Collective foraging in heterogeneous landscapes

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1. Introduction

Many organisms collectively gather resources for survival. For a lone animal looking for sources of food, the foraging efficiency is decided by its searching strategy and the distribution of the targets [1,2]. However, when others are around, the interactions between them may become important in determining the behaviour of the individuals. For example, an animal that is unsuccessful in locating food by searching on its own can instead locate other distant members who are successful and join them. Such behaviour is well documented across different species [3–5]. However, what kind of interactions would be the most advantageous for the individuals in the group? Traditionally, this problem has been studied in behavioural ecology under the paradigms of producer–scrounger and information-sharing models [5,6]. The information-sharing theory, in its canonical form, considers foragers simultaneously searching for food as well as looking for opportunities to join others [7]. In the producer–scrounger games, the simultaneous execution of the above activities is not possible [8].

With the advancement of different data logging techniques in animal experiments [9,10], it has been possible to record the trajectories of animals searching for food. The information from such experiments has allowed for detailed statistical analysis and has helped in shedding light on the possible relationship between movement patterns and efficiency of search. The emergence of heavy tails in the walk-length distributions has prompted physicists to explain the foraging movement of animals in terms of Lévy walks and flights [11]. Lévy walks are characterized by move lengths (l), which are distributed according to a probability density function $P(l)\sim l^{-\mu}$ (for large values of l), with $1<\mu\leq3$, and by uniformly distributed turning angles between consecutive moves. Although small in number, large move lengths occur often when an animal is executing a Lévy walk. However, the moves are not instantaneous, and an animal is assumed to traverse a distance l with a finite velocity. For $\mu>3$, the walks essentially become Brownian motion where large move lengths are...
extremely rare. In the limit, \( \mu \rightarrow 1 \), the motion is ballistic, where the path of the animal is rather a straight line, when observed over a finite time. The most efficient searching, by a single forager looking for targets, is supposed to happen when \( \mu \approx 2 \) [1,12,13]. However, investigations [12,14–16] have also probed the robustness of Lévy walks and have found these to be actually optimal or only marginally advantageous under conditions pertaining to the nature of the encounter with targets (destructive or non-destructive), the presence of memory, geometry of the foraging region, among others. Deviations greatly reduce the advantage of Lévy walks in favour of ballistic or Brownian motion. In addition, the presence of patchy environments may lead the foragers to use composite search strategies which also result in fat-tailed distributions for step lengths [17].

In general, the success with which the individuals in a group forage, as well as the emergent patterns in the movement of foragers, depends on several factors. When food is abundant, there is hardly any benefit for individuals to join others, so that encounters with food sources are increased. However, when the distribution of food is ephemeral or patchy, interaction between foragers may become important. Several field studies and theoretical models have investigated these aspects. The producer–scrounger paradigm was used to model the collective behaviour of foragers [18,19]. Cooperation in foraging was shown to develop in a stochastic environment [20]. Explanation for observed scale-free move lengths observed in spider monkeys [21] has been based on their social behaviour [22]. Such mobility patterns of foragers were modelled in [23] with the agents having unbounded velocities. The role of information transfer in the recruitment of foragers has been studied in colonies of social insects [24–26]. Very recently, the influence of communication on the foraging pattern of gazelles was investigated [27]. The study showed that communication over intermediate length scales results in faster searches.

