Collective detection based on visual information in animal groups

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Collective behaviour course research seminar report

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Jacob D. Davidson et al. investigated how is individual and collective visual detection dependant on various parameters. This project aims not only to study and replicate the team's results but also to implement a simple predator avoidance algorithm to observe how individual and collective visual information change according to predator movement.
To replicate the paper's results We have conducted trials with four groups with different number of agents each, measured how does individual and collective visual detection behave and compare the results with the original paper's results. The code is written in Python. For the predator algorithm, the approach was to a predator agent to the space, selecting a specific fish and moving towards the fish, affecting the whole fish swarm organization, and as a sequence, their individual and collective visual information.
We have concluded that as the number of individuals increases the average detection coverage decreases resulting from occlusion caused by neighbours and the variance of individual external visual coverage in the group increases. Also, small changes in position over a short period of time could reduce the decrease in detection coverage caused by having a blind angle. Regarding collective detection, the results show that the external detection is higher when the group occupies a larger area. When a predator attacks, the group separates into smaller ones. Because of that, their individual external visual coverage increases, but the variance of visual coverage decreases, and the blind angle is more visible. On the other hand, the collective external detection is higher because each group area is smaller.

Collective behaviour | Collective Visual Detection | Predator avoidance | Fish schooling | Golden shiner fish | Group dependency

Introduction

To avoid predator threats and better locate resources, animals use the strategy of forming a group, because as the "many eyes" hypothesis states, as the size of the group increases, there are progressively more eyes scanning the environment [1].

In [2], the team investigated how is individual and collective visual detection dependant on various parameters ie. the number of individuals in a group, the state of the group (swarming, milling, polarization etc.), the position of the individual within the group etc. The result of the authors' research was a model which estimates the visual capabilities of a given group depending on two main parameters which is the probability of visual blockage by a neighbour and the density of the group. This model constructs the simplest possible minimal model that is able to capture how visual detection capability changes when there are more individuals in the group. They used this model to explain the results they got from their experiments.

The team's research was performed on real life data. The team studied the behaviour of gold shiner fish and recorded their behaviour in an aquarium, which in their estimation was a good enough of an approximation of a real life scenario.

The goal of this project is to replicate the result that the team achieved using synthetic data ie. create a collective behaviour model which simulates the movements of golden shiner fish and collect the same metrics that the team has done. In order to build upon the research that has already been made, we have decided to add a predator to the context, implementing a simple predator avoidance algorithm and observe how individual and collective visual information change with respect to the predator attack.

Methods

To study and analyse visual detection we focused on two aspects: individual detection coverage and collective detection capability, where detection coverage is the fraction of the external visual field that an individual can see. In order to be able to obtain the same results, the authors have also made their code available online [3].

In order to encapsulate the main findings of [2] we have decided to conduct trials with four groups, each having different number of agents (40, 80, 110 and 181), which simulate the experiments with real life gold shiner fish. For each group we measured how does individual and collective visual detection behave and compare that with the results that the team in [2] has shown. As we have seen in [2] the state of the group does not have an effect on individual or collective detection, therefore we have decided to omit this in our project. Instead we focused on adding a predator to the context. The main idea is to explore how does individual and collective detection change when a predator gets close enough so that the group disperses in order to be able to avoid getting caught. To implement it, we have decided to use the algorithms explained in [4], adding a predator agent to the space, where it selects a specific fish and moves towards the fish, affecting the whole fish swarm organization, and as a sequence, their individual and collective visual information. The predator is initiated outside the prey collective and moves towards the center of mass of the prey school with the double of their velocity. The predator and prey model is available at https://github.com/PaPeK/PredatorPrey.

The code to reproduce the main paper's results is written in Python, and the predator algorithm is written in python and C++.

Problem Definition. Some species of fish, like the golden shiners, adapt to using visual stimuli for survival [5]. Analyzing the connection of the visual feedback from each fish is important for making future realistic predictions [6]. For instance, how an individual's reaction to spotting food or seeing a predator affects the rest of the group's movement, or how does a startled fish at the end of the line make the whole school alarmed. The probability that the group will respond to these cues is largely dependent on the available visual perception at any given moment.

The problem that needs to be addressed is having a correct description of the dependency of the group vision in schooling fish on the individual fishes' position in the school. The approach to solving this issue is by analyzing the vision that each golden shiner fish has in the group. The analysis suggests that the field of view is mainly dependent on the size of the schooling fish. Namely, the more fish there are, the more reactive the group is. This is formally defined in a model that shows the capabilities of detection using geometric principles.

