

Herding Behavior: The emergence of large-scale phenomena from local interactions

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Abstract

Herding behavior can arise as the collective action by individual agents that base their movement only on information about their neighbors; global properties can arise from strictly local interactions. Simulation models are used to explore the influence of individual decisions on group pattern, and to investigate the mechanisms underlying such patterns.

1 Introduction

The phenomenon of herding is a common one among large land mammals. Herd members can realize a variety of benefits by joining large groups, many of which relate to protection from predation and reduction of search time for patchy resources (Pulliam and Caraco, 1984). Although numerous theories exist to explain the advantages of grouping, the proximate mechanisms that form and maintain them are not obvious. The structure of herds emerges from decisions taken by individuals, and a fundamental problem is to explain how grouping patterns relate to those individual decisions.

It is nearly impossible, and unnecessary for the maintenance of groups, for an individual in a large herd to assess the group's global structure. Herding animals typically react to a small subset of their neighbors to reduce the amount of information that they must process. It is the degree of information sharing and the size of a herd member's perceptual neighborhood that concern us.

Many models have been constructed to demonstrate that stable herd-like behavior in large groups can emerge even when individuals only interact with their nearest neighbors (Reynolds, 1987; Huth and Wissel, 1992; Gueron, Levin, and Rubenstein, 1995; Grünbaum, 1995). In this paper, individual-based models are applied specifically to data from the observation of wildebeest herds, and used to investigate how changing local rules changes observed patterns. Properties such as spatial distribution and stability are examined. Wildebeest are ideal study organisms for such work because of their extremely large herd sizes during the migratory season.

2 The model

A variety of patterns characterize observations on wildebeest herds (Sinclair, 1977; Scott, 1988). Wave-like fronts, undulating trails, and patchy distributions all have been observed. How can these be understood as emerging from the aggregate behaviors of individuals? How do changes in individual behaviors affect global patterns? To approach this question, we begin from a collection of agents that base their movements on the states of their surrounding neighbors. This approach follows the general development of Grünbaum (1995); Gueron, Levin, and Rubenstein (1995); and Huth and Wissel (1992). All agents follow the same set of rules, with no special kin relationships or other such affinities. This assumption seems reasonable given Sinclair's (1977) observation that:

"The main migratory population of three-quarters of a million animals acts like one enormous herd, with individuals showing no particular attachment to any subgroup. In fact, the evidence suggests that there are no well-defined subgroups, (except for the mother, her calf, and for a brief period her penultimate calf). At times in the wet season they may all combine into one herd." (p.152)

For our simulation, agents have information relating to their own location on a cartesian plane, speed, and a directional bias. The bias is the direction the individual would travel in the absence of neighbors. This direction of the bias shifts in time, reflecting the imprecision of its directional sense. It is randomly set between $-\theta$ and $+\theta$. During each time step, each individual calculates its desired speed and accelerates to match it. An agent's intrinsic walking speed, its speed when it has no neighbors, has a magnitude equal to its normal walking speed in the direction of its "bias." If there are neighbors nearby, their states may affect the individual's desired speed.

The interaction paradigm used in this study is similar to Huth and Wissel's (1992) and Gueron *et al.*'s (1995). Each individual is surrounded by three concentric spatial "zones" (Figure 1). The three zones are designated the stress zone, the neutral zone, and the attraction zone. These represent the three classes of reactions an individual will have to a neighbor, including attraction and repulsion. Attraction holds the herd together, while repulsion keeps animals from colliding. The desired behavior in the neutral zone is less obvious, and different strategies were implemented, which are discussed later. An individual will only react to neighbors in its nearest occupied zone. For example, an animal will only react to a neighbor in its attraction zone if it sees no one in its stress zone (Figure 2). We take zones to be rectangular rather than circular to allow faster computation, and with the individual at the center. Wildebeest have essentially 360 degree vision.

The "stress zone" immediately surrounds the individual. This zone represents an animal's need for space, and the size of the zone is the minimum distance an animal will tolerate a neighbor to approach. If an individual finds a neighbor in its stress zone, it tries to move diametrically away from the intruder. If there are one or more neighbors in its stress zone, the individual calculates its "desired" direction in the following manner: it determines the vectors from itself to the intruders, takes the sum of these vectors divided by their magnitudes cubed, then normalizes the magnitude to -1.5 times its normal walking speed. The individual will accelerate in this direction. The desired speed is normalized to a magnitude higher than normal walking speed; this allows an agent to walk faster in order to evade an intruder entering its stress zone from the rear, and the minus sign makes this force a repulsive one. The influences of the neighbors are weighted by the inverse of their distances cubed so that the closest have the strongest effect by an inverse-square law. Obviously, the choice of parameters as well as the cubic dependence are arbitrary; they emphasize the need for data as to how individuals respond to their neighbors. The simulations should be understood as an initial and qualitative inquiry, and sensitivity analyses are essential to determine how observed behavior depends on the assumptions. Our objective is simply to demonstrate the wealth of patterns that can result from simple local rules.

