

Computer simulation of emergence of group intelligence in fish school

その他（別言語等）のタイトル	魚群における群知能発現のコンピュータシミュレーション
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journal or publication title	Bulletin of the Nippon Dental University. General education
volume	27
page range	27-38
year	1998-03-20
URL	http://doi.org/10.14983/00000480



Computer Simulation of Emergence of Group Intelligence in Fish School

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(Received November 26, 1997)

We have made the computer simulations to clarify the essential mechanism of fish schooling. Though each fish does not know the movement of entire school and there is no leader in the group, they gather and move together in our simulation model. The effect of lateral line of fish was also studied. The frequency of changing direction and the fish density of school decreases when the individuals use only the information of lateral line.

We are trying to clarify a group intelligence of fish school. We assume that group intelligence are abilities emerged when individuals make shoal. One of the most important functions of schooling behavior is to reduce the probability that any given individual will be attacked by predators. In order to clarify what the group intelligence is and how the group intelligence emerges, we study predator-avoidance behaviors of fish school using our fish school model.

1. Introduction

Schooling behavior of fish is a typical example of self-organized grouping in which numerous fish individual perform a unified collective movement. The fish schools are

not formed by leaders but by relatively local interactions between fish individuals. A fish group shows a great diversity in schooling behavior depending on its condition. When the group is on a movement the fish swim in highly parallel with each other. While feeding or resting the fish show a nearly random orientation. When the fish are attacked by predators, the fish show several kinds of predator avoidance collective behaviors such as split, cruise, flash expansion and vacuole [1]. The schooling mechanism has been actively investigated experimentally and theoretically [2-4,7]. The results suggest that mutual attraction and parallel orientation contribute mainly to school formation. It was also shown that the most important senses for schooling are the eyes and the lateral line. However, it is not clear how diverse collective behaviors are organized under various situations, because observation of the behaviors could be made in only several limiting conditions [1-3]. In the present paper, we formulate a model of fish schooling mechanism for school organization. Especially, we have interest in emergence of group intelligence in fish school. One of the most important function of fish schooling behavior is to reduce the probability that any given individual will be attacked by a predator. To facilitate this function, individuals within the school engage in a repertoire of group tactics that confer protection upon them. In order to clarify what the group intelligence of fish school is and how the group intelligence is emerged, we study predator-avoidance behaviors of fish school using our fish school model.

2. Basic Observed Results for Fish Schooling

2-1. Interaction between neighboring fish based on visual information

Schooling results from the interaction that an individual controls its movement in relation to neighbors and affects simultaneously on the neighbors [2]. Many workers consider three basic behaviour patterns responsible for schooling: avoidance, approach and parallel orientation. A fish adjusts its distance to neighbors based on the information from its eyesight [2,5]. If a neighbor which an individual remarks is too near, the individual will avoid the neighbor. If the neighbor is too far, the individual will approach to the neighbor. The individual will move to the same direction as the neighbor's movement, when the neighbor is within the parallel orientation area. Fig.

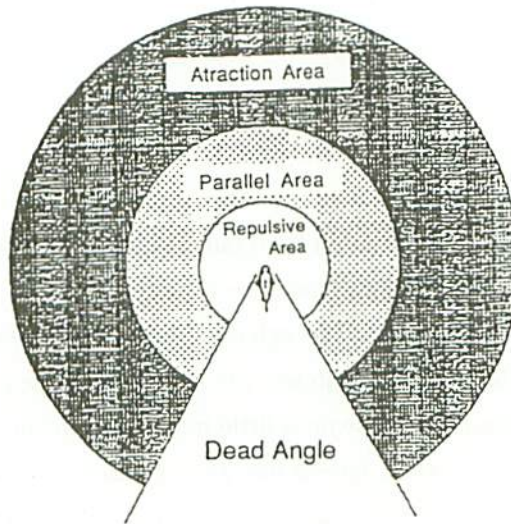


Fig. 1 Ranges of three reaction areas.

1 shows ranges of the three reaction areas. Every fish can not see the outside of attraction area and the dead angle area. The dead angle is $+30$ to -30 degree outside behind the fish. Followings are the numbers of parameters [2,5].

Repulsive area	$0 < D_{ij} \leq 0.5 L$
Parallel area	$0.5 L < D_{ij} \leq 2.0 L$
Attraction area	$2.0 L < D_{ij} \leq 5.0 L$

Where L is body length, D_{ij} is distance from fish i to j .

