Optimal cooperative searching using purely repulsive interactions

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HIGHLIGHTS

- We explore how repulsive interactions could enhance cooperativity in groups of diffusing foragers.
- We find an optimal repulsive range, where the time to find a resource/target is minimal.
- Optimal repulsion strikes a balance between minimizing redundancy and maximizing total area searched.
- Our results are insensitive to the exact form of the repulsive interaction and scale in a simple manner with forager density.

ARTICLE INFO

ABSTRACT

Foraging, either solitarily or collectively, is a necessary behavior for survival that is demonstrated by many organisms. Foraging can be collectively optimized by utilizing communication between the organisms. Examples of such communication range from high level strategic foraging by animal groups to rudimentary signaling among unicellular organisms. Here we systematically study the simplest form of communication via long range repulsive interactions between multiple diffusing Brownian searchers on a one-dimensional lattice. We show that the mean first passage time for any one of them to reach a fixed target depends non-monotonically on the range of the interaction and can be optimized for a repulsive range that is comparable to the average spacing between searchers. Our results suggest that even the most rudimentary form of collective searching does in fact lower the search time for the foragers suggesting robust mechanisms for search optimization in cellular communities.

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1. Introduction

Understanding the process of searching or foraging in living systems has been of great interest in many disciplines, such as biology, physics, computer science, and robotics (Viswanathan et al., 2011). The mechanisms by which different organisms forage for food can be quite varied, for example bears and wolves use their sense of smell in order to acquire food (Mattson, 2005), while bats and dolphins use echolocation to locate their food (Au and Snyder, 1980; Schnitzler and Kalko, 2001). Some animals have the ability to search for food individually; however, many other organisms must work in tandem in order to efficiently find food, such as ants and fish (Ioannou et al., 2012; Jackson and Ratnieks, 2006). Studying collective foraging patterns in nature can reveal basic algorithmic features that can be directly compared with artificial searching algorithms used in computer science and robotics (Shoghian and Kouzehgar, 2012). This type of analysis can help animal behavioral scientists and

computer scientists understand how these algorithms evolved over time and became robust over the wide range of environmental scenarios. One application of these searching process is currently used in robotics, where robots can utilize collective searching motifs that help them to navigate unexplored terrain and also assist in search and rescue efforts (Saeedi et al., 2009; Ko and Lau, 2009; Reich and Sklar, 2006; Hoff et al., 2010). Cooperation among both living systems and artificial ones strives for the same goals, such as minimizing the search time (i.e minimize energetic cost) while maximizing the search space.

Collective foragers or searchers, found in nature, display a high degree of coordination and communication within the collective as compared to a single searcher on its own. In fact, movement at the individual organism level within a collective is strongly correlated with the information that is being derived from their surrounding neighbors. There are several biological systems that generically display foraging behavior at the individual level; however the type of foraging strategies that these various systems utilize span a wide range of spatial and temporal scales, such as sub-diffusive, diffusive and super-diffusive (Bartumeus et al., 2002; Golé et al., 2011; Seuront and Stanley, 2013).

A major theme arose from the suggestion that Lèvy walks can be seen in the foraging ants because their fractal and super-diffusive properties are likely to be advantageous when searching (Shlesinger and Klafter, 1986). Analytical and experimental studies (Schuster and Levendowsky, 1996; Levendowsky et al., 1997; Viswanathan and et al., 1999; Bartumeus et al., 2002; Humphries et al., 2012; Raichlena and et al., 2013) subsequently showed that Levy walks are indeed advantageous when searching for randomly distributed resources, and are typically more effective than other simple search patterns, such as Brownian walks and ballistic (straight-line) movements. Natural selection may therefore have led to adaptations for Levy searching. This prediction is now supported by a wide variety of empirical studies (Viswanathan et al., 2011). However, it has been recently shown that such strategies are only an optimal modality of foraging for certain environmental conditions and can also depend on the species under study (Seuront and Stanley, 2013). In the case of "blind searchers" (e.g. basking sharks, jellyfish predators, leatherback turtles, and southern elephant seals), if one considers discrete Lèvy flights and not continuous walks, the optimal search strategy depends on the location of the intended target (food), and for targets that are in close proximity to the searcher Brownian motion is the optimal search strategy (Palyulina et al., 2013).

