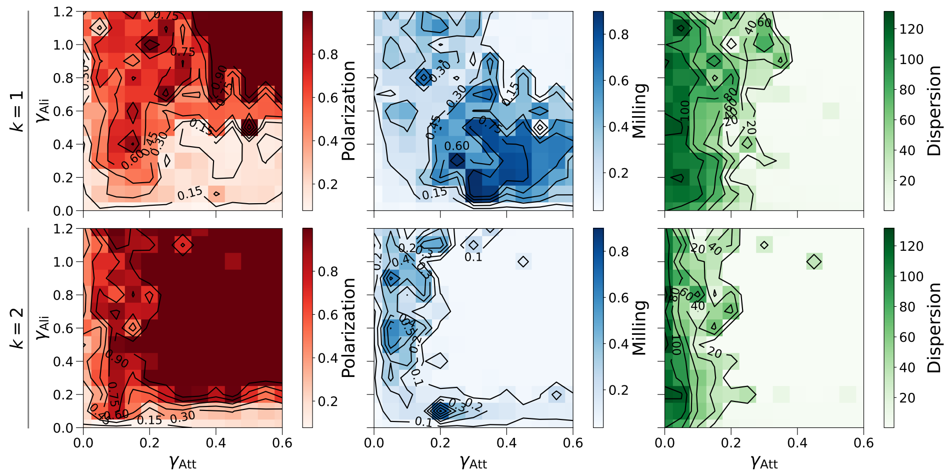

Figure 8. Extended model with $\omega = 0.5$ and $n_\omega = 10$. The polarized region (red) is slightly larger and more contiguous compared to lower ω, indicating that the school becomes locked into a parallel formation. In this regime, alignment emerges partly from kinematic persistence in addition to social interactions. Milling is moderately suppressed, as evidenced by weaker and more diffuse peaks, consistent with sustained speed causing agents to overshoot circular trajectories. Dispersion is slightly reduced compared to the $\omega = 0$ case at the same n_ω, suggesting that while n_ω primarily governs cohesion, sustained propulsion further enhances dynamic coupling within the school.