2-2. Detection of averaged movement of fish group around a fish based on

Lateral line is a organ through which the fish measures pressure of water. A fish can know roughly the movement of whole school through the lateral line [6]. However, the information of the movement caught is not the moving direction and speed simply averaged over whole but the direction and speed averaged with weight which is inversely proportional to a cube of the distance to each fish. Therefore, the information caught through the lateral line is practically the information made by neighbors

only, i.e. almost local information. Following equation is the information from lateral line.

$$\alpha_{L,i} = \frac{\sum_j \theta_j D_{ij}^{-3}}{\sum_j D_{ij}^{-3}} \quad (1)$$

Where $\alpha_{L,i}$ is directional information from lateral line, θ_j is a direction (heading) of other individual j , D_{ij} is a distance from j to i .

Effects of the information caught through eyes and lateral line on fish motion were studied detailedly by Partridge and Pitcher [3]. The fish whose eyes are masked can follow the school movement, but swim a little more apart from neighbors than does a normal fish. The fish of which lateral line are cut also can follow the school, but swims a little closer to neighbors than does normal fish [6]. Thus, the density of school becomes somewhat high when all fish act only by using vision.

2-3. Swimming speed of individuals

Aoki [2] analyzed the magnitude distribution of swimming speeds of *Gnathopogon elongatus* and *Trachurus japonicus*. It was shown that the magnitude distribution for both species is reasonably represented by gamma distribution. The gamma distribution is given by

$$f(v) = \frac{A^K}{\Gamma(K)} e^{-Av} v^{K-1} \quad (2)$$

where v is velocity, K and A are constant parameters, $v \geq 0$, $K > 0$, $A > 0$, $\Gamma(K)$ is a gamma function. We take 4 and 3.3 as the values of K and A , respectively, based on the observations of Aoki [2,5].

Since correlations of swimming speed between fishes in both *Gnathopogon* and *Trachurus* school are weaker than correlations of swimming direction, the absolute magnitude of speed of each fish is less important than the movement direction. Apparent uniformity of speed is considered to be due to similarity in the swimming ability of schooling members rather than the adjustment of speed [1]. It does not result from their intentional adjustment of speed.

3. Model for Single Fish Behaviors

A fish can not get any information about the movement of its group as a whole, schooling behavior may be formed based on only the local interaction between neighboring fishes. Therefore, we present here the results only for behaviors of an individual fish interacting with another individual. Behaviors of a fish group are generated by computer simulation made based on the following basic rules.

- 1) Time evolution is discretized. One step of time is represented by Δt .
- 2) Each fish moves in a two-dimensional horizontal plane without boundary.
- 3) At the beginning of the simulation, the positions and the moving directions of all fishes are given by using an uniform random number, where the positions are within a circle area with a certain radius. The initial value of speed for each fish is generated by a random number with a gamma distribution of eq.2.
- 4) One fish is picked up randomly from within the fish group at each time step and moved to a new position.
- 5) The new position after one time step Δt is determined as follows. At first, the fish j , to which the relevant fish i attends, is picked up out of the neighbors according to the probability proportional to D_{ij}^{-1} .

The position $x_i(t), y_i(t)$ of i -th fish at time $t + \Delta t$ is calculated as

$$x_i(t + \Delta t) = x_i(t) + v_i(t) \cos \alpha_i(t) \quad (3)$$

$$y_i(t + \Delta t) = y_i(t) + v_i(t) \sin \alpha_i(t) \quad (4)$$

$$\alpha_i(t + \Delta t) = \alpha_i(t) + \beta_{ij}(t) + \sqrt{2} \beta_o R_g \quad (5)$$

Where $\alpha_i(t)$ is a moving direction of i -th fish at time t , $\beta_{ij}(t)$ is a variation in the direction of i -th fish which is determined based on the relative relation to a neighbors j , $\sqrt{2} \beta_o R_g$ means a spontaneous fluctuation of the moving direction, β_o denotes the maximum fluctuation. R_g is a gaussian random number between -1 and +1, $v_i(t)$ is the speed of i -th fish at time t . The constant β_o takes 15 degree based on the observations of Aoki [2]. β_{ij} is determined by the following rules.

When the fish j is in the attractive area shown in Fig.1, β_{ij} is the direction from i to j .

When the fish j is in the parallel area, β_{ij} is the same direction of j .

When the fish j is in the repulsive area, β_{ij} is the direction from i to j plus 90 degree or minus 90 degree.

In every case, the value of β_{ij} is adjusted so as to be in the range of -45 to $+45$.

