数理モデル化と問題解決 34−8
（２００１． ５．１１）

# 突発的騒乱への魚群の秩序的対応を創発する個体間相互模倣の働き

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**摘要** 突発的騒乱に対して魚群が示す秩序的集団対応において個体間の相互模倣がどのような働きをするのかを調べるために, 我々は魚群の群行動をシミュレーションするモデルを提案した。このモデルは個体の意志決定のルールに基づくモデルである。近隣個体に対する模倣は群れ行動になる一つの要素として考えられている。そのほか, 衝突回避行動も群れ行動になるもう一つの方策と思われている。我々の研究では, 個体が隣魚の何をどのように、そしてどの程度真似することについて調べた。スクール運動に最適な相互模倣をする群れは自己組織臨界状態であることを明らかにした。さらに, 最適模倣の群れは, 突発的騒乱に対して優れた動的安定性を持つのかについて調べた。本研究では, 魚群の突発的分裂および発散を二種類の突発的騒乱として採用された。魚群の動的安定性を評価する量は分裂及び発散された群れが一つの群れに戻る回復時間と回復臨界距離の二つの量である。調べた結果により我々のモデルは突発的騒乱に陥った魚群の秩序的対応に対しても有効であることが分かった。

# Effectiveness of Allelomimesis of Individuals in Dynamical Response of Fish School to Emergent Affairs

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**Abstract** A simulation model of collective motion of a fish group was presented to investigate the role of allelomimesis of fish individual in emergence of dynamically stable schooling behaviors. It was shown that the schooling behaviors generated using the optimal values of the allelomimesis rate correspond to a self-organized critical state. The main purpose of the present modeling is to investigate whether the tactics of individual decision-making suited to generate good schooling behaviors work well also in maintaining dynamical stability of the fish school under emergent affairs. It was found that the tactic suitable for schooling generates the dynamically stable response of the school to emergent affairs.

# 1 Introduction

It has been observed clearly [1] that the large populations of fish individuals in a school can change systematically their collective behavior under the emergent affairs, although there is no leader and every fish can know only about local situations around itself. It is a quite interesting problem whether the individual fishes use the same tactic to decide their next actions in the schooling behaviors as in the dynamically stable response to emergent affairs.

In order to solve this problem, we present a dynamical model of fish school and investigate the response by various disturbances applied suddenly to the school. We consider allelomimesis, that is, doing what your neighbors do, as the essential tactic based on which individuals decide their actions. Besides the allelomimetic actions of individuals, we introduced the collision avoidance actions to the present model too.

# 2 The Present Model of Fish School

In the present model, we assumed that the allelomimetic actions are made based on the visual information about the local situation and the avoidance actions are made based on the information about the water flow around the neighborhood. Each fish uses its eyes and its lateral lines simultaneously to make its decision of moving direction [1].

## 2.1 Areas for classification of influence of neighbors

The influence of a neighbor on the fish's action changes depending on the position of neighbor relative to the fish's position. According to Aoki's model [2], we classified the space into four kinds of areas, where we consider fish's motions in a two dimensional space without boundary. The four areas are named avoidance area, parallel orientation area, attraction area, and invisible area [1], respectively.

## 2.2 Determination of the movement of individual fish

### 2.2.1 Moving direction

Fish $i$ determines its direction $\alpha_i(t+\Delta t)$ of new movement taking simultaneously account of both the directions ${\beta_i}^{AL}(t+\Delta t)$ and ${\beta_i}^{AV}(t+\Delta t)$ convenient for allelomimetic action and collision avoidance, respectively. Then, $\alpha_i(t+\Delta t)$ is represented as

$$\alpha_i(t+\Delta t) = \gamma_{AL}{\beta_i}^{AL}(t+\Delta t) + \gamma_{AV}{\beta_i}^{AV}(t+\Delta t) \quad , \qquad (1)$$

where $\gamma_{AL}$ and $\gamma_{AV}$ represent the degree of contribution of allelomimetic action and collision avoidance, respectively, to the decision of new moving direction, and $\gamma_{AL}+\gamma_{AV}=1$.

**1. Contribution from the allelomimetic action**

(1) Fish $i$ pays attention instantaneously to one of the neighbors in both the parallel orientation and attraction areas, and the neighbor $j$ is chosen as follows. Fish $i$ chooses one direction $\theta_0$ randomly in its view $-130° \leq \theta_0 \leq 130°$ and looks for the nearest neighbor in the region of both the areas between $\theta_0 - 20°$ and $\theta_0 + 20°$. If there is no fish in the region, fish $i$ tries to choose another direction between $-130°$ and $130°$.

