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Effects of Differences in Swimming Speed on Heterogeneous Fish Schools in a Set-Net Environment

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Abstract: Set-net fishing often captures multiple fish species simultaneously, necessitating labor-intensive sorting and leading to lower survival rates for released fish. To mitigate these issues, this study examines how differences in swimming speed affect the behavior of heterogeneous fish schools in a rectangular set-net environment. By extending a schooling model to incorporate species-specific parameters, we conducted simulation experiments with two fish species. Our results reveal that differences in swimming speed can lead to spontaneous spatial separation of the schools. These findings shed light on the critical parameters underlying mixed-species dynamics and offer guidance for designing set-net structures and operational strategies aimed at selective capture, with the potential to contribute to the efficient and sustainable use of fisheries resources.

Keywords: Schooling Behavior, Separation of Schools, Heterogeneous Fish Schools

1. INTRODUCTION

Set-net fishing is a crucial coastal fishing method in Japan. It accounted for approximately 49% of the nation's coastal fisheries production in 2022. This fishing method has the advantage of being conducted in fishing grounds located near ports, allowing captured fish to be kept alive within the nets until landing, thereby ensuring high freshness. Additionally, the structural modification of the net enables the capture of a wide variety of marine species. However, set-net fishing is a passive fishing method that relies on fish schools swimming into the nets, resulting in the capture of multiple species. As a consequence, non-target species must be manually sorted and subsequently released . The survival rate of released fish is likely to be low , and the manual sorting process requires significant labor. Therefore, developing methods to selectively capture fish by species within the set-net is a critical issue for both environmental conservation and improving fishing efficiency.

Understanding how multiple fish species with different characteristics—such as swimming speed and field of vision—affect school behavior is essential for developing methods to guide and separate them. Such advancements could potentially contribute to improving the efficiency of set-net fishing. One of the primary approaches for gaining deeper insights into fish school behavior is simulation. For example, Gautrais et al. [1] developed a mathematical model describing how fish schools form and move, based on the Boid model [2], a well-known model for collective behavior. Through simulations of this model, they identified key factors influencing fish school behavior. Similarly, Huse et al. [3] used simulations to evaluate the effect of fish with specific destinations on the behavior of the school. Moreover, research has been conducted to simulate fish school behavior in order to better understand the impact of set-net structures on fish movement [4].

The aforementioned studies investigate fish school behavior by focusing on a single species. However, in actual set nets, multiple fish species often enter. Nevertheless, the impact of species heterogeneity on fish school behavior has not been fully understood. In particular, it remains unclear which specific species differences lead to changes in fish school behavior.

This study aims to examine how interspecific differences in traits such as swimming speed or vision range affect heterogeneous fish schools in a set net. To achieve this, a simulation model was employed in which multiple fish species swim within a rectangular net. Using the results of this simulation, the effects of characteristics such as swimming speed and field of vision on fish school behavior were examined. Through this investigation, we aim to identify species differences that induce behavioral changes in heterogeneous fish schools and enhance our understanding of their dynamics.

2. FISH SCHOOLING MODEL

In this section, we describe the mathematical model of fish schools considered in this study. This model primarily follows Gautrais et al. [1] for inter-fish interactions. For the fish response to the nets, we adopt the approach of Takahashi et al. [4].

A cubic net encloses the fish in 3D space, serving as a boundary that influences their movement through avoidance or approach (see $A(t)$). Each fish perceives the environment within a spherical field of vision. Additionally, there is a conical blind spot behind the fish, with its axis aligned with the fish's direction of movement. The opening angle of this cone is set to $180^\circ - \theta_{\text{view}}(\theta_{\text{view}} \geq 0)$. We generate fish inside a cubic net, where each fish determines its movement direction by reacting to other fish and to the net within its field of vision.