4. Emergence of Schooling Behaviors

To investigate the condition under which the schooling behaviors are made by individuals using only the information from vision, the effect of three types of adjusting principles was examined. Under the first principle, an individual adjusts its motion only to the nearest anterior fish. Schooling did not emerge in this case, but many unstable groups of fish appeared. Under the second principle, a fish always adjusts to the nearest neighbor within the visible range. The result of simulation was similar to the first case. In the simulation under the third principle, in which every individual adjust to one of neighboring fishes with the frequency inversely proportional to the distance, they gathered and moved together. A snapshot of schooling in the simulation is shown in Fig.2. The school sometimes changed its moving direction, where the leading group in the school firstly changes the direction, and then, the others follow the leading group.

The effect of lateral line on the schooling was also studied by computer simulations. Lateral line has an effect to parallel orientation of fish. When the individuals use the

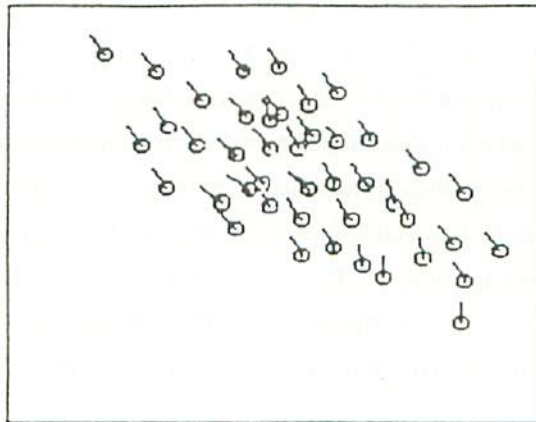


Fig. 2 A snapshot of schooling.

information only from lateral line, the formation of school is long and the density of the school is low in comparison with the school which is made by using only the information from vision. The frequency of changing direction decreases when the individuals use only the information from lateral line.

Fig. 3 shows the temporal variations of a expanse and polarity of a school starting in a dispersed state. Expanse represents extent of fish group around the center of mass. Polarity means standard deviation from the moving direction averaged over whole school. They gathered first and then all individuals were within a parallel area of someone at the step 29. It is seen from the fluctuation of polarity shown in Fig.3 that the school often changed the direction. This fluctuation comes from the time delay required for the fishes tailing the top group to adjust their direction to a new moving direction. This corresponds to the observed latency of response in the experiment of fish school [2].

Fig. 4 shows the frequency distribution of time periods required for a school formation since the fish group starts from the various initial states determined by the method described in section 3. The simulation has been made 5000 times to obtain the results shown in Fig. 4. It is defined as a schooling state that each individual is within a parallel

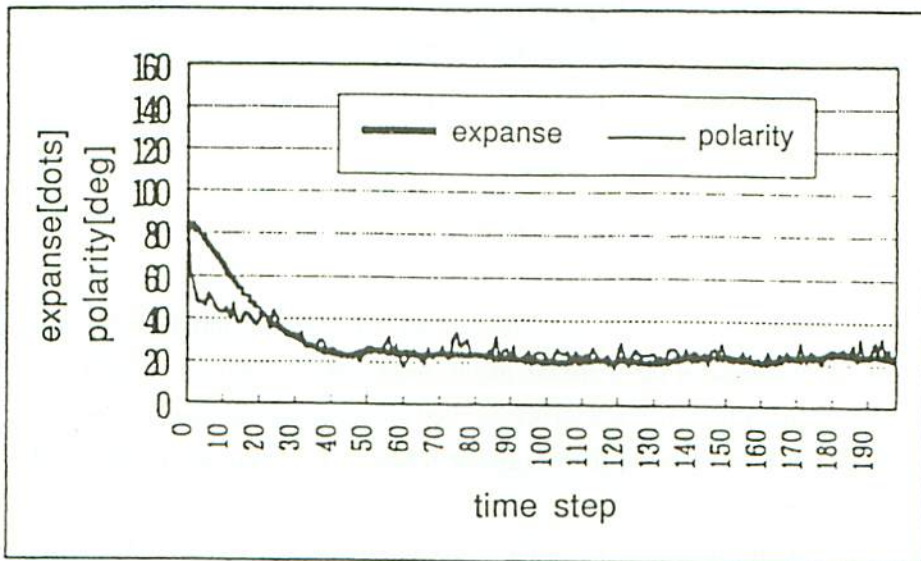


Fig. 3 Temporal variations in expanse and polarity of a school.