(2) When the neighbor $j$ is in the parallel orientation area, fish $i$ turns so that is moves in the same direction as fish $j$.

(3) When the neighbor $j$ is in the attraction area, fish $i$ moves in the direction of fish $j$.

**2. Contribution from the collision avoidance action**

Each fish needs to decide its new moving direction so as to avoid colliding with fishes in the avoidance area based on the information about the movements of the neighbors, which is obtained through its own lateral lines.

The new moving direction ${\beta_i}^{AL}(t+\Delta t)$ of fish $i$ is given by

$${\beta_i}^{AV}(t+\Delta t) = \frac{1}{N_{av}}\sum_{j=1}^{N_{av}} Dir_j(t) \pm 90^\circ \quad ,(2)$$

where $N_{av}$ is the number of neighbors in the avoidance area, $Dir_j$ is the direction of the fish $j$.

### 2.2.2 Moving speed

According to Aoki's model [2], the new speed $v_i(t+\Delta t)$ of fish $i$ is chosen independently of the other fish. The value of $v_i(t+\Delta t)$ is calculated by chance with the typical distribution given by the experiments, a Gamma distribution given by

$$P_{sp}(V) = \frac{A^K}{\Gamma(K)} exp(-AV)V^{k-1} \quad , \qquad (3)$$

where V is the speed measured in the unit of BL/sec, $K = 4, A = 3.3$, and $\Gamma(K)$ is the Gamma function. When the distance moved is expressed in the unit of body length BL, the average speed $V_{av}$ of each fish becomes 1.2BL/sec.

### 2.2.3 The new position

The new position of fish i at $(t+\Delta t)$ is given by

$$x_i(t+\Delta t) = x_i(t) + \Delta t v_i(t+\Delta t) cos\alpha_i(t+\Delta t) \quad ,(4)$$

$$y_i(t+\Delta t) = y_i(t) + \Delta t v_i(t+\Delta t) sin\alpha_i(t+\Delta t) \quad ,(5)$$

where $v_i(t+\Delta t)$ and $\alpha_i(t+\Delta t)$ are the magnitude(speed) and direction of the velosity, respectively, of fish $i$ at time $t+\Delta t$. We used in the present paper 0.1sec fot $\Delta t$.

# 3 Role of Allelomimesis in Emergence of Schooling Behaviors

## 3.1 Effect of allelomimesis on collective motion

**1. Values of $\gamma_{AL}$ generating collective motions**

First, we investigated the range of values of the allelomimesis rate $\gamma_{AL}$ in which a fish group does not split into more than two subgroups. We changed the value of $\gamma_{AL}$ in the range between 0.0 to 1.0. The result is shown in Fig.1, where the probability that the fish group gathered at $t = 0$ is not splitted until $t = 5000$ time step, is represented as a function of $\gamma_{AL}$ for groups with different number of individuals. The every group maintains schooling behaviors in the probability more than 90% when the allelomimesis rate $\gamma_{AL}$ of individual becomes more than 0.3. As the value of $\gamma_{AL}$ becomes smaller, the fish groups become easy to split.

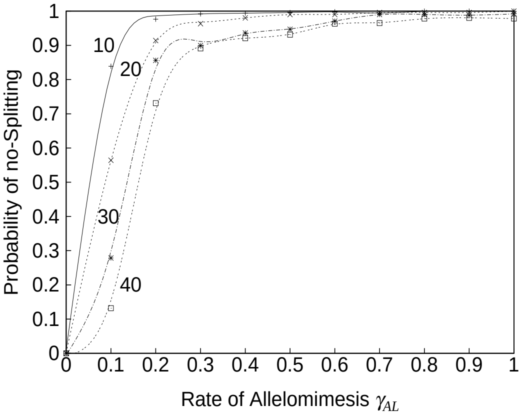

Fig.1: Dependence of the probability of making a unifild fish group on the allelomimesis rate $\gamma_{AL}$.

Based on these results, we found that the values of allelomimesis rate $\gamma_{AL}$ suitable for good schooling behaviors are within the range from 0.6 to 0.8.