Below, we detail how each fish updates its position and direction at each time step. Let $x_i(t)$ and $v_i(t)$ be the position and unit direction vector of fish i at time t, with a constant speed $s > 0$. Thus, the velocity of fish i is

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given by the product of the constant speed s and the unit direction vector $v_i(t)$, or $s \cdot v_i(t)$. At each time step, the position of fish i is updated by $x_i(t+1) = x_i(t) + sv_i(t)$. This update occurs at each time step $t = 0, 1, 2, \ldots$. The unit direction vector $v_i(t)$ in this equation is initially determined by the desired heading $h_i(t)$, and, if necessary, adjusted to comply with the maximum rotation angle constraint. The desired direction $h_i(t)$ will be described later. Specifically, if the angle between $h_i(t)$ and the unit direction vector $v_i(t-1)$ from the previous step exceeds $\theta_{\max}$, the vector $v_i(t)$ in the next step is obtained by rotating $v_i(t-1)$ by an angle of $\theta_{\max}$ towards $h_i(t)$. If the angle is less than or equal to $\theta_{\max}$, then we set $v_i(t) = h_i(t)$.

We now describe how $h_i(t)$ is determined. Let $R(\theta, u)$ be the rotation matrix representing a rotation by an angle θ around the axis u. The desired direction $h_i(t)$ of fish i is defined as

$$h_i(t) = R(d\gamma, q)\frac{D(t) + A(t)}{\|D(t) + A(t)\|} \tag{1}$$

where $d\gamma$ is a random rotation angle introduced to prevent the fish from moving in a perfectly straight line, $D(t)$ is a vector representing the response to other fish, and $A(t)$ is a vector representing the response to the net. Furthermore, we define q as a random unit vector orthogonal to $D(t) + A(t)$. In this study, the rotation angle $d\gamma$ follows a normal distribution with a mean of 0 and a variance of 0.0012, as in the model proposed by Gautrais et al. [1].

We describe the vectors $D(t)$ and $A(t)$ in equation (1). In defining the former vector, this study follows the model by Gautrais et al. and assumes that each fish's response to other fish is determined by the distance between them, selecting from three types of reactions. These three types of responses are repulsion, alignment, and attraction. The first response, repulsion, occurs at short distances, where the fish moves away from the other fish. The second response, alignment, occurs at intermediate distances, where the fish moves in the same direction as the other fish. The final response, attraction, occurs at long distances, where the fish moves toward others. Let r_r be the threshold distance for repulsion, r_o the threshold for alignment, and r_a the threshold for attraction. We assume that these three distances satisfy the relationship $r_\mathrm{r} \le r_\mathrm{o} \le r_\mathrm{a}$ Under this assumption, the vector $D(t)$, which represents the response to other fish, is given by:

$$D(t) = \begin{cases} w_1 \displaystyle\sum_{j \in N_\mathrm{r}(t)} \frac{x_i(t) - x_j(t)}{\|x_i(t) - x_j(t)\|}, & \text{if } |N_\mathrm{r}(t)| > 0, \\ w_2 \displaystyle\sum_{j \in N_\mathrm{o}(t)} \frac{v_j(t-1)}{\|v_j(t-1)\|} + \\ \qquad w_3 \displaystyle\sum_{j \in N_\mathrm{a}(t)} \frac{x_j(t) - x_i(t)}{\|x_j(t) - x_i(t)\|}, & \text{otherwise.} \end{cases}$$

Here, w_1 is the weight coefficient for the repulsion response, and $N_\mathrm{r}(t)$ denotes the set of fish whose distance from fish i is at most r_r. Similarly, w_2 and w_3 are the weight coefficients for alignment and attraction responses, respectively. The sets $N_\mathrm{o}(t)$ and $N_\mathrm{a}(t)$ represent the fish whose distance from fish i is greater than r_r and at most r_o, and those whose distance is greater than r_o and at most r_a, respectively.

Next, we describe the response to the net, $A(t)$. The response $A(t)$ represents either an avoidance behavior or an approach behavior toward the net. The selection between these two behaviors depends on the fish's velocity at time $t-1$. The first behavior, avoidance, occurs when the inner product of the normal vector $n(t-1)$ of the nearest visible net surface and the movement direction vector at time $t-1$ is negative. In other words, avoidance is triggered when the fish is moving toward the net. The avoidance behavior is computed using the weight coefficient for the net avoidance response, w_4, and $n(t)$ as $A(t) = w_4 n(t)/\|n(t)\|$. The second behavior, approach, occurs when the inner product of the normal vector $n(t-1)$ of the nearest visible net surface and the movement direction vector at time $t-1$ is greater than zero. In other words, the approach behavior is triggered when the fish is moving away from the nearest visible net. The approach behavior is computed using the weight coefficient for the net approach response, w_5, and $n(t)$, as $A(t) = -w_5 n(t)/\|n(t)\|$.