If there are no neighbors in the individual's stress zone, it will search its neutral zone. The three strategies of neutrality, speed matching, and centering for neutral zone interactions were tested in this study. In the "neutral" model, agents do not react to neutral zone neighbors. In the "speed-matching" model, the agent tries to match its speed to the average of those in

the neutral zone. This tendency should improve group cohesiveness and directionality (Huth and Wissel, 1992). The “centering” model causes an agent to move towards the “center of mass” of its neighbors in the neutral zone, in effect “centering” itself within its neutral zone neighbors. This tendency will have little effect on individuals in the center of a group but will have a great effect on those on the edge of a group (Reynolds, 1987). Those on the edge will tend to move towards the center of the group. This cohesion reflects an animal’s attempt to avoid group boundaries, where predation may be highest (Hamilton, 1971). An agent’s desired velocity is set to the weighted sum of the agent’s intrinsic walking speed, designated to be the “neutral” tendency, and a vector derived from one of the above strategies, with weights summing to 1.0. If the weight of the neutral tendency is set to 1.0, the agent exhibits the “neutral” model behavior. Neutral tendency is never set to 0.0, since the agent would lose its intrinsic directional sense and the herd would not move. The influences of neighbors are not weighted by the distance from the agent because it is assumed that all neighbors in the neutral zone have the same importance.

The next area that an individual will search is its attraction zone. As with the stress zone, the individual calculates a vector by summing the distances of the neighbors in the zone weighted by the inverses of their distances cubed, but the sum is normalized to 1.5 times its normal walking speed, not -1.5. Because there is no negation, the agent will accelerate towards its attraction zone neighbors. This tendency helps solitary individuals form herds or join currently-existing ones.

The herd is initialized by placing a number of agents randomly in a square of a given size with all agents travelling at their intrinsic walking speeds. The square’s size and the number of agents in the simulation determine the initial density of the herd. The model is run in discrete time steps for a given length of time. At each step, all agents simultaneously determine their desired velocities and accelerate to match them. The time steps are sufficiently small that the agents will react to each other quickly enough to prevent collisions. A small time step size also helps stabilize the speed of the agents.

3 Methods

The sizes of the zones and speed of the agents in the model were based on analysis of tapes of wildebeest herds. Measurements of speed and distance were taken in units of adult body lengths, roughly 2 meters. Wildebeest were found to travel at 0.6 body lengths per second. The boundaries of the zones were derived by noting where changes in inter-animal interaction seemed to occur.

The size of the stress zone determines the closest approach a wildebeest will tolerate. This figure can be estimated by observing the spacing of animals in a dense configuration. This appeared to be between 0.5 and 2.0 body lengths for walking wildebeest. In the model, we use the larger figure.

The neutral zone is the region in which neighbors will neither speed up nor slow down in response to the proximity of each other. We determined this distance by measuring the distances between animals walking in a single file. If these inter-animal distances remained stable over a significant distance, we assumed that the animals were in each others' neutral zones. These distances tended to be between 3 and 5 body lengths, so we use 5 as the radius of the neutral zone.

To determine the boundaries of the attraction zone, we observed changes in an individual's behavior as the distance to its nearest neighbor changed. If a wildebeest makes a sharp change in direction or velocity towards another animal, the location of this change marks the outer boundary of the wildebeest's attraction zone. When the wildebeest then settles into a steady walk that matches the direction and velocity of its neighbor, we postulate that the neighbor crossed the boundary between the attraction and neutral zones. This distance proved harder to measure, since the moment of decision was difficult to determine. However, the size of the attraction zone is not very important in the simulation, since agents will almost always have neighbors in their neutral or stress zones in sufficiently dense herds. The attraction zone only needs to be large enough so that stragglers can detect nearby animals and move towards them. We believe that the outer boundary of the attraction zone is roughly 10 body lengths.

We ran the model under a variety of initial conditions. Most tests were performed with all agents having the same intrinsic speed and directional bias in order to determine the effects of varying the initial density, neutral zone size, and neutral tendency strength. The speed and bearing variations were later introduced to test the robustness of the behaviors observed. To quantify the scattering of the herds in some cases, the average of the number of neighbors within 10 units of each agent was calculated. This average is positively correlated to the density of the herd; but because a complex, two dimensional structure is reduced to such a simple metric, the results must be treated with some skepticism.