Model. To mathematically represent the visual perception of a single fish in a group in a fixed group area, the Poisson distribution is used:

$$P_{ext}(r,\theta) = e^{-\lambda g(r,\theta)}, 0 <= r <= R$$

Where r is the distance from the center of the group to the edge, denoted by R which is set to 1 to avoid loss of generality. The angle θ represents the direction in which a single fish is looking, and λ is the blockage probability. The distance from an individual fish to the edge of the group is calculated by the law of cosines, giving the following:

$$g(r,\theta) = rcos\theta + \sqrt{R^2 - r^2 sin^2\theta}$$

To find the total external detection of a single golden shiner fish the integral of all possible angles is taken:

$$v(r) = \frac{1}{2\pi}\int_{-\pi}^{\pi} e^{-\lambda g(r,\theta)} d\theta$$

Since the fish are moving, they may change the area they occupy [2] as it is shown in Figure 1. We calculate the size of external visual detection using the following equation:

$$v(r,\alpha) = \frac{1}{2\pi}\int_{-\pi}^{\pi} e^{-\lambda_1 g_1(r_1,\theta)} d\theta = \frac{1}{2\pi}\int_{-\pi}^{\pi} e^{-\lambda g(r,\theta)\alpha} d\theta$$

Where α = R/R1, the ratio of average and current radius respectively. The changes in group radius are found using a Gaussian with a mean $\alpha = 1$:

$$P(\alpha) = \frac{1}{M} exp(-\frac{(\alpha-1)^2}{2\sigma^2})$$

Where σ is the magnitude of changes in the radius, and M is the normalization factor.

To add a predator to the context, for simplicity, we consider that the preys move with fixed speed $v = v_0$ and the predator with $v_p = 2v_0$ according to

$$\frac{d(\phi)_p}{d} = \frac{1}{v_p}\mathbf{e}_p.\mathbf{F}_p$$

with $\mathbf{F}_p$ as the pursuit force [4]. The preys respond to a combined force $\mathbf{F}_i = \mathbf{F}_{i,alg} + \mathbf{F}_{i,d} + \mathbf{F}_{i,flee}$ by adapting its position and heading ϕ_i as

$$\frac{d\mathbf{r}_i(t)}{dt} = \mathbf{v}_i(t)$$

$$\frac{d\phi_i(t)}{dt} = \frac{1}{v_0}(F_i(t) + \sqrt{2D}(t)$$

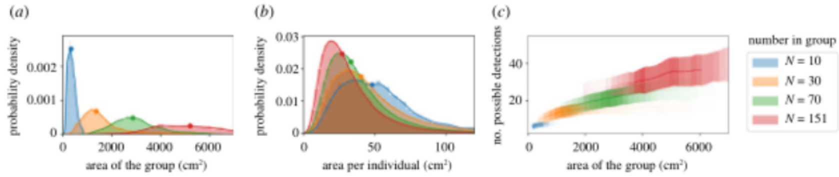

Figure 1. Area occupied and collective detection. (a) Distributions of the total spatial area occupied by groups of different numbers of individuals. Points denote the median of the distribution. (b) The spatial area per individual, calculated using Voronoi tesselation, for groups of different numbers of individuals. Points denote the median of the distribution. (c) The total instantaneous detection capability among all group members, averaged over all possible directions over time, plotted as a function of the total area of the group at that time. The line shows the mean and the shading shows the standard deviation of the number of possible detections. The transparency of the lines is proportional to the probability that the group has a certain area value (see distributions in (a)) [2].

with $F(i)(t) = \mathbf{F}_i(t).\mathbf{e}_i$ as the combined force along the direction $\mathbf{e}_i = [-\sin\phi_i, \cos\phi_i]$. [4].

The predator considers its frontal Voronoi neighbors (N) as targets and selects them with the same probability ($p_{select,i} = 1/|N_p|$), attacking only one fish at a time.

As the predator attacks, the preys direction changes, as well the angle θ representing the direction in which they are looking.

Results

We conducted trials with groups of 40, 80, 110 and 181 fish. Individual detection coverage will be examined first, followed by collective detection capability.

Individual detection coverage. In small groups (with 40 members), all fish have a large detection coverage and can see almost the entire range around the group in all directions. But as the number of individuals increases the average detection coverage decreases resulting from occlusion caused by neighbours and the variance of individual external visual coverage in the group increases, due to members having their visual field increasingly dominated by others 2. The detection coverage decreasing due to blind angles have largest effect for the group of 40, because in large groups it is more likely that blind angle is already blocked by a neighbour.