In this paper, we develop a minimal model of collective foraging where the motion of the individual foragers would be random in the absence of any interaction. We investigate the effect of the interaction on the search efficiency and the spatio-temporal scaling that emerges in the movement of foragers. The foragers are walkers on a two-dimensional square lattice, whereas targets are immobile but regenerative. The foragers have local information about the distribution of the targets. We are primarily interested in the emergent complexity that should result from the interactions between the foragers; therefore, we begin with a simplistic assumption about the movement of a forager independently searching for targets. We assume that such a forager, at any instant of time, has no preference while choosing the direction of movement, and hence executes a random walk (RW) on the lattice. The forager is only able to detect targets at the site where it has arrived. Let \((x'_t,y'_t)\) be the position of a forager \(i\) on the lattice at time \(t\) and let \(j\) be the nearest of the all the foragers in the neighbourhood which have consumed one target at time \(t\). The rules governing the behaviour of \(i\) are the following:

1. If there are targets at \((x'_k,y'_k)\), then the forager stays at that site and consumes one target. Let \(h(x,y)\) denote the number of targets at a site \((x,y)\) at time \(t\). Thus, \((x'^{t+1}_i,y'^{t+1}_i) = (x'_i,y'_i)\) and \(h^{t+1}(x'^{t+1}_i,y'^{t+1}_i) = h(x'_i,y'_i) - 1\). If at any instant of time the number of targets at any site exceeds the number of targets available, then the targets are distributed randomly between the foragers.

2. If the site \((x'_j,y'_j)\) is empty with the forager having arrived at this site by taking a random step (defined below), or the forager being there in the presence of food (at time \(t-1\)), then the movement of the forager is decided according to the following rules.
   a. If there is no successful forager in the neighbourhood, then the forager takes a random step, i.e. \((x'^{t+1}_i,y'^{t+1}_i)\) becomes equal to one of the nearest neighbour coordinates \((x'_i \pm 1,y'_i)\) or \((x'_i,y'_i \pm 1)\) with equal probability.
   b. If there is a successful forager \(j\) in the neighbourhood, then with a probability \(p_l\), the forager ‘moves’ in the direction of the former and with a probability \(1 - p_l\) moves out by taking a random step. Here, \(p_l = \exp(-a d_{ij})\), where \(d_{ij}\) is the Euclidean distance between \((x'_i,y'_i)\) and \((x'_j,y'_j)\). The movement in the direction of \(j\) implies moving to a nearest neighbour site such that the distance between \((x'^{t+1}_i,y'^{t+1}_i)\) and \((x'_j,y'_j)\) becomes less than \(d_{ij}\). We term this movement as a targeted step in contrast to a random step and let the forager remember this distance as \(d_{ij} = d_{ij}\).

3. If the site \((x'_j,y'_j)\) is empty and if the forager has arrived at this site by taking a targeted step, then the movement of the forager is decided as follows.

2. The model

In the following, we describe our model in more detail. We consider a two-dimensional square lattice of size \(L\) with periodic boundary condition (PBC). The PBC is applied with regard to the movement of foragers as well as the regeneration of the targets. There are \(N_f\) foragers which are initially distributed randomly on this lattice. The targets (food) are regenerative such that at every time step the total (amount) is \(N_f\). We define the neighbourhood of a forager as a circular region of radius \(R\) centred on it. We assume that at any instant of time, a forager is able to determine which are the foragers in its neighbourhood that have been successful in identifying and consuming food. However, a forager is only able to detect targets at the site where it has arrived. Let \((x'_t,y'_t)\) denote the number of targets at a site \((x,y)\) at time \(t\).

[The rest of the text continues with the detailed description of the model, including the equations and dynamics of the system.]
(a) Same as (2)(a).
(b) If there is a forager \( j \) in the neighbourhood and \( d_{ij} < d_j^{\gamma^{-1}} \), then the forager takes a targeted step towards \( j \) and \( d_j = d_{ij} \).
(c) If there is a forager \( j \) in the neighbourhood and \( d_{ij} \geq d_j^{\gamma^{-1}} \) then same as (2)(b).

(4) This rule pertains to the regeneration of targets at every instant. Let \( \Delta N(t) \) be the number of targets that have been consumed at any instant of time \( t \). We randomly select one of the remaining \( N_T - \Delta N(t) \) targets. At a distance \( d \) (\( 1 \leq d \leq L/\sqrt{2} \)) from the location of this target, a new target is placed, in a random direction. The distance \( d \) is chosen from a distribution \( P(d) \sim d^{-\gamma} \), where \( \gamma \) is a parameter. This process is repeated another \( \Delta N(t) - 1 \) times. Thus, the total number of targets at the beginning of the time step \( t + 1 \) again becomes equal to \( N_T \).