4 Results

The initial herd density had noticeable effects on early herd structure in all models. In the neutral model, these effects were persistent. After agents had adjusted their inter-agent distances so that their stress zones were empty, the overall herd patterns stabilized because the agents had perfect directionality and no variation in walking speed. Sparse starting herds tended to remain sparse; dense configurations expanded to satisfy the need for individual agents' space then stabilized in relatively tight aggregations (Figure 3). In the centering model, herds fragmented earlier when they had sparser initial configurations (Figure 4). It does not appear that steady-state subgroup sizes depended on initial density unless the initial configuration was so sparse that only small, widely-spaced aggregations could form. Unlike the neutral model, the centering model usually did not reach a steady state immediately after

all agents had empty stress zones. Large aggregations tended to fragment. The agents in the speed-matching model were given a $\pm 10\%$ speed and a ± 0.2 radian directional bias variation because the model would be almost identical to the neutral model otherwise. The effects of initial density resembled those observed in the neutral model, but they were blurred by the variation (Figure 5). The herd with a high initial density had a larger central grouping, while that with the sparse initial density remained sparse.

The neutral and speed-matching models did not generate herds with identifiable large-scale features. Neutral zone size in the neutral model did not seem to contribute to the spatial distribution of the agents (Figure 6). The speed-matching model displayed a less-scattered herd when the weight of the matching tendency was increased from 30% to 70% (Figure 7). The neighborhood occupancy metric, averaged over 10 runs for each of these two conditions, appeared to detect this difference. With a speed-matching tendency of 30%, the average number of neighbors within 10 units of each agents was 9.78, while at 70% the average was 11.89. Similar effects could be seen when the size of the neutral zone was decreased from 8.0 to 3.0, while other zone radii were kept constant (Figure 8). The 10-unit-radius neighborhood occupancy was 9.39 for the 8.0 unit neutral zone, and 9.92 for the 3.0.

The centering model produced identifiable large-scale phenomena. If the centering tendency was given a greater weight, the herd became more orderly and cohesive at the expense of speed (Figure 9). A larger neutral zone resulted in larger aggregations (Figure 10). The herds of size 45 and 720 featured aggregations of the same scale (Figure 11).

The introduction of a ± 0.2 radian variation in the agents' directional biases effectively added noise to agent directionality. The neutral and speed-matching models produced similar results: herds that were broader and shorter (Figure 12). The centering model displayed a noticeable scattering, but distinct subgroups still formed. The variation of intrinsic speed by $\pm 10\%$ elongated all herds along the direction they were travelling but did little to alter their shapes (Figure 13).

5 Discussion

As established by other investigations, local rules of interaction are sufficient to maintain a wide variety of global patterns of spatial organization. By only reacting to neighbors in a limited range, individual agents are able to maintain cohesion and order. Three zones, observed from animal behavior studies seem necessary and sufficient to the maintenance of that order. A stress zone keeps inter-animal distances above a certain limit, reducing collisions and traffic jams; an attraction zone reduces the number of strays. A neutral zone also seems to play a crucial role in the overall spatial characteristics of the herd.

The herds generated by the neutral and speed-matching models shared many characteristics. The stability of sparse formations allowed initial herd density to have a persistent

effect. In the neutral model, herds that started sparse remained sparse. Speed-matching is a unifying force that polarizes the speed of agents in aggregations. However, since the simulation represents migrating animals, the agents shared roughly the same directional biases. A speed-matching tendency amplified by either increasing the strength of the tendency or increasing the neutral zone size produced more coherent herds, though the effect was not strong.

The centering model produced large-scale formations independent of herd size and relatively insensitive to initial herd density up to a certain point. The size of the formations was positively correlated with the neutral zone size. The strength of the centering tendency also affected the size of the aggregations, with aggregation size being proportional to the centering tendency strength. Although large aggregations could form in runs with small neutral zones or weak centering tendencies, these groups were not persistent. Both a large neutral zone and a strong centering tendency make large groups more stable. When either of these parameters was weakened, large aggregations tended to fragment.

Agents in all models used the position of neighbors implicitly by having spatial zones, but the centering model used neighbor positions explicitly. The centering strategy displayed the most interesting herd structures, and the use of the relative locations of neighbors appears to be necessary for the formation of regular spatial patterns. The neutral and speed-matching models had a cohesive force that allowed aggregations to form, but they displayed no distinct spatial features. The speed-matching model may be more suited to non-migrating animals, for which directionality is not as well-defined.