While Lèvy strategies have enhanced efficiency for individual foraging, a wide range of organisms ranging from single cells to mammals perform movements that are predominantly modeled by correlated or persistent random walks, which, at large spatio-temporal scales, become Gaussian or Brownian random walks (Turchin, 1998). One question that arises in this context is whether such Brownian searchers can collectively improve their efficiency by sharing information via interacting in some manner. An example model system, which spans both types of foraging behavior (solitary or collective), is the eukaryotic cell Dictyostelium discoideum (Dicty). Solitary Dicty can search their environment in a persistent Brownian random walk when food sources are high (Shenderov and Sheetz, 1997; Selmeczi et al., 2005). On the contrary, Dicty can form colonies that can search their environment collectively by utilizing chemotactic signaling (Keating and Bonner, 1977; Konijn et al., 1968; Pan et al., 1972). These chemotatic chemical interactions, which tend to correlate the motions of individual Dicty, allow for collectively foraging that can optimize foraging efforts, such that the entire colony benefits (Gelbart, 2010). At much larger length scales and with higher quality of information, Mongolian gazelles perform movements that are well approximated by simple Brownian motion but enhance their collective efficiency in finding sparse patches of vegetation by calling to each other when they find food (Martinez-Garcia et al., 2013). Intriguingly the study finds that there is an optimal intermediate range of communication that maximizes efficiency. Furthermore, this enhancement via communication extends qualitatively to Lèvy foragers as well but with significantly less quantitative improvement (Martinez-Garcia et al., 2014). While high-quality information sharing can lead to higher group efficiency, an intriguing question is whether there exist rudimentary or minimal interactions during the search process that can speed up the collective search for resources. For this to happen, it would be desirable for the interactions to minimize redundancy in searching while still maintaining sufficient exploration. We hypothesized that a simple and easily implementable interaction with this property that would prove advantageous for Brownian searchers, such as the ones mentioned above, would be repulsion or mutual avoidance. In this study, we examine how Brownian foragers *cooperate* with each other via purely repulsive interactions, while searching for a single target (e.g. food). We ask how the search time depends on the density of searchers, the range of repulsion and the functional form of the repulsion.

We address these questions by simulating multiple Brownian particles that search for a fixed target on a closed one-dimensional lattice. In the simplest case we first study this system without any interaction between two searchers and then compare this with the more complex system of two interacting Brownian particles by measuring the average mean first passage time (MFPT) to the target (Cepa and Lepingle, 2001; Sokolov et al., 2005). We also studied systems with three searchers and different forms of the interaction potential. We found that interactions among the searchers affected the search time, and an optimal repulsive range for foraging was found. This suggests that in order to optimize collective foraging, organism should interact such that they minimize redundant search patterns and maximize the search area in their environment. In Section 1, we discuss our model and the dynamics of our simulation. In Section 2 we present our results; in Section 3.1, we compare the MFPT of three different systems; one searcher, two searchers without interactions two, searchers with interactions as well as varying the form of the interaction potential; in Section 3.2, we present, by dimensional analysis, the relationship between the optimal repulsive strength and the lattice size; In Section 3.3, we present the relationship between the average encounter time and the lattice size and discuss the extension of these results to the case with three interacting searchers. In Section 3, we discuss the implications of our results.

2. Model and simulation

We study a discrete system consisting of two interacting Brownian searchers (random walkers) that move along a one-dimensional periodic lattice with N sites (Fig. 1). Initialization of both searchers and the target is selected from a uniform random distribution, such that the domain of the distribution corresponds to the lattice size, N. The dynamics of this model are such that the bare diffusion constant for both searchers when they are not interacting is

$$D = \frac{a^2}{T} = 1, \tag{1}$$

where the lattice spacing is $a=1$.

Repulsive interactions are considered only between the two mobile searchers. Specifically we use an inverse power of the distance between the two searchers similar in form to an electrostatic potential between two like charges. The form of the potential in general is $V = \alpha/r^\gamma$ and for our simulations $\gamma = 1$. The range of the potential is set by the parameter α and in our simulations it is given in terms of the lattice spacing a, which can range from 0 to $2N$. The distance between the two searchers is
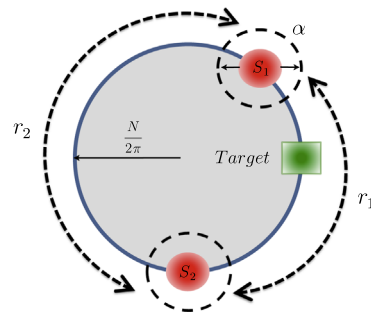

Fig. 1. The pictorial representation of our simulation model. S_1 and S_2 are the positions of the two searchers (red circles), the green square is the target and the black dotted circles are the repulsive boundary set by the value of α. r_1 and r_2 are the distances between the two searchers, and $N/2\pi$ is the effective radius of periodic system. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)