We choose such a scheme for the regeneration of targets with a twofold view. First, it ensures that at any instant the distribution of resources is heterogeneous. The power-law form for \( P(d) \) generates targets distributed in well-separated clusters with the parameter \( \gamma \) effectively characterizing the degree of patchiness of the distribution. A similar scheme was used to model the spacings between marine food patches in [10].

Second, the method allows, in general, the preservation of the overall statistical nature of the foraging environment during the time evolution of the model. A more realistic model would allow the simulation in an infinite lattice where the patches need not regenerate at every time step. In effect, our model provides a method to produce a foraging environment that is highly variable in space and time [20, 29, 30].

We call a consecutive sequence of random steps a RW and a consecutive sequence of targeted steps a TW. A forager which searches independently executes a RW until it encounters a target. However, there is a finite probability that such a forager may decide to move towards sites where foragers have already encountered food assuming that targets are clustered in space. It is natural that this probability is distance dependent as there is an energy cost associated with the movement of a forager [31]. In addition, travelling over a large distance takes more time during which the targeted patch becomes increasingly exploited [32]. Therefore, nearer the location of the sites, relocation to the target site is more probable. This fact is quantified through the definition of \( p \) in (2)(b). In the limit \( \alpha \to \infty \), the trajectories of the foragers are essentially RWs. The tendency of foragers to travel towards distant locations, where targets have been discovered, increases with a decrease in the value of \( \alpha \). Thus, trajectories become mixtures of RWs and TWs.

Note that a TW, when initiated, is not aimed at a particular individual but towards a particular site. The variable \( d \) ensures that forager has a memory of the distance to the targeted site, and therefore the instantaneous movement of the forager is in a direction so as to minimize this distance. On appearance of another site, where food gets detected, closer than the original, the TW gets directed towards it and \( d \) is accordingly modified. In the case where the last targeted site is exhausted and some feeding site in the neighbourhood gets detected at a distance larger compared with the distance to the former, then the forager probabilistically adopts that target depending on the distance. This rule accounts for the fact that when a forager has adopted a strategy of moving towards targets detected by others, will not easily abandon it and return to searching independently. In addition, a forager actually approaching a cluster of sites should not get deterred if one of the sites gets emptied. A model with some-what similar but rather deterministic rules for the movement of the foragers was considered in [33] where the effect of group size on foraging rate was studied. The randomness in our model is naturally built in by the probabilistic choice of the step directions of the foragers and the scheme used for the regrowth of the targets.

In the present study, we assume that \( R \) is larger than the system size, i.e. at any instant, a forager is informed about state of all other foragers. However, it is obvious that the actual use of this information is manifested through the distance dependent probability \( p \). In addition, we take \( N_T = N \) which would correspond to the case of targets being rather scarce; at the same time this equality also ensures that the maximum possible value of targets encountered per unit time per forager is unity.

3. Results

In general, not only the regeneration process, but also the interaction with the foragers is supposed to influence the distribution of targets at long times. However, with the parameters used in this paper, our simulations reveal that the heterogeneity in the spatial distribution of targets at all times is qualitatively independent of \( \alpha \) and is controlled through \( \gamma \). The larger the value of \( \gamma \), the more clustered the targets become and the power-law form for \( P(d) \) resulting in rare, but very large values of \( d \) gives rise to large separation between clusters.