The actions and reactions of agents to each other can be thought of as information transfer. When an individual causes a neighbor to react, the neighbor's behavior may influence others, with the consequences of the initial action rippling through other agents. The agents are a medium through which messages from individuals travel. The stress and attraction zone sizes establish the density of the medium by regulating the spacing among individuals. The neutral zone size relative to the attraction zone size determines the reliability of signal transfer over a distance, with a large neutral zone leading to higher reliability and a small neutral zone leading to lower reliability. Reliability, and therefore neutral zone size, corresponds to the distance a signal can travel. The strength of the "neutral" tendency is analogous to the decay rate of the signal because a strong neutral tendency diminishes the reaction an individual would have to a neighbor.

Stated more strongly, the agents are part of a self-organizing structure which has properties that are encoded in each individual. The agents themselves are the mode of communication that gives the herd a coherent global behavior. Once a stable density is established by the stress and attraction zones, the nature of the "messages" transmitted through the herd depend entirely on neutral zone behavior and manifest in the herd structures that emerge. In the neutral model, no information is passed through neutral zone interaction, so the herd will stabilize at a certain density but will have no form. For example, the neutral model herd shown in Figure 3c does not reorganize — it basically retains its initial shape, a square.

Speed-matching behavior has the effect of polarizing the direction of the herd. If the neutral zone were infinitely large and the neutral tendency were set to zero, then every agent would be travelling at the same speed, no matter how large the scatter in the intrinsic walking speeds of the individuals. The medium would have perfect transmission of messages that enable the herd to polarize direction perfectly. In the centering model, perfect transmission would cause the herd to converge to a perfect circle, similar to the sub-herds shown in Figure 9a.

The ideal structure of the self-organizing herd is corrupted by the decay of signals from the imperfect transmission properties of the agents and from the sparsity of the herd. If the herd is small enough, even poor transmission may be sufficient to bring about a coherent global structure, as can be seen in the circular subherds forming in the centering model herd in Figure 11b. The strength of the centering tendency and the size of the neutral zone are sufficiently large to give the small herds circular shapes. This simple shape is unstable for a larger herd with the same parameters because the transmission properties are insufficient to carry signals great distances. To make a large circular herd, one must either increase the centering tendency (Figure 9a) or the neutral zone size (Figure 10b), both having the effect of increasing the interconnectedness of agents from an information transfer point of view. In a sparse herd, signals are not capable of travelling far. The self-organizing properties would therefore operate on smaller subgroups, rather than over the entire herd. This effect can be seen in the large herd in Figure 4c, which has a large number of unconnected sub-herds because the initial density was too low to establish a coherent transmission medium.

The concept of animal aggregations as information transfer mediums may be useful to ethologists. From the nature of the herd, one can deduce the nature of an individual's behavior and vice versa. If an aggregation has a strong spatial order, as in the centering model, each individual may be using the positions of its neighbors to adjust its behavior. If an aggregation has a strongly polarized direction that seems self-organized in nature, as in fish schools, individuals may be using the speeds of neighbors. In the case of wildebeest, it appears that individuals are using the position of neighbors when distinct herd fronts form. The "fingers" that can appear in these herds might be the manifestation of the limits of information transfer among the wildebeest, which may in fact be trying to minimize the herd boundary. The situation is naturally complicated by environmental noise and differences among the individuals, but we can learn much about the behavior of individuals from the observation of groups.

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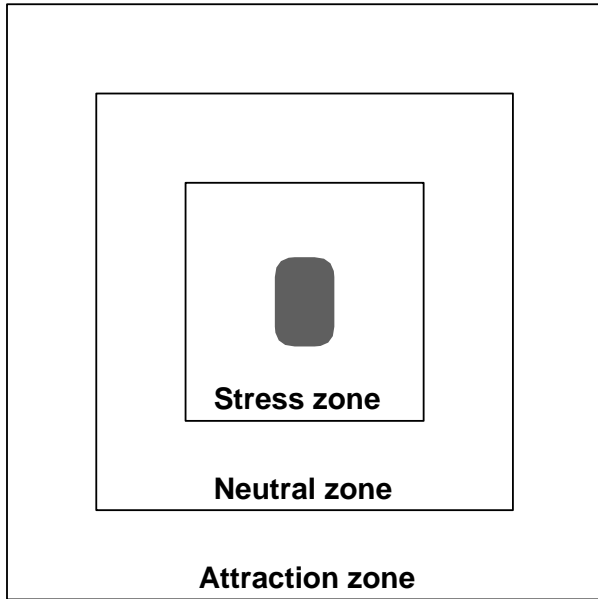


Figure 1: The three concentric zones. The agent's reaction to a neighbor will depend on its zone.

