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Characterization of fish schooling behavior with different numbers of Medaka (*Oryzias latipes*) and goldfish (*Carassius auratus*) using a Hidden Markov Model

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A B S T R A C T

Fish that swim in schools benefit from increased vigilance, and improved predator recognition and assessment. Fish school size varies according to species and environmental conditions. In this study, we present a Hidden Markov Model (HMM) that we use to characterize fish schooling behavior in different sized schools, and explore how school size affects schooling behavior. We recorded the schooling behavior of Medaka (*Oryzias latipes*) and goldfish (*Carassius auratus*) using different numbers of individual fish (10–40), in a circular aquarium. Eight to ten 3 s video clips were extracted from the recordings for each group size. Schooling behavior was characterized by three variables: linear speed, angular speed, and Pearson coefficient. The values of the variables were categorized into two events each for linear and angular speed (high and low), and three events for the Pearson coefficient (high, medium, and low). Schooling behavior was then described as a sequence of 12 events ($2 \times 2 \times 3$), which was input to an HMM as data for training the model. Comparisons of model output with observations of actual schooling behavior demonstrated that the HMM was successful in characterizing fish schooling behavior. We briefly discuss possible applications of the HMM for recognition of fish species in a school, and for developing bio-monitoring systems to determine water quality.

1. Introduction

Schooling in fish is an emergent state of behavior in which a group of fish moves together in a coordinated fashion, and forms patterns. Patterns vary according to fish species and environmental variables, and can take a range of shapes from simple ellipsoids to complicated vortex arrangements [1]. Several hypotheses have been proposed, concerning the ways in which schooling behavior may be advantageous to the survival of fish.

The main advantage of schooling is in predator detection and avoidance [2]. Individual fish have limited vision, but schooling fish have an expanded view of the surrounding environment, and as a result are better able to detect predators. Behavioral changes in schooling fish provide signals to the group when a predator is detected, and the entire school can attempt to escape together. Other advantages of schooling behavior include the facilitation of migration to spawning areas [3], and reproduction [4]. Schooling also has hydrodynamic advantages [5]. For example, oxygen consumption per fish in schools is less than that of solitary fish [6]. This finding is supported by a report showing that fish in schools have slower tail beats, which helps to conserve energy [7].

To date, physicists and theoretical biologists have suggested use of simulation models to examine fish schooling behavior. Takagi et al. [8] suggested the mathematical model to simulate the schooling of fish in a water tank with the shape of the

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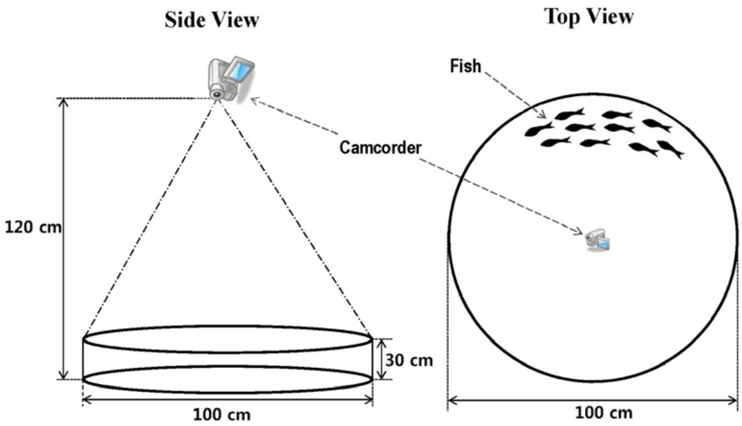

Fig. 1. Schematic diagram of the experimental equipment. The aquarium water depth was 5 cm. The digital camcorder was mounted horizontally above ground at a height of 120 cm.

squares of various side lengths and/or circles of various diameters. Huth and Wissel [9] suggested a simulation model based on four types of patterns by interaction force among individuals without environmental stimulus through experimental and simulation data. Niwa [10] proposed a self-organizing dynamics model of fish schooling based on a nonlinear equation. Takagi et al. [11] used the model suggested by Matsuda and Snnomiya [12] to investigate the influence of tank shape and size on fish behavior.

These simulation studies have advanced our understanding of fish schooling behavior. However, they focused exclusively on two aspects of this behavior: the details of the mechanisms through which schooling behavior is generated, and the physics underlying schooling dynamics. In spite of the fact that fish school size is thought to be one of the major factors affecting schooling behavior, these models were not sufficiently successful to reveal the effects of school size [13,14]. The model limitations result from two constraints. The first lies in using assumptions about perceived schooling behavior, rather than applying results of direct observations [15]. Thus, while random functions may yield schooling behavior, they may not be sufficient to understand real schooling behavior. The second constraint lies in the functional type of interaction forces among individual fish. The functional type used in the traditional model of fish schooling was not based on the experimental data obtained from the behavior of real fish. Such experimental data are technically difficult to obtain for specific species, because of the need for a three-dimensional (3-D) multi-particle tracking system with high resolution.

In the present study, to overcome these problems, we introduced a Hidden Markov Model (HMM) to characterize the schooling behavior of *Oryzias latipes* (Medaka) and *Carassius auratus* (Goldfish) for different sized schools (10–40 individuals).

Use of the HMM has proven advantageous in studying animal behavior because the model does not assume the functional types or equations governing how animals move in different environments [16,17]. Rather, HMMs use sequences of observation events defined in such a way that, they can capture changes in behavior. Medaka is a model organism that is used in many areas of biological research. Nearly all aspects of the Medaka life cycle have been analyzed, including sexual behavior, genetic inheritance of coloration, spawning habits, feeding, pathology, embryological development, and ecology [18]. The behavioral response of goldfish to chemical and physical stresses has been extensively studied in relation to their physiology [19,20]. In this study, we show that, HMMs can successfully characterize the schooling behavior for various sized populations of Medaka and goldfish, and briefly discuss the possible extensions of the HMM.

2. Materials and methods

2.1. Test species and observation system

Medaka (*Oryzias latipes*) and goldfish (*Carassius auratus*) were purchased from a commercial fish farm aquarium. For the experiments on both species, 250 fish of each species were housed in circular holding aquaria (diameter: 100 cm; height: 30 cm). The fish were acclimated to laboratory conditions for 4 weeks prior to the experiment (12:12 light/dark cycle and 20 °C water temperature). Natural sunlight was blocked and fluorescent light was used for the light/ dark cycle. Fish were fed TetraMin flake food (Tetra Werke; Melle, Germany) daily (Medaka: 1 g/day, goldfish: 5 g/day). The mean body length of Medaka and goldfish was 31.67 ± 4.71 mm and 53.23 ± 8.21 mm, respectively. The distribution of the body length was almost Gaussian for goldfish, and bimodal with two peaks at $\sim$27 and $\sim$37 mm for Medaka. To investigate the effect of school size on schooling behavior for both species, we introduced $N(10, 20, 30,$ and $40)$ individuals to a circular holding aquarium of the same dimensions as the stock aquarium. In this study, school size was defined as N. Water depth was 5 cm, and the laboratory was protected from environmental stimuli. A digital camcorder (SONY CX-550) was fixed at a height of 1.2 m above the bottom of the aquarium, for observation of the entire aquarium (Fig. 1). A wide-angle lens (Raynox QC-505)