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Hydrodynamic effects on a predator approaching a group of preys

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HIGHLIGHTS

- A predator–preys system is immersed in a viscous fluid.
- The impact of the hydrodynamics on the predator's attack is elucidated.
- The sole behavioural equations are insufficient to predict the predator's performance.

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ABSTRACT

A numerical approach to predict the hydrodynamics involving a predator approaching a group of 100 preys is presented. A collective behavioural model is adopted to predict the two-dimensional space–time evolution of the predator–preys system that is supposed to be immersed in a fluid. The preys manifest mutual repulsion, attraction and orientation, while the predator is idealized as an individual to be strongly repulsed. During the motion, the predator experiences a resistance induced by the encompassing fluid. Such effect is accounted for by computing the hydrodynamic force and by modifying the predator's velocity given by the behavioural equations. A numerical campaign is carried out by varying the predator's drag coefficient. Moreover, analyses characterized by progressively wider predator's perception areas are performed, thus highlighting the role of the hydrodynamics over the behavioural interactions. In order to estimate the predator's performance, an ad-hoc parameter is proposed. Moreover, findings in terms of trajectories and angular momentum of the group of preys are discussed. Present findings show that the sole collective behavioural equations are insufficient to predict the performance of a predator that is immersed in a fluid, since its motion is drastically affected by the resistance of the surrounding fluid.

1. Introduction

Many animal groups, such as flocks of birds, schools of fishes or swarms of insects, tend to move by forming organized groups [1–3]. Such organization is common even at different levels of living organisms, such as bacteria [4], humans [5] and across different animal species [6,7], and it emerges since the single individuals and the whole group experience a benefit and a improvement from the organized system. For example, birds are used to move in V-shaped formations, since rear birds benefit from the wing-induced vorticity generated by the front ones [8]. Moreover, ants form groups to provide food recruitment [9,10]. In addition, an organized emergent behaviour has been experienced even in locusts, identifying a critical density for the onset of coordinated marching in locust nymphs [11]. An additional kind of benefit is identified in predatory

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avoidance in schools of fishes [12–14], consisting of evasive manoeuvres confusing the attacking predator [15]. Specifically, in Ref. [16] a model leading a fish to choice between schooling, cooperative escape, and selfish escape behaviour patterns with proper timing has been proposed, thus determining the condition minimizing the probability of any individual to be eaten. The mechanism of protection from a predatory risk takes an advantage by a common altruistic behaviour, aiming at confusing the approaching predator [17]. Intriguing findings have been discussed in Ref. [18], where four predator–preys systems have been investigated, showing that tactile predators appear to be generally susceptible to be confused, whereas visual predators are susceptible mainly when their preys are highly agile, probably due to the superiority of the visual sensory system. In Ref. [19] the cooperation of preys under attack has been discussed, highlighting that if an individual can increase the survival rate of its mates, then its own predation risk will decrease. Moreover, in a recent work [20] the predator–preys dynamics has been widely investigated. In particular, it has been demonstrated that the predator confusion provides a sufficient selection pressure to evolve swarming behaviour in preys, which, in turn, exerts pressure on the structure of the predator's visual field, favouring the frontally oriented, high-resolution visual systems commonly observed in predators that feed on swarming animals. As it is possible to understand, a rapid and efficient transfer of information between the individuals plays a crucial role in increasing the chances of survival for preys. Several works [21–29], show how the number of informed individuals affects the decision-making and leader identification processes for the uninformed ones. In order to deeply predict the behaviour of a group of individuals, a lot of numerical models are developed [30–34]. Such methods are based on metric [35–37] or topological [38,39] collective behavioural rules, which describe the mutual interaction in terms of reciprocal repulsion, attraction and orientation.