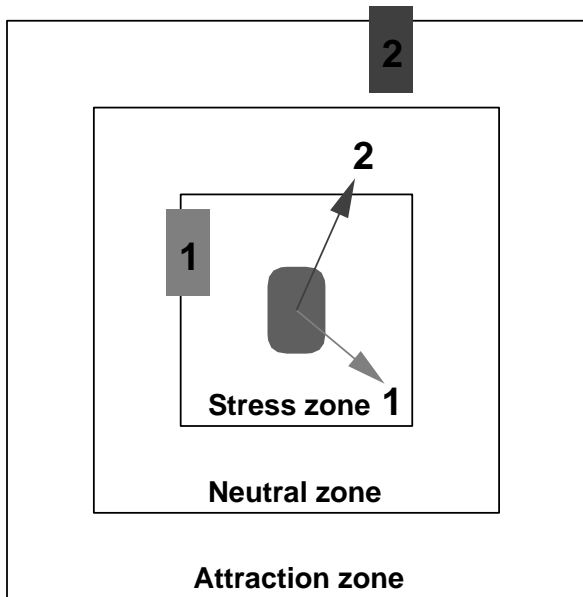


Figure 2: A sample interaction. The agent will want to avoid neighbor 1 and move toward neighbor 2. Since the agent only reacts to neighbors in its nearest occupied zone, it will ignore 2.

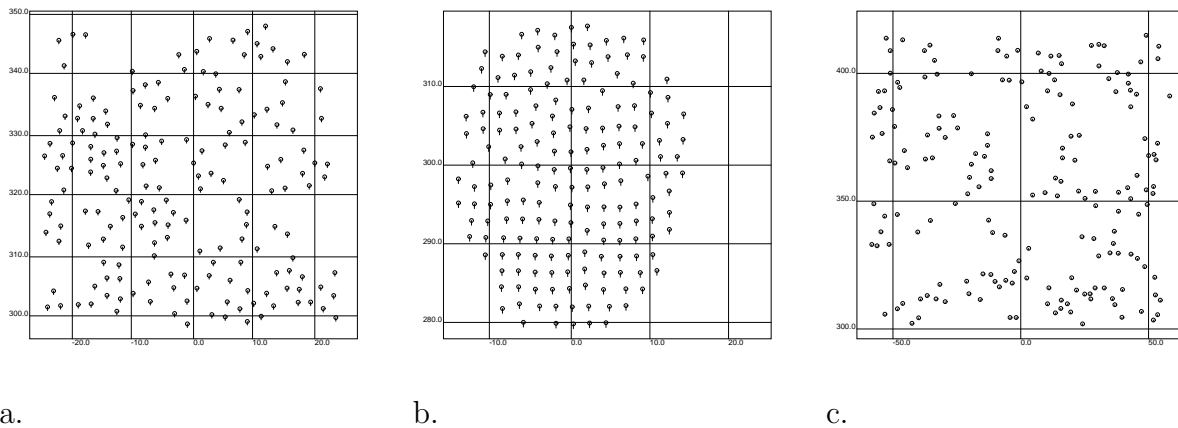
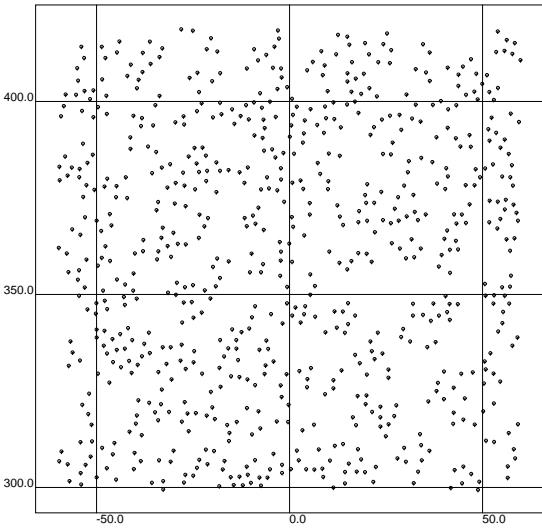
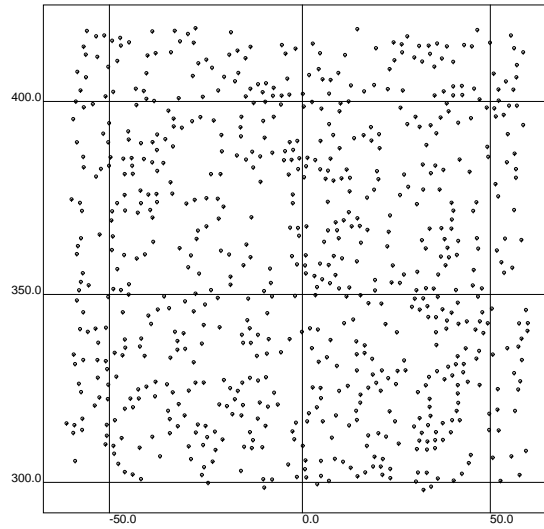