In figure 1, we show the time evolution of the model for the parameters \( N = 128, L = 128, \gamma = 2.5 \) and \( \alpha = 0 \). The dynamics is deterministic to a certain extent because \( \alpha \) is zero. Initially (figure 1a), the targets appear to be distributed in two well-separated clusters, and the foragers are mostly away from these targets. At a later time (figure 1b), the foragers are found to have aggregated over one of the clusters. This happens as soon as one of the foragers is successful in detecting a target belonging to that cluster. The trajectory of a typical forager is shown. Once the targets in the region where the foragers are present get depleted, there is a searching phase (figure 1c). The trajectory of the foragers at this stage is mostly RWs. The search ends as soon as a site in the second cluster is detected by any forager, and all the others relocate towards the site. The trajectory during this relocation mostly comprises of TWs (figure 1d,e). Eventually, the second cluster is also consumed and another searching phase follows (figure 1f). The simultaneous development of clusters of targets in other regions of the lattice is also visible in the figure.

We assume that the cost involved in foraging is proportional to the distance travelled by the foragers. The efficiency of searching [1], defined as the ratio of the total number of targets consumed to the total distance travelled by all the foragers, is given by

\[
\eta = \frac{\sum_{t=1}^{T} \Delta N(t)}{\sum_{t=1}^{T} N_W(t)},
\]

where \( N_W(t) \) is the number of walkers at time \( t \). The statistics is collected in the stationary state for \( T = 10^5 \) time steps in each configuration and \( \langle \cdots \rangle \) denotes the average
over 200 configurations. In figure 2a, we plot $h$ as a function of $a$. For $N = 512$ and $L = 512$, we are able to compare the efficiency of the searches for target distributions at different degrees of patchiness characterized by $g$. When the targets regenerate randomly across the lattice, we find $h$ to increase with $a$ and then saturate to a value in the limit of $a \to \infty$. Thus, searching independently is overall beneficial. However, for a patchy distribution of targets, the scenario is
found to be very different. For example, when $\gamma = 2.5$, the maximum in the efficiency is found to occur around much smaller values of $a$. This signifies that the optimal strategy in this case is a mixture of independent searching and joining others. The reason being the following. When targets are clustered in space, we expect that a forager travelling to a region where targets have already been discovered increases its own chance of encountering a target. However, indiscriminately taking such decisions may not be beneficial. When a large fraction of the foragers perform TWs to a single cluster, this delays the discovery of other clusters in space. In addition, by the time the foragers reach a distant region, it becomes depleted of targets. Therefore, the most efficient strategy for encountering targets is joining others when the clusters are discovered nearby and opting to search independently otherwise. Unlike the scenario described in figure 1 ($\alpha = 0$), an intermediate strategy may amount to the simultaneous discovery and exploitation of more than one cluster or faster discovery of newly generated clusters. The results in the case of $\gamma = 2.0$ and $3.5$ are found to be qualitatively similar. Additionally, for $\gamma = 3.5$, when the targets are extremely clustered in space, the efficiency in the limit $\alpha \to 0$ is found to be larger than that of the $\alpha \to \infty$ limit unlike for lesser values of $\gamma$. This is because the regenerated clusters appear very close to each other and as such aggregation allows the foragers to move from one cluster to another with least amount of exploration. A comparison between different values of $N = 256, 512$ and $1024$ shows that the maximum value of efficiency is larger for larger values of $N$. We quantify this effect by a scaling collapse of $\eta$ versus $\alpha$ plots for five different values of $N$ in figure 2b with $L = 512$ and $\gamma = 2.5$. The collapse reveals that the width of the maximum in $\eta$ scales as $N^{\beta_2}$, where $\beta_1 = 0.15$ and the maximum value of the efficiency, $\eta_{\text{max}}$, scales as $N^{\beta_2}$ with $\beta_2 = 0.70$. We define $\alpha_m$ as the value of $\alpha$ for which $\eta = \eta_{\text{max}}$. The values $\alpha_m$ for which the collapse becomes possible are plotted against $N$ in the inset of figure 2b. The plot shows that $\alpha_m \sim N^{\zeta}$ with $\zeta = 0.65$.