On the other hand, if an individual has detection capability in a given direction at time t if there was visual access in that direction at any time within the previous T seconds [7], the coverage increases, with the largest effect on the largest group. This demonstrates that consideration of small changes in position over a short period of time could effectively "mitigate" the decrease in detection coverage caused by having a blind angle.

As expected, and as we can see in Figure 1 with 25% of probability of out-of-plane effects, this effect increases the individual's detection coverage, with the largest change for the group with 181 members.

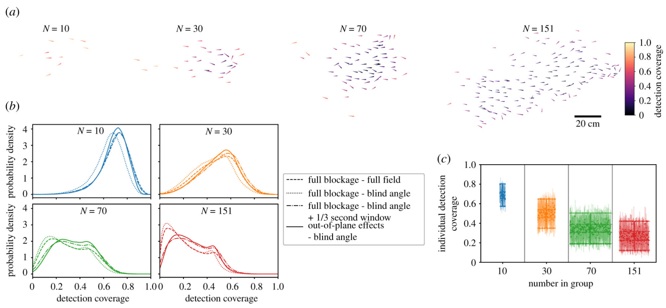

Figure 2. Individual detection coverage. (a) Example snapshot of the external detection coverage for groups with different numbers of members. (b) Distributions of individual detection coverage for the groups, combining all individuals during a trial, calculated using different settings: full blockage–full field, full blockage–blind angle, full blockage–blind angle with detection capability any time over a 1/3 second time window, and out-of-plane effects. (c) Detection coverage, comparing individual differences to the combined distribution.

Collective detection capability. As already mentioned, the total number of possible external detections between all group members in any direction does not depend on the state of the group (polarised, milling, swarming or other configuration) [8], but it does depend on the group area. Groups with more individuals occupy a larger spatial area. However, the median spatial area per individual decreases as individuals tend to pack slightly more tightly when there are more individuals in the group (figure 1b).

In the end, the external detection is higher when the group occupies a larger area, because when individuals more widely spaced, each neighbour blocks less the external view visual field of others (figure 1c).

The team has discovered that the detection ability also depends on the angle with respect to the direction of movement of the group. In the case of fish, detection capabilities are higher towards the front of the group than towards the sides, or to the rear due to the blind angle [9]. Detection ability then decreases with distance to the front edge.

Predator attack. Regarding the predator attack, if it attacks towards the central of mass of the group it affects the whole group. As a result, the group disperses and forms other smaller groups for a short period. During this time, the number of members in each group and their area decreases, which, as seen before affect their individual and collective visual detection. Their individual external visual coverage increases, but the variance of visual coverage decreases and the blind angle is more visible. On the other hand, the collective external detection is higher, because the group area is smaller. After that, the group joins again, and their individual and collective visual detection goes back to the same as before the attack.

Discussion

When dealing with various species of fish, their capability to use the different biological sensory elements for survival need to be considered. For instance, in the paper of K. Kotrschal et al. [10], the wide variety of saltwater and freshwater fish have special advantages over the other fish that puts them at a higher survival rate in the specific environment they are used to. Fish that scavenge for food on the shallow waters have a better vision which takes advantage of the sunlight penetrating the surface of the waters. On the other hand, fish that feed at the bottom of the seas have their visual senses completely removed, and substituted by other stronger senses such as listening and feeling. One of the features of schooling fish, like our golden shiners, is the visual capabilities that enlarge the field of view and the chance to spot predators and prey.

So far we have taken into account the 25-degree blind angle behind the fish. In [11] it is described how the blind fish are capable of detecting objects without the use of any sight. For future work, we may use this to supplement the missing sight of fish. The Blind Cave Fish uses its lateral line organ to detect objects in darkness, and since most fish have this organ, we can implement the algorithm to other fish that have a vision as a supplement to the individual visual detection. For example, the predators that rely on being still, like the Scorpionfish, can be avoided. By doing this we can get a higher detection probability where vision falls short, like in camouflage.

Data accessibility

Data is available at https://datadryad.org/stash/landing/show?id=doi%3A10.5061%2Fdryad.sbcc2fr2h and code is available at https://github.com/anamarisamacedo/CollectiveBehaviour

Authors' contributions

Ana Macedo wrote the Abstract; part of the Introduction, Methods, Model and Results; added code to the implementation; polished the report and the bibliography; did part of the slides. Patricia Alcázar wrote the Results with their corresponding images and references. Vulnet Alija wrote the Problem Definition, Model, and Discussion with their appropriate references; uploaded the source code and the link to the necessary data to run the program; did part of the slides. Žan Jonke wrote part of the Introduction and part of the Methods. All authors studied the main and predator papers, and analysed the models.

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