Figure 3: Initial herd density effects on the neutral model at time 500. Sparser herds appear more fragmentary, but no subgroups form. If the initial density is too high, the agents will space themselves out, as in b). All herds contain 180 agents with the initial herd radii: a) 24.0, b) 8.0, and c) 60.0.

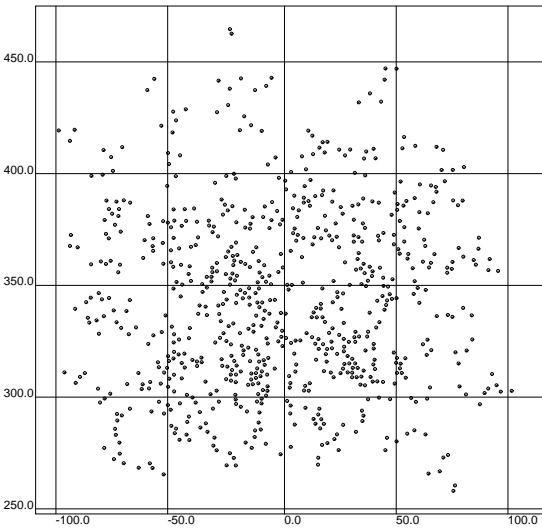


a.

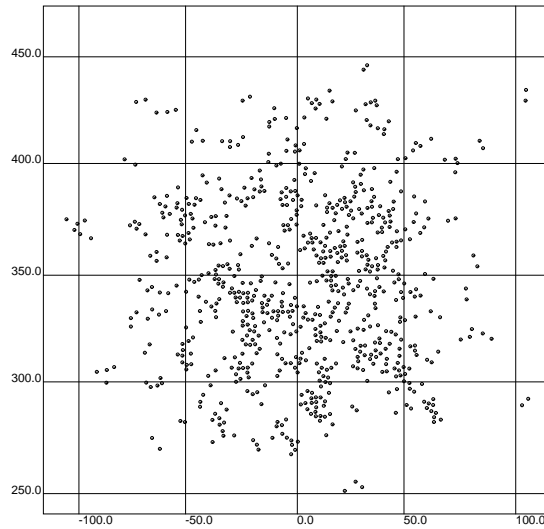


b.

Figure 6: Neutral zone size expansion has little effect on the neutral model. The neutral zone sizes are: a) 3.0 and b) 8.0.

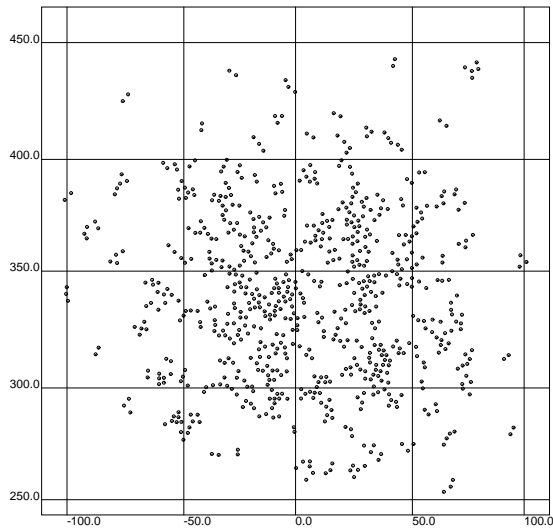


a.