The unit direction vector $v_i(t)$ at step t is determined by two cases, depending on the magnitude of the angle $\theta_{\text{diff}}(t)$ between the desired direction $h_i(t)$ without considering the maximum turning angle and the unit direction vector $v_i(t-1)$ from the previous step. If the cross product of $h_i(t)$ and $v_i(t-1)$ defines the rotation axis as $p(t)$, the unit direction vector $v_i(t)$ is given by:

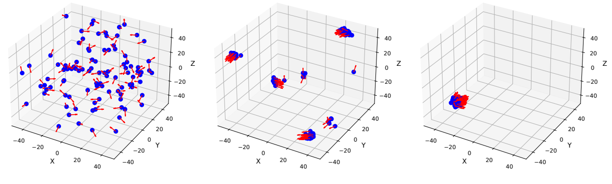
$$v_i(t) = \begin{cases} h_i(t), & \text{if } \theta_{\text{diff}}(t) \le \theta_{\max}, \\ R(\theta_{\max}, p(t))v_i(t-1), & \text{otherwise.} \end{cases}$$

In the above model, there may occur exceptional cases where a fish's position ends up outside the net. In such instances, the fish will move back into the net without reacting to other fish or the net itself.

3. SIMULATION METHOD

This section describes the simulation setup for analyzing fish school behavior using the model from Section 2. We first describe the initialization of fish positions and velocities, then outline the parameter settings and termination criteria, and finally explain how we assess the resulting behavior. At step $t = 0$, 100 fish are placed within a cubic net of side length 100. Specifically, each fish's position is generated from a uniform distribution over the interval $[-50, 50]$ for each dimension. Moreover, the initial heading of each fish is also assigned randomly by sampling from the interval $[-1, 1]$ in each coordinate and then normalizing the resulting vector.

Two types of simulations were conducted. In Simulation 1, we generate 100 fish of the same species as a reference for comparison with Simulation 2, which will be described later. The parameters in the fish school model were based on the models by Gautrais et al. [1]



(a) $t = 0$ (b) $t = 500$ (c) $t = 1000$

Fig. 1: Schooling behavior (Simulation 1)

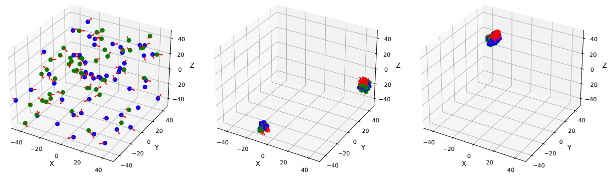
and Takahashi et al. [4]. Specifically, the fish's constant speed was set to $s = 1.5$ and its view angle $\theta_{\text{view}} = 135°$. Additionally, the maximum turning angle was set to $\theta_{\text{max}} = 19.763°$. The threshold distances for repulsion, alignment, and attraction responses among fish were set to $r_{\text{r}} = 1.0$, $r_{\text{o}} = 10.0$, and $r_{\text{a}} = 20.0$, respectively. The weight coefficients for these behaviors were assigned as $w_1 = 1.0$, $w_2 = 1.0$, and $w_3 = 1.0$. For net avoidance, the threshold distance r_{n} was set to 20.0, and the corresponding weight coefficients for avoidance and attraction responses were assigned as $w_4 = 1.5$ and $w_5 = 0.15$, respectively. The simulation was terminated at step $t = 1000$ to ensure the system reaches a steady state. An example of the fish school behavior in Simulation 1 is shown in Figure 1, at steps $t = 0$, $t = 100$, and $t = 750$. Initially, the individuals were randomly positioned, but eventually, they formed a cohesive school.