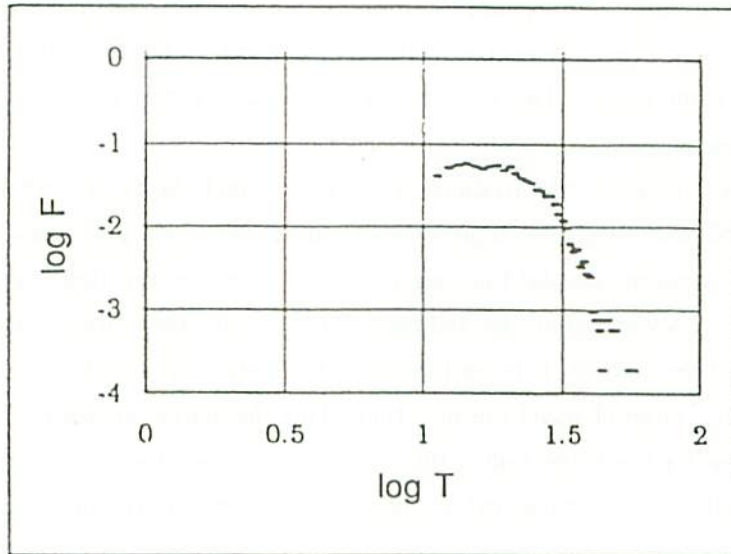


Fig. 4 The frequency F of each time period required for a school formation.

area of someone and there exists only one school. The information from vision and lateral line are adopted for determination of a next direction in the ratio of 0.9 to 0.1 in the case of Fig. 4, because the vision is much important to approach. The number of fish in this model was 60. Fig. 4 shows stability of the model in a dynamical sense. The simulation of 30 fish group was also run 5000 times. In the case of 30 fish model, the peak of frequency shifts to 1.35. This indicates that the attracting force is proportional to density of school.

5. Behaviors for the Predator Evasion

Various types of manoeuvres have been observed in the antipredator behaviors of fish school [1]. Some of them are the avoid, herd, vacuole, hourglass, split and flash expansion. Generally, a fish school is reformed quickly after dispersion of school [1]. Using our model, we studied the reforming behavior of a fish school after split and flash expansion occurred.

Fig. 5 shows the temporal variations of expanse and polarity in the reforming process after the splitting into two groups. These groups of 30 fishes were put within

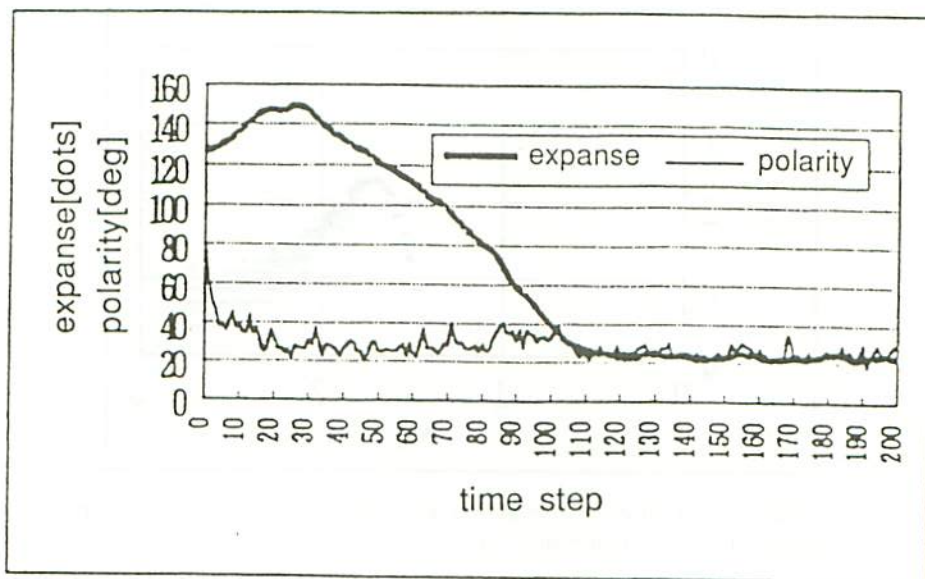


Fig. 5 Temporal variations of expanse and polarity in the reforming process after the splitting into two groups.

the two circles with $5L$ (L : body length) radius at the beginning of simulation. Distance between the centers of two circles was set to $25L$. The two groups joined at the time step 96 and after that one school of 60 fishes retained. Fig.6 shows the frequency distribution of time periods required for a single school formation since the various initial states of the splitting.

We simulated also the reforming behavior after the flash expansion shown in Fig. 7. The frequency distribution of time periods required for a single school formation after the various flash expansions is shown in Fig.8, where the simulation was made 15000 times.