Interestingly, near the maximum of efficiency, we find that there is a maximum for the fraction of walkers executing TWs. In figure 3a, we plot the averaged quantity, $f_t$, defined as the ratio of the number of foragers executing TWs to the total number of walkers at any instant. As expected $f_t$ goes to zero as $\alpha \to \infty$, because the foragers do not follow each other. In addition, $f_t$ is large as $\alpha \to 0$. The activity of the foragers in this limit is similar to the scenario illustrated in figure 1. The dominant activity is searching (through RWs) between the discovery of clusters and, also, the simultaneous discovery of clusters is rare. The TWs only occur in short bouts. For intermediate values of $a$, when there is a possibility that a cluster can be detected while another one is being exploited, the TWs take place more frequently. This results in $f_t$ having a maximum. When targets regenerate randomly across the lattice, the TWs are not beneficial in terms of the efficiency as already seen from figure 2a. Decrease in the value of $a$ favours the increase in aggregation of the foragers through TWs, whereas the aggregation reduces the number of forager–target encounters. This competition results in the maximum of $f_t$ for random regeneration. The effect of random reappearance of targets coupled to extreme aggregation for $\alpha \to 0$ and the fact that we use a PBC gives rise to a stable moving band in the steady state as shown in figure 4a. The band travels parallel to either of the axes.

When a forager comes across a site ($x$, $y$) having targets, the time spent at that site, before it moves away, is in general equal to the number of targets present, $h(x, y)$ (unless other foragers are also present at the site). Large values of $\gamma$ result in sites with $h(x, y) \gg 1$. As a result, the presence of a forager at such a site is of longer duration. Now, if $a$ is also small then such a forager, at any instant, draws towards the site a large number of foragers who execute TWs. During the time the former spends consuming targets, the TWs of the latter align. Such an alignment of the paths of a set of moving foragers generates an overall pattern of a moving column. Such a case is illustrated in figure 4b where two such perpendicular columns are seen giving rise to a wedge. Such a formation persists and as a whole travels until the adjacent targets are not depleted.

The observation of different patterns encouraged us to investigate the general nature of collective motion.
measured the order parameter popularly used to characterize motion of flocks of self-propelled particles [34]. As the motion of the foragers is restricted to the lattice, the order parameter is

$$\Phi = \left\langle \left( f_{x,} - f_{-,} \right)^2 + \left( f_{y,} - f_{-,} \right)^2 \right\rangle,$$

(3.2)

where $f_{x,}$ denotes the fraction of foragers moving towards the positive $x$-direction at any instant and likewise. A large value of $\Phi$ would imply that, on the average, the foragers are moving in the same direction, at any instant of time. Temporal and configuration averaging is denoted by $\langle \cdots \rangle$ and is similar to the calculation of $\eta$. In figure 3b, the plot $\Phi$ versus $a$ is shown. We find that the maximum of $\eta$ is accompanied by a transition from a regime where the value of $\Phi$ is dominated by fluctuations, owing to random movement of the foragers, to higher values of $\Phi$. The higher values of $\Phi$ occur when foragers migrate from one cluster to another. However, the actual values of the order parameter are low because of the movement on the lattice and the fact that just after the depletion of a cluster, the foragers diffuse in all directions.

The influence of the collective searching on the movement of individual foragers is evidenced in the distribution of lengths of TWs. The tendency to search independently is less when $a$ is small and long TWs are probable. In figure 5, we plot the probability density function, $P(l)$, of length of TWs of length $l$. We find that TWs become scale-free in the limit of $a \to 0$ for patchy distributions. For $N = 512$, $L = 512$, $\gamma = 2.5$ and $a = 0$, we find $P(l) \sim l^{-\mu}$ with $\mu = 2.80$ (using regression analysis [35]). As $a$ increases, the TWs become shorter and the distribution falls off faster. These are shown in figure 5a. For random distribution of targets and extremely clustered distribution ($\gamma = 3.5$) which correspond to moving bands and columns, respectively, there is a deviation from power law (figure 5b). In the limit $a \to 0$, we generally find that scale-free TWs arise for values of $N$ which are either equal to $L$ or larger but close to $L$ (figure 5c,d). For $N \gg L$, the distribution is fat-tailed but not a power law. In the case of $N < L$, the clusters are exploited so fast that long TWs become rare.