In recent years, some models arose to investigate the predator–preys interaction, aiming at providing a robust and effective framework to perform simple, efficient and accurate numerical/mathematical computations [40,41]. Besides these uniquely *social* approaches, here the modelling of a predator hunting a shoal of 100 preys is enriched by accounting for the resistance to the motion exerted by the surrounding fluid. Specifically, the predator's velocity vector computed by the collective behavioural equations is corrected by determining the hydrodynamic force experienced during the motion through a simple expression that accounts for the density of the encompassing fluid and the drag coefficient, the latter being dependent on the shape of the predator and on the viscosity of the surrounding fluid. Several scenarios are analysed by varying the drag coefficient. The performance of the predator are assessed by proposing a parameter that is computed as the ratio between the distance covered by the predator and the number of survived preys. The higher the ratio, the more effective the attack is. Notice that such ratio is time-dependent. Moreover, findings in terms of number of eaten preys, trajectories described by the predator–preys system and angular momentum of the group of preys are discussed. In addition, the weight of the hydrodynamics over the behavioural rules is investigated in scenarios characterized by progressively broader perception areas exhibited by the predator. Numerical findings show that the collective behavioural equations are insufficient to predict the predator's hunting performance if it is immersed in a fluid, since the resistance to the motion exerted by the encompassing medium plays a crucial role. Notice that the novelty of the present work with respect to the existing literature is represented by the insertion and the investigation of the dependence of the predatory attack on the surrounding fluid dynamics.

The paper is organized as follows. In Section 2, the adopted numerical methods are shown. In Section 3, results from a numerical campaign are discussed. Finally, some conclusions are drawn in Section 4.

2. Methods

Making reference to Fig. 1, the adopted collective behavioural model is based on the fact that the generic individual i (red circle) is surrounded by three concentric areas. The smallest one is the so-called repulsion area, whose radius is r_r. If the individual i at the position $\boldsymbol{X}^i$ identifies here an individual, namely k, it moves in order to avoid collisions. The second one is the attraction–orientation zone: the individual i tends to get attracted and aligned with respect to individuals found in the area of radius $r_{a,o} - r_r$. The largest one is the danger zone. If a particular kind of individuals (i.e. the predator) is recognized in the zone of area r_d at the position $\boldsymbol{X}^p$, the individual i moves in order to escape. The danger zone can be idealized as a wider repulsion zone, that becomes active only if a particular kind of individual is met. Moreover, the individual i possesses a blind conic zone of angle α that is located in the direction opposite to the motion (red arrow). Individuals which are detected here are neglected, independently from their kind and position. According to such zone-based model, at the time instant t the individual i modifies its velocity vector $\boldsymbol{V}$ as follows:

$$\boldsymbol{V}^i(t) = (1 - w_d)[\boldsymbol{V}^i_r(t) + \boldsymbol{V}^i_{a,o}(t)] + w_d \boldsymbol{V}^i_d(t) + \boldsymbol{V}^i_h(t), \tag{1}$$

where

$$\boldsymbol{V}^i_r(t) = -\sum_{k \neq i} \frac{\boldsymbol{X}^k - \boldsymbol{X}^i}{|\boldsymbol{X}^k - \boldsymbol{X}^i|}, \quad \text{if } |\boldsymbol{X}^k - \boldsymbol{X}^i| \leq r_r, \tag{2}$$

$$\boldsymbol{V}^i_{a,o}(t) = w_a \sum_{k \neq i} \frac{\boldsymbol{X}^k - \boldsymbol{X}^i}{|\boldsymbol{X}^k - \boldsymbol{X}^i|} + w_o \sum_{k} \frac{\boldsymbol{V}^k}{|\boldsymbol{V}^k|}, \quad \text{if } r_r < |\boldsymbol{X}^k - \boldsymbol{X}^i| \leq r_{a,o}, \tag{3}$$

$$\boldsymbol{V}^i_d(t) = -\frac{\boldsymbol{X}^p - \boldsymbol{X}^i}{|\boldsymbol{X}^p - \boldsymbol{X}^i|}, \quad \text{if } |\boldsymbol{X}^p - \boldsymbol{X}^i| \leq r_d. \tag{4}$$