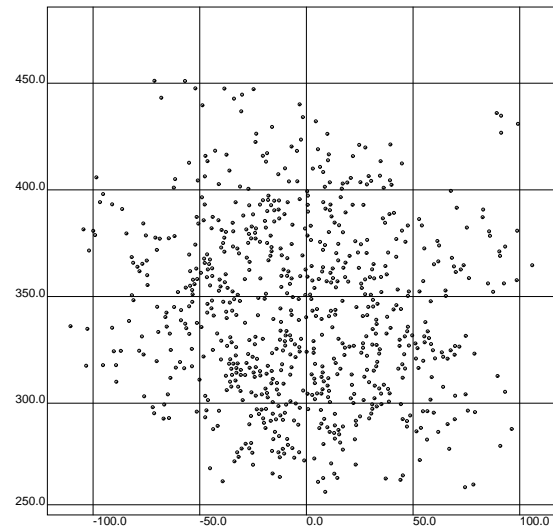


b.

Figure 7: Effects of speed-matching tendency strength. A stronger speed-matching strength may result in somewhat more clustered groups. Speed-matching is 30% in a) and 70% in b).

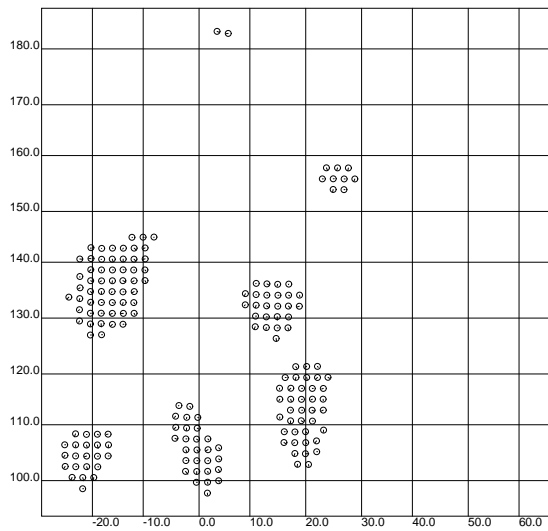


a.

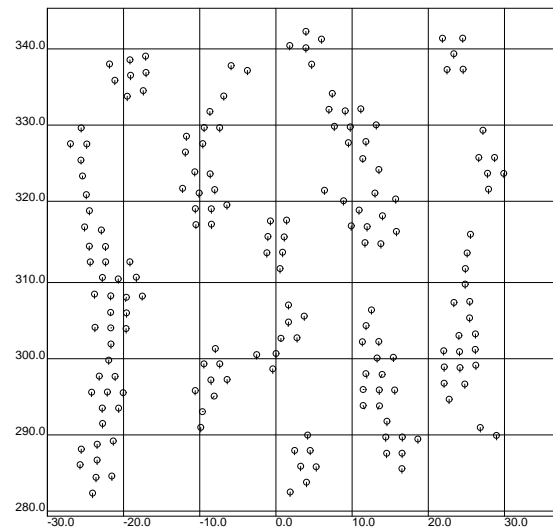


b.

Figure 8: The size of the neutral zone may be correlated with cohesion in the speed-matching model, but the effects are not obvious. The neutral zone sizes are: a) 3.0 and b) 8.0.

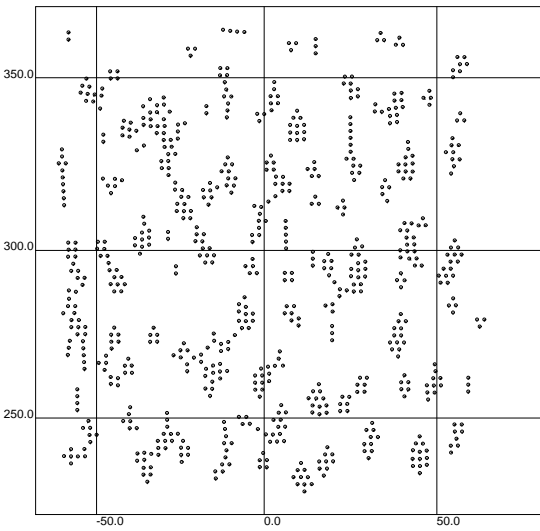


a.



b.

Figure 9: A stronger centering tendency leads to a more orderly and cohesive herd at the expense of speed. Note that the herd in a) did not move as far. The centering strengths are: a) 40% and b) 2.5%.



a.

b.