Simulation 2 investigates fish movement with two species having interspecific differences. A total of 100 fish were divided into two groups of 50: one group consisted of fish with fixed parameters (C-fish), while the other group consisted of fish whose parameters were varied (V-fish). The V-fish had two parameters, speed and view angle, individually varied for the simulation. Each parameter combination was simulated 100 times with random initial conditions, and the simulation ended at step $t = 1000$. Results were compared to identify how interspecific differences affect schooling behavior.

4. RESULT

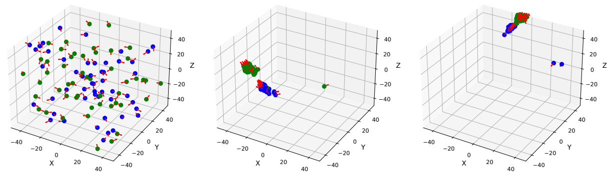
In this section, we describe the results of the simulation. By conducting the simulations, we observed the state transitions of the fish. Figure 2 illustrates the state transitions of the fish in Simulation 1, while Figures 3, 4, 5, and 6 show examples of state transitions observed in Simulation 2. Based on the simulation observations, it was confirmed that the overall dynamics of the school transitioned through six distinct states. The characteristics of each of these six states are described in detail.

- **Dispersion**
As shown in Figures 2(a), 3(a), 4(a), 5(a), and 6 (a), neither C-fish nor V-fish form a single cohesive group.
- **V-aggregation**
As shown in Figure 3 (b), C-fish are dispersed and do not form a group, whereas V-fish form a single cohesive group.
- **C-aggregation**



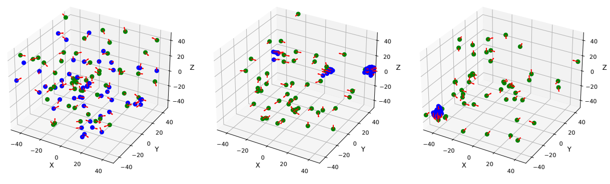
(a) $t = 0$ (b) $t = 500$ (c) $t = 1000$

Fig. 2: State transition of fish in Simulation 1



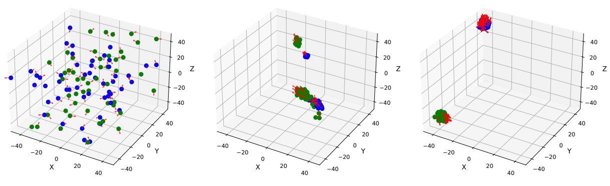
(a) $t = 0$ (b) $t = 500$ (c) $t = 1000$

Fig. 3: State transition at $s = 2$(V-fish)



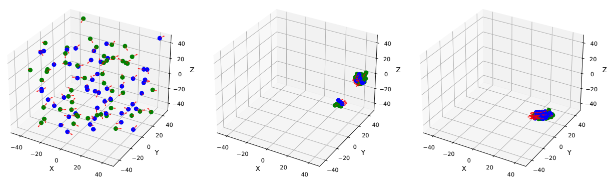
(a) $t = 0$ (b) $t = 500$ (c) $t = 1000$

Fig. 4: State transition at $\theta_{\text{view}} = 30°$(V-fish)



(a) $t = 0$ (b) $t = 500$ (c) $t = 1000$

Fig. 5: State transition at $s = 2.5$(V-fish)

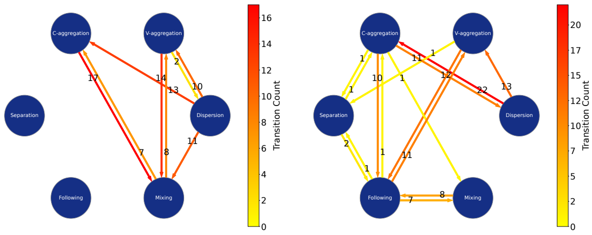


(a) $t = 0$ (b) $t = 500$ (c) $t = 1000$

Fig. 6: State transition at $\theta_{\text{max}} = 109.763°$(V-fish)

As shown in Figure 4 (c), C-fish form a single cohesive group, while V-fish are dispersed and do not form a group.
- **Separation**
As shown in Figure 5 (c), both C-fish and V-fish form separate cohesive groups, but there is a large distance between the two species.
- **Following**
As shown in Figure 6 (c), both C-fish and V-fish form a single cohesive group, with one following the other.
- **Mixing**
As shown in Figure 2 (g) to (i), C-fish and V-fish mix together, forming a single cohesive group.

