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Understanding Environment-Influenced Swarm Behavior from a Social Force Perspective

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ABSTRACT

The relevant research on swarm behavior has focused on the facts that when individuals agree with other members in the system globally consistent behaviors are generated and that individual decisions are completely dominated by other members. In fact, when individuals generate their own behavior strategies, they tend to consider not only the influences of other members but also autonomically consider their current environment. For example, in the social foraging of flocks, the behavior strategy of each individual animal is influenced by the food distribution, and individual movement patterns are characterized by a highly efficient search strategy—Lévy walks. To investigate this, this paper proposes using an environment-driven social force perspective to explore the Lévy walks of individuals in a group in patchy food environments. This model adopts the concept of social force to quantify the social effects and the interactions between individuals and food. The coordination between forces is a key in the formation of individual behavior strategies. Our simulation results show a power-law frequency distribution for agent flight lengths that conforms to Lévy walks and verifies the hypothesis of a relationship between food density and the Lévy index. In our model, the flock still exhibits collective consistency and cohesion and yields a high value for the order parameter and population density when moving between food patches. In addition, our model explains the intraspecific cooperation and competition that occurs during foraging as proposed in related work. The simulation also validates the impact of two inducements for individual behaviors compared with several benchmark models.

Keywords

Swarm behavior; behavior strategy; Lévy walks; consensus; social force model.

1. INTRODUCTION

There is an extensive perception that swarm behaviors are generated by the actions and interactions of individual members [1]. Many simulation models have discussed the formation of individual behavior strategies and how individual behavior strategies induce swarm behaviors [2-4]. They mostly emphasize the spatial interactions that occur between neighbors where individual behaviors are completely subject to other mates. In fact, individual behavior strategies not only depend on collective effects but also involve the external environment around the focal individuals [1, 7, 9, 10-15]. For example, in social foraging heterogeneous resource distributions cause complex behavior patterns in animals that differ from single-order phenomena [8, 10]. Furthermore, because of the common motive to maximize the probability of resource encounters in foraging, these complex behaviors can be classified as special movement strategies, i.e., Lévy walks.

Many related works have reported that in a patchy environment, Lévy walks are the optimal search strategies for heterogeneously distributed resources [7, 8, 10]. Lévy walks are characterized by a power-law frequency distribution $P(l) \sim l^{-\mu}$ of flight lengths (l) where $1<\mu\leq 3$ [5, 7, 8, 10]. Such a movement pattern for an animal in a heterogeneous environment maximizes the probability that it will encounter resources. Animals can adjust their speed and sinuosity of their movement paths based on food distributions [6, 10]. This paper aims to interpret the effect of the external environment on individual behavior strategies using Lévy walks.

Lévy walks can be generated based on two opposing mechanisms, cooperation and competition [7, 22], which indicates that although Lévy walks are supposed to maximize individual searching efficiency, their existence still relies on collective characteristics. The environment drives individuals to search for better food resources while the interactions among conspecifics constrains individual behaviors from going too far astray. Therefore, for example, it is easy for individuals to experience a conflict between remaining close to the group center or moving further away to graze for better food [29]. The key to forming individual behavior strategies is to solve such conflicts when moving. Another challenge in characterizing Lévy walks is how to implement the two opposing mechanisms and transition between them depending on the different circumstances.

Social force model is a method to model swarm behavior [30][31]. In this paper, we propose using an environment-driven social force perspective to explain individual behavior strategies by considering both conspecific and environmental effects. The social force model is introduced to quantify the interactions between individual agents using food and conspecifics as different force vectors with magnitudes and directions [15-17]. The trade-off of directions and the comparison of magnitudes among the forces determine the effect to which agents give priority. Two modes are established in our model, a search mode and a feeding mode due to the two opposing mechanisms of cooperation and competition [18-20]. We expect that under the influence of the environment, the motion of an arbitrary agent in our model will present the characteristics of Lévy walks but that the group of agents will maintain its collective characteristics. These aspects have been verified by our simulation results. Interspecific cooperation and competition in Lévy walks are also revealed by population density. We explored the effect of heterogeneous food distribution on foraging efficiency and found that the food consumed by agents is non-monotonic with respect to the food patch size because of the mismatch between patch size and the food replenishment rate [21].

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