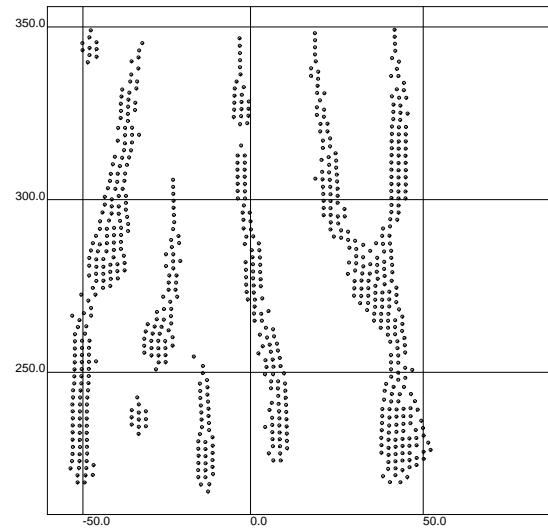
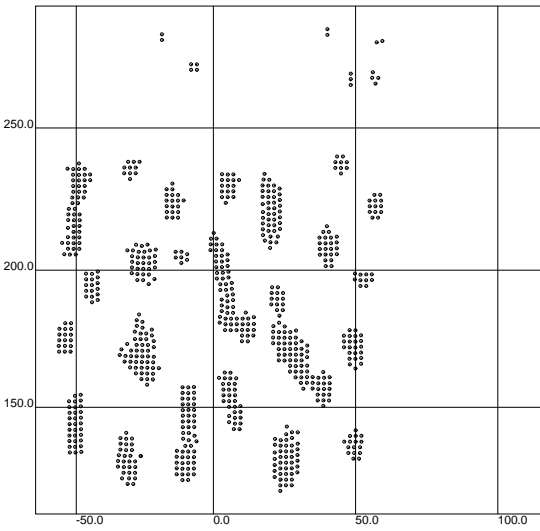


Figure 10: The subgroup size is correlated with the size of the neutral zone in the centering model. The neutral zone sizes are: a) 3.0 and b) 8.0.



a.

b.

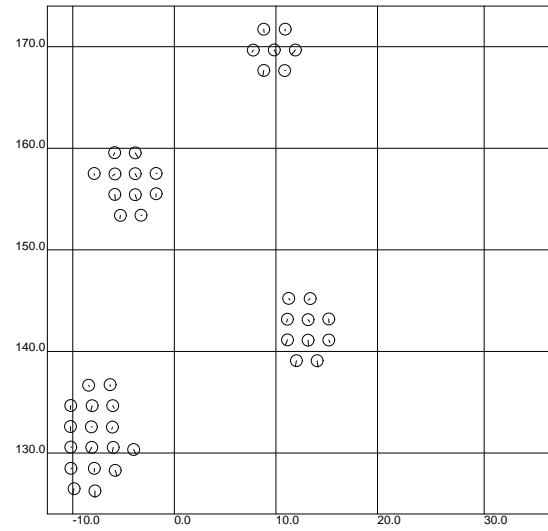


Figure 11: The features that emerge in the centering model are independent of initial herd size. Herd sizes are 45 in a) and 720 in b).

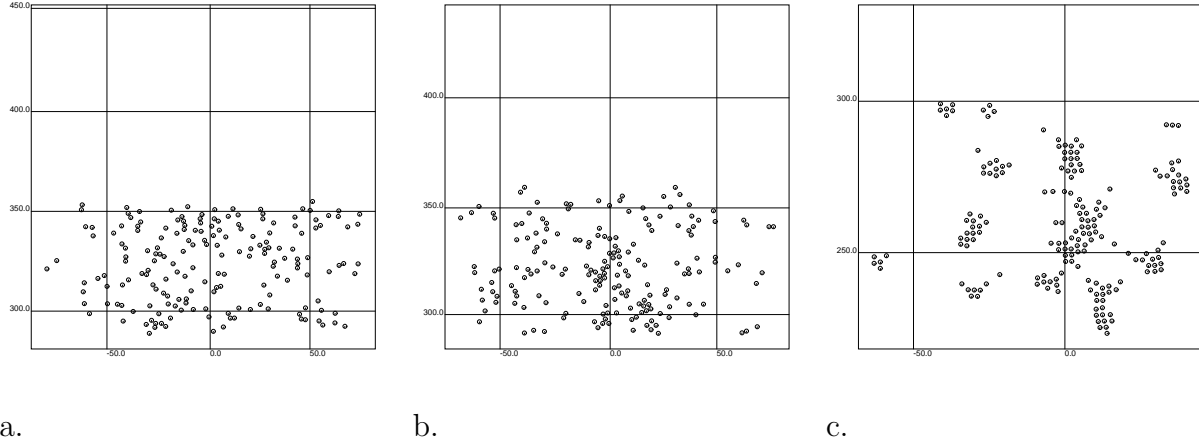


Figure 12: The effects of a ± 0.2 radian variation in intrinsic directionality of agents in a) neutral, b) speed-matching, and c) centering models. All herds were broader and shorter, but otherwise closely resembled the herds without directionality variation.