To objectively classify fish dynamics into six states,



(a) Simulation 1 (b) $s = 2.5$

Fig. 7: State transition diagram

we used positional variance and interspecies centroid distance as key indicators based on the observational results. Since schooling reduces positional variance, it was used as an indicator. Additionally, since the centroid distance between the species decreases in the order of separation, following, and mixing, it was also used as an indicator. Using these indicators, the fish dynamics were classified into six distinct states. Let F_1, F_2 be index sets of C-fish and V-fish, with sizes n_1, n_2, respectively. The centroids at step t are represented as $\bar{x}_C(t)$ and $\bar{x}_V(t)$. Then, the positional variance of C-fish is defined as $\sigma_C^2(t) = \frac{1}{n_1}\sum_{i \in F_1} \|x_i(t) - \bar{x}_C(t)\|^2$. Likewise, the positional variance of V-fish is given by $\sigma_V^2(t) = \frac{1}{n_2}\sum_{i \in F_2} \|x_i(t) - \bar{x}_V(t)\|^2$. Finally, The centroid distance at step t, is defined as $L(t) = \|\bar{x}_C(t) - \bar{x}_V(t)\|$

If the calculated variance is less than 30, that species was considered to form a school, and the formation of the school was determined based on this criterion. When the variances of both C-fish and V-fish are less than 30, there are three possible states: separation, following, and mixing. Therefore, the centroid distance was additionally used to make the determination. Specifically, if the centroid distance is greater than 36, the state is classified as separation; if the centroid distance is between 3 and 36, the state is classified as following; and if the centroid distance is less than 3, the state is classified as mixing.

The dynamics of the fish school in Simulation 1 were analyzed, with the number of trials for each state transition shown in Figure 7(a). The system transitioned from the dispersion state to V-aggregation, C-aggregation, or mixed states. Since all 100 fish were the same species, the number of trials where either V-fish or C-fish formed a school first, or both formed simultaneously, was similar.

Next, the dynamics of the fish school were analyzed under the condition where the speed parameter was set to $s = 2.5$. In the case where the speed s is varied, the number of trials in which each state transition occurred during 100 trials is shown in Figure 7(b).

For $s = 2.5$, in most cases where transitions occurred, either the C-fish or the V-fish formed a school from the dispersed state. When only the V-fish formed a single school, it frequently returned to the dispersed state. However, when the C-fish formed a school first, the V-fish followed and formed a school as well, and the transition to the state where the C-fish school followed the V-fish school was mainly observed. In this state, when the V-fish school was far from the net, the V-fish outran the C-fish, transitioning to the separated state. On the other hand, when the V-fish group approaches the net, the C-fish catch up with the V-fish, often leading to a transition into a mixed state.

Hence, these results confirm that the schooling behavior transitions through the six states under various parameter combinations. Notably, the separation state may appear the most favorable for selective fishing, whereas the mixed state may complicate species-specific capture.

5. DISCUSSION

Among the six states, in the dispersion state and the mixed state, since the two species of fish are mixed together in the same state, it is considered difficult to selectively fish a particular species. On the other hand, in the separation state, where the two species of fish gather separately and are distanced from each other, selective fishing is considered easier. In the following state, although the fish species are separated front and back, it is considered somewhat easier to selectively catch a particular species compared to the separation state. Additionally, in the C-aggregation or V-aggregation state, if some mixing is allowed, it is possible to selectively catch the species forming the school. Thus, the degree of separation of fish species may vary depending on the school's state, which in turn affects the difficulty of selective fishing.

6. CONCLUSION

This study investigated how interspecific differences in key parameters—such as swimming speed and visual field—impact fish-school behavior within a static set net. Our simulation revealed six distinct states, including complete separation and mixed schooling, each influenced by parameter variations. Notably, speed differentials led to spontaneous separation, while more uniform parameters resulted in mixed or following states.

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