



Effects of random motion in traveling and grazing herds

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ABSTRACT

We examine the role that randomness or noise in individual motion may play in forming effective grazing strategies for herd members as they collectively move toward a destination. Through a model where animals are attracted to Voronoi neighbors as well as a destination endpoint, we show that including a significant random motion component can speed up the movement of a herd toward this destination, increase the efficiency that food is acquired during the travel, and facilitate a natural herd shape that mitigates predation risk. Specifically, if the influence of the Voronoi neighbors on individual motion is equal to the pull toward the destination, we find that optimal travel time and food consumption efficiency occurs for noise approximately twice as strong as the influence of herd members to each other, in a range of herd sizes from 10 to 100. We find that reducing the destination influence lowers this optimal noise only slightly, with random motion still exceeding the influence of neighbors. For a destination influence exceeding that of the Voronoi neighbors, an additional travel mode appears with minimal noise and aligned velocities in which the herd marches directly toward the endpoint. Our results are consistent with observational evidence of random motion in several animal groups, and motivate its generalization to traveling and grazing herds.

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1. Introduction

Many animals congregate into flocks or herds, which offer protection against predators (Hamilton, 1971; Vine, 1971) especially while foraging (Barnard, 1980). Herds themselves may migrate in response to seasonal variations in food, water, or for breeding (Webster et al., 2002). This raises a central question: what influences drive the motion of each individual animal? More specifically: to what extent are particular animals influenced by their herdmates, and to what extent is the lure of the destination a primary drive? What other influences might optimize the travel time or foraging opportunities as a herd migrates? While answers to these questions certainly depend on specific types of animals and environments, simulations can give insight to commonalities that may underlie herding behavior more generally. In this paper, we show that including a random motion (or noise) component in the movement of individual animals can play a very significant role in reducing travel time and increasing foraging efficiency as a herd moves toward a destination.

In a recent study of cows, Gajamannage et al. (2017) constructed a cost function that attempts to characterize multiple behaviors: resting, grazing, and association with other herd members

for protection. Though such a cost function may approximate certain observed behaviors, it seems unlikely that cows themselves cognitively process information with this degree of sophistication. In this work, we present a simpler model that may apply to a variety of herding animals: namely, taking animal movement as the (normalized) vector sum of an attraction toward an individual's Voronoi neighbors, an attraction to a destination, and a random motion component. We find that substantial random motion in this model not only lowers predation risk (similar to Ose and Ohmann, 2017), but can actually speed travel toward a destination and improve foraging efficiency along the way.

Substantial support for including random motion in animal movement comes from observational studies in very different groups. Yates et al. (2009) showed that the movement of individual locusts become more random if group alignment is lost, and that this random motion actually helps restore coherent group dynamics. In large starling flocks, Cavagna et al. (2013) showed that random motion is responsible for the reshuffling of neighbors. Murakami et al. (2014) showed that random motion helps enable soldier crabs enter what is normally an avoidance area. Murakami et al. (2015) also report that individual movement in schools of ayus have an inherent noise component. Our results in this paper motivate the likelihood that random motion generalizes to grazing and traveling animals as well, and suggest the need for additional field observations to confirm or refute this claim.

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2. The computer model

The central idea of our simulations is to explore herd dynamics and food consumption under the influence of noise as the herd “grazes” toward a destination a considerable distance away. To that end we construct our simulations on a homogeneous two-dimensional flatland, following [Ose and Ohmann \(2017\)](#). In each of the 100 runs in a given simulation, we randomly distribute initial positions of the herd animals within a 200×200 grid, with grid distances measured in terms of the body length (BL) of a herd animal. We divide each simulation run into discrete time steps, during which each animal moves 1 BL in the direction specified by the vector sum of the influences on it, unless it would otherwise move too close to a neighboring animal (which we take to be within 2 BL). Animal movements are updated simultaneously with each new time step. In the event that multiple animals seek positions within 2 BL of others, conflicts are resolved in a particular order. Animals lower in the hierarchy remain in place, yielding to those more highly ranked. In this way, our model is consistent with the graded dominance hierarchy found in beef cattle ([Šárová et al., 2010](#)).

We use a backward update rule, with the position \vec{r}_i of individual i at time step $t + 1$ based on the position and velocity \vec{v}_i calculated at the previous time step t :

$$\vec{r}_i(t + 1) = \vec{r}_i(t) + \vec{v}_i(t). \quad (1)$$

The velocity in turn is the normalized sum of three explicit directional influences $\hat{d}_{i,Vor}$, $\hat{d}_{i,Dest}$, $\hat{d}_{i,Noise}$ for each individual i in the herd, each with its own weighting coefficient:

$$\vec{v}_i = \frac{\vec{d}_i}{|\vec{d}_i|} \quad (2)$$

where

$$\vec{d}_i(t) = A_{Vor}\hat{d}_{i,Vor}(t) + A_{Dest}\hat{d}_{i,Dest}(t) + A_{Noise}\hat{d}_{i,Noise}(t). \quad (3)$$

The following paragraphs describe in detail the neighbor, destination and noise influences on the movement of each animal: $A_{Vor}\hat{d}_{i,Vor}$, $A_{Dest}\hat{d}_{i,Dest}$, and $A_{Noise}\hat{d}_{i,Noise}$ respectively.