**2. Dependence of time average of $\eta_p(t)$, $\eta_{NND}(t)$ and $\eta_{EX}(t)$, and of $\eta_{CF}$ on $\gamma_{AL}$**

In order to investigate the effects of allelomimesis on collective motion of a fish group, we calculated the instantuneous values of polarization $\eta_p(t)$, nearest distance $\eta_{NND}(t)$, expanse $\eta_{EX}(t)$ and collision frequency $\eta_{CF}$, which are averaged over all fishes for various values of $\gamma_{AL}$. Changing the value of $\gamma_{AL}$ between 0.1 and 1.0, we obtained the time averages of $\eta_p$, $\eta_{NND}$, and $\eta_{EP}$, and $\eta_{CF}$. Based on the results, we found that the values of allelomimesis rate $\gamma_{AL}$ suitabel for good schooling behaviors are within the range from 0.6 to 0.8.

### 3. Power spectra of $\eta_P(t)$, $\eta_{NND}(t)$, and $\eta_{EX}(t)$

In order to investigate dynamical origins of the temporal fluctuations of $\eta_P(t)$, $\eta_{NND}(t)$,and $\eta_{EX}(t)$, we calculated the power spectra $S_X(\omega)$ (X = P, NND, and EX). The result of $S_p(\omega)$ is approximated with the power law $\omega^{-\lambda}$, where $\lambda = 1.02$. We also calculated the value of exponent $\lambda$ in case of $\gamma_{AL} = 1.0$, and the result is 1.27 .

## 4 Effectiveness of allelomimesis under emergent affairs

We considered two kinds of emergent affairs, emergent splitting of a school into two groups and flash expansion of a school. These affairs occur frequently when fish groups are attacked by predators [1]. In order to evaluate the dynamical stability of fish schools, we used two kinds of measures, recovery time and critical splitting distance. The recovery time $T_R$ means the time period which it takes the fish group splitted to recover the schooling behavior. The critical splitting distance $D_{CS}$ is defined such that if the splitting distance is larger than the critical one, the fish group splitted can not return to a single school in a probability of 50%.

We measured the recovery times for a definite splitting distance $D_{ES}$ changing the value of $\gamma_{AL}$ within the range of 0.4 to 0.9. We made $10^4$ times simulations for each case with $D_{ES} = 7.0BL$ for various values of $\gamma_{AL}$. It is seen in Fig.2 the value of most probable restoring time $T_{MPR}$ is decreased with increasing $\gamma_{AL}$, but the $T_{MPR}$ becomes insensitive for $\gamma_{AL}$ larger than 0.7. The minimum value of $T_{MPR}$ was obtained by using the allelomimesis rate in the range of 0.8 to 0.9. It is seen also in Fig.2 that the value of $D_{CS}$ becomes maximum for $\gamma_{AL} = 0.7$.

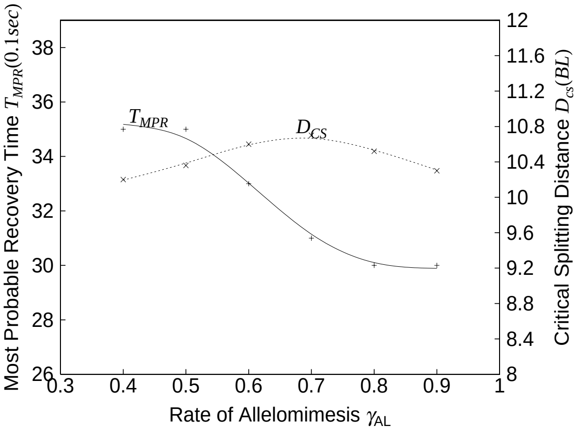

Fig.2: Dependences of the most probable recovery time period $T_{MPR}$ under the emergent splitting with $D_{ES} = 7.0BL$ and the critical splitting distance $D_{CS}$ on the value of $\gamma_{AL}$ in case of $N_{fish} = 30$. The simulation was made 2000 times for each datum point.

The similar results are found in case of flash expansion.

Based on these results we found that the values of allelomimesis rate $\gamma_{AL}$ suitable for good schooling behavior being aroud 0.7, generates the optimal response to the emergent splitting and expansion of the school.

## References

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[2] Aoki, I.: A simulation study on the schooling mechanism in fish, Bull. Japan. Soc. Sci. Fish. Vol. 48, pp. 1081-1088(1982).