The fact that fat-tailed distributions of TWs result in the limit $a \to 0$ also raises the question as to whether the primary cause behind the long TWs is the choice of the interaction radius $R$ being larger than the system size. To investigate this, we study the effect of decreasing $R$ on the nature of $P(l)$ when $a = 0$. If there are $N$ non-interacting random walkers in a region having area $L^2$, then the average separation between them is of the order of $r_0$, where, $r_0 = L/\sqrt{N \pi}$. We consider the values of $R$ in units of $r_0$ such that $R = m r_0$, where $m$ is a positive integer. Having $m \ll (L/r_0)$ ensures that at any instant, on the average, a forager remains informed about the state of $n$ other foragers where $n \ll N$. In figure 6a, we plot the values of $n$ for five different values of $m$ when $L = 512$ and $N = 512$. The power-law fit reveals $n \sim m^\nu$ with $\nu \approx 2.23$. In figure 6b, we plot the distributions $P(l)$ corresponding to the different values of $m$. We also show $P(l)$ corresponding to the case when $n = N$, that is, $R$ is larger than the system size. Interestingly, we find that the development of the power law starts when $n$ is still much smaller than $N$. Below $n \approx 4$ ($m = 2$) the fall in $P(l)$ is fast, and from $n \approx 20$ ($m = 4$) and above, the fall becomes rather slow and the power-law region becomes prominent. Thus, even when a forager is only interacting with a small number (when compared with the total number of foragers) of other foragers in its locality, long TWs may arise.

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Figure 4. Snapshots of two different patterns exhibited by the model corresponding to regrowth rules for targets and for the parameters $N = 512$, $L = 512$ and $a = 0$. A stable moving band, observed when targets regenerate randomly across the lattice (a) and wedge formation for $\gamma = 3.5$ (b) (only the section of the lattice where foragers and targets are concentrated is shown). In (a), the foragers are marked with blue and the targets are marked with green. The path of a typical forager is shown with a colour scheme similar to the inset of (a). A colouring scheme for the multiple occupation of sites by targets is used (provided in legend).
Figure 5. The plots of probability density function, $P(l)$, of the length of targeted walks. (a–d) The different sets of values of $N$, $L$, $\gamma$ and $\alpha$, as indicated in the legends. The dashed line in (a) is a guide to the eye and indicates the power-law nature in the region for the curve with $N = 512$, $L = 512$, $\gamma = 2.5$ and $\alpha = 0$. Regression fit with $P(l) \sim l^{-\mu}$ gives the value of $\mu = 2.80$. In (c), the values of $\mu$ corresponding to different values of $N (=L)$ resulting from regression fits are provided in the legend. (Online version in colour.)

Figure 6. (a) The plot of average number of neighbours $n$ as a function of $m$, where $R = m.n$, The bars indicate the standard deviations obtained from averaging over time snapshots and initial conditions. The straight line corresponds to a power-law fit having exponent equal to 2.23. (b) The plots of probability density function, $P(l)$, of the length of targeted walks when $\alpha = 0$, corresponding to different values of $m$ as indicated in the legend. (Online version in colour.)
The reason behind this is the fact that a TW once initiated may continue even when the originally targeted site gets depleted of targets. On the detection of targets at some site within a radius $R$ from the current position of the forager, the TW gets directed towards that site (rules (3)(b) and (c) of the model).