These simulation for split and flash expansion indicate the stability of fish school in our model. The schooling dynamics of our model seems to be good enough to study the response to predator. If the schooling dynamics is weak, fish of the school are easily dispersed by attack of predators and easily eaten by the predators. As long as a school attacked by predators maintains collective motion, the fishes are not easily eaten.

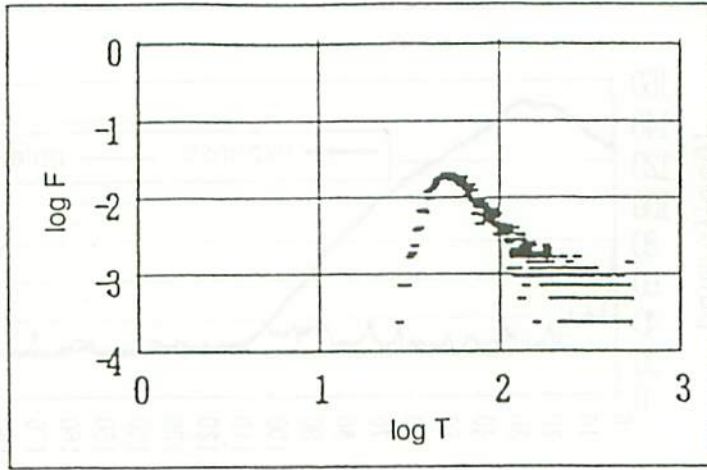


Fig. 6 The frequency F of each time period T required for a single school formation. The simulation was made 5000 times.

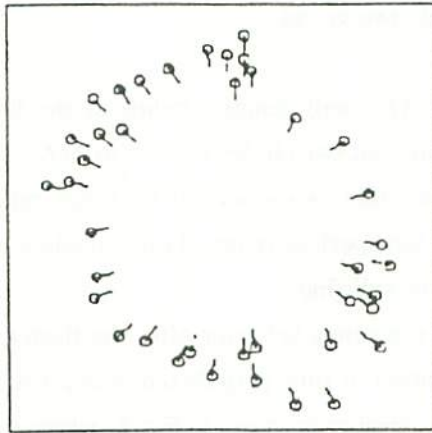


Fig. 7 Flash expansion behavior of a fish group.

6. Concluding Remarks

The various simulations have been performed to clarify the essential mechanism of fish schooling in the present paper. This work made a base to study of group intelligence. The mechanism of group intelligence will be examined by a new model made based on the present model. As mentioned before, we assume that group intelligence

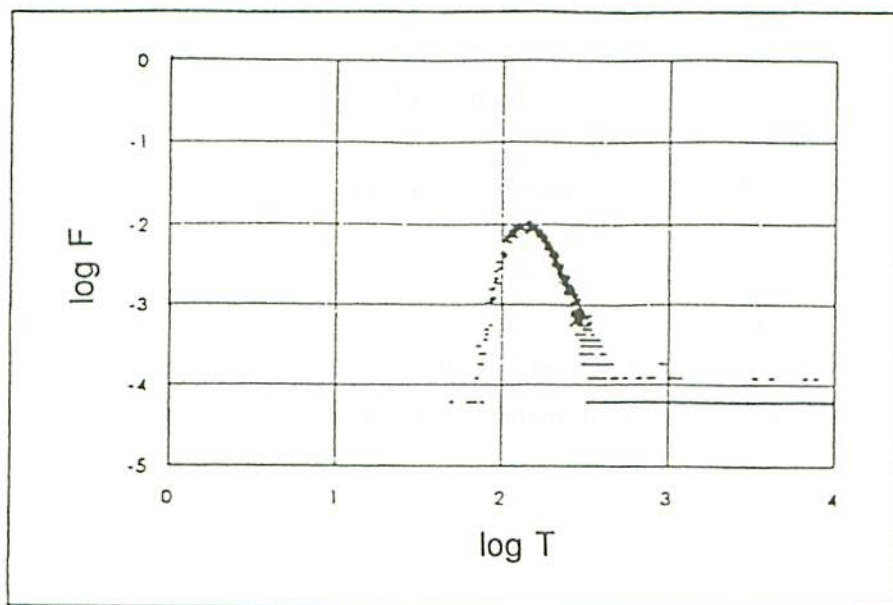


Fig. 8 The frequency of each time period T required for a school formation after each flash expansion. The simulation was made 15000 times.

in fish group is abilities emerged when school is formed.

We are highly interested in group intelligence emerged on the behavior of predator evasion, because group intelligence may be the most clearly exerted to evade attack of predator. In order to clarify what the group intelligence of fish school is and how the group intelligence is emerged, we are going to make a model applicable to the predator-avoidance behaviors of fish and attacking behaviors of predator.

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