The first influence $A_{Vor}\hat{d}_{i,Vor}$ describes the animal-to-animal interaction within the herd for which we use the Voronoi (V) model ([Ginelli and Chaté, 2010](#); [Schubring and Ohmann, 2013](#); [Strandburg-Peshkin et al., 2013](#)). In the Voronoi model individual animals are affected only by their neighbors in a Voronoi tessellation. The V model is *topological* rather than *metric*, so that interactions are based on relative positions rather than distances. Topological interactions have been documented, for example, in starlings ([Ballerini et al., 2008](#); [Cavagna et al., 2010](#); [Bialek et al., 2012](#)). Other herding models might be considered, such as the metric Local Crowded Horizon (LCH) model ([Viscido et al., 2002](#)), though [Ose and Ohmann \(2017\)](#) showed that LCH and V models can result in similar herd cohesion and predation risk when noise is added. [Fig. 1](#) illustrates the Voronoi model, with a particular animal highlighted in red and its Voronoi neighbors in green. At each time step, we take the Voronoi contribution for individual i to be the normalized sum of the unit vectors \hat{d}_{ij} toward each of the individual's N neighbors:

$$\hat{d}_{i,Vor} = \frac{\sum_{j=1}^N \hat{d}_{ij}}{\left| \sum_{j=1}^N \hat{d}_{ij} \right|}. \quad (4)$$

As a topological model, all Voronoi neighbors have equal influence; this is reflected in the use of directional unit vectors \hat{d}_{ij} in [Eq. \(4\)](#). For animals that respond primarily to visual stimuli, a blind spot

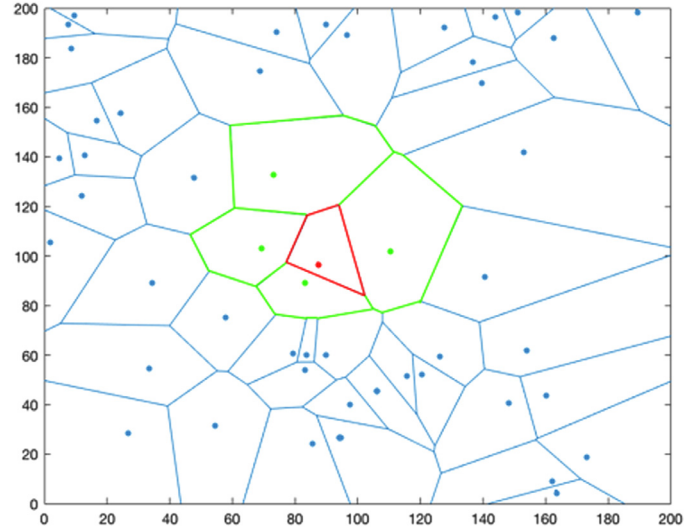


Fig. 1. Example of a Voronoi tessellation with a herd of 50 animals (shown as dots) randomly distributed on an initial 200×200 grid. Surrounding Voronoi polygons encompass the area nearer to each individual than to any other. Each polygon represents the Domain of Danger describing predation risk to a particular individual in the herding area. For illustration, one animal is highlighted in red, with its Voronoi neighbors in green.

could be incorporated that eliminates the influence of neighbors out of the field of view ([Couzin et al., 2002](#)). However, here we assume that animals respond to multiple overlapping sensory stimuli (e.g. sight, hearing, smell) and are equally affected by each Voronoi neighbor. All simulation runs set the weight of the overall Voronoi contribution equal to one: $A_{Vor} = 1$.

The contribution $A_{Dest}\hat{d}_{i,Dest}$ in [Eq. \(3\)](#) describes the destination influence, with $\hat{d}_{i,Dest}$ taken as the (normalized) direction of an individual i toward grid point (600,600). This destination grid point might directly represent a physical feature such as a lake or valley to which each individual may have an instinctual attraction. Alternatively, with a slightly different interpretation $A_{Dest}\hat{d}_{i,Dest}$ may represent the influence that lead herd member(s) moving toward a destination have on the rest of the herd, such as described by [Toulet et al. \(2015\)](#). Unless otherwise noted, all simulations set the destination weight to one: $A_{Dest} = 1$, equal to the Voronoi contribution. In [Section 3.5](#) we discuss the implications of changing this condition, in which the instinctual drive toward a destination may be stronger or weaker than the influence of neighboring animals.

The third influence $A_{Noise}\hat{d}_{i,Noise}$ is random noise, with a random direction $\hat{d}_{i,Noise}$ chosen for each individual i at each time step, and with a weight A_{Noise} that generally differs from A_{Vor} and A_{Dest} . The random motion component incorporates conditions that include environmental factors like small-scale terrain irregularities as well as internal and external stimuli like hunger or sensory information. Including noise as an explicit part of motion captures the variance of these impacts on different individuals.

In each run we record the time needed for the center of the herd to reach its destination, from which we determine an average travel time (and its variance) at each noise level. In this way our simulations gauge the effects that various amounts of randomness in individual movement have on the overall herd travel time to a destination.

As shown in [Fig. 2](#), we take the destination point to be the grid point (600, 600), with the herd deemed to have effectively reached its target when the herd center first comes within 50 BL of this destination point. From initial starting positions centered roughly

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