The interdependence between the foragers is also evident in the temporal behaviour of the model. When targets are clustered there is usually a waiting time corresponding to the searching phase between the discovery of clusters. We define $\tau$ as the time between successive encounters with targets by the group as a whole. In figure 7, we plot the probability density function $P(\tau)$. With the decrease in the value of $\alpha$, the states of the foragers become increasingly correlated. This is reflected in the power-law nature of $P(\tau)$. For $N = 512 = L$ and $\gamma = 2.5$, we find $P(\tau) \sim \tau^{-\delta}$ with $\delta = 1.67$ for values of $\alpha$ between $5.0 \times 10^{-4}$ and 0 (figure 7a). We find the power-law form for $P(\tau)$ to be retained for larger values of $\gamma$ as well. The value of $\gamma$ becoming less finally leading to a random distribution of targets makes $P(\tau)$ fall faster (figure 7b). Faster decay of $P(\tau)$ also occurs when $N > L$ (figure 7c,d). This is because when both targets as well as foragers are abundant the long waiting times become rare.

4. Discussion

Our model demonstrates that the presence of interactions within a group of foragers can help maximize the efficiency of searching. The decision of an individual as well as the cost of joining are assumed to depend on the distances between the foragers. The optimal strategy, from which the individuals benefit, is a mixture of searching independently and joining other foragers. The dependence of the efficiency on the parameter $\alpha$ and the fact that $\alpha$ is the inverse of a length scale supports the notion that the exchange of information above a length scale may not be really useful for maximizing the individual success rates. We also find that such interactions can lead to scale-free walks by the foragers in certain limits. Interdependence between the foragers also correlates the states of the foragers manifested by power-law-distributed waiting times. The model also shows that under
certain conditions steady or transient patterns of collective motion can emerge. We conclude that our model can help understand overall foraging patterns of animal groups in terms of simple strategies at the level of the individual animals.

Foraging experiments, using clumped distributions for food sources, with different species of birds such as pigeons [36], sparrows [8], spice finches [37] and great tits [38] have revealed that individuals closely watch their conspecifics, take cues from their activity, or are attracted by their vocalizations, and home in towards the latter when the latter discovers food. The artificial arrangements of food are substitute for patchy distributions found in the actual environments. Such distributions are also ephemeral in the sense that a source starts depleting once it is detected. A real-world example involves birds preying on fish schools. The school can only be detected close to the water surface and may become undetectable when it submerges to larger depths [39]. Similar foraging behaviour has also been observed in fish [40], primates [41], human populations [42] and other mammals [43]. However, the case when the majority of the foragers consistently keep relocating to the region where food has been discovered is, in general, found to be disadvantageous. Observation on greenfinches [44] with depletable patch conditions have revealed that such behaviour leads to a decrease in the average food intake with the increase in the group size. Similar results were also obtained in [37]. The disadvantage is largely attributed to the suppression of simultaneous discovery of multiple patches which is very true for our model. In addition, in our model, the decrease in efficiency with increase in number of foragers can be seen from figure 2n in the limit of $\alpha \to 0$ and $\gamma = 2.5$. In a study on the Mongolian gazelle [27], it was found that the gazelles exchange information about locations of resources at such distances that result in the optimal search. The authors also discussed other possibilities (other than search efficiency) that may result from communication at very short and long distances. Remarkably, the movement of gazelles was found to be Brownian. A study on terns noted that even when the observed maximum movement of gazelles was found to be Brownian. A study on terns 

[43x349]on terns [45] noted that even when the observed maximum movement of gazelles was found to be Brownian. A study

References


The text in the image is a collection of references and abstracts from various scientific papers. The text is not a natural reading of a single document but rather a compilation of multiple sources. The references are written in English and cover a range of topics including biology, ecology, and animal behavior. The papers discuss topics such as foraging strategies, group decision-making, and the role of social interactions in animal movements.

To provide a more detailed understanding, I will highlight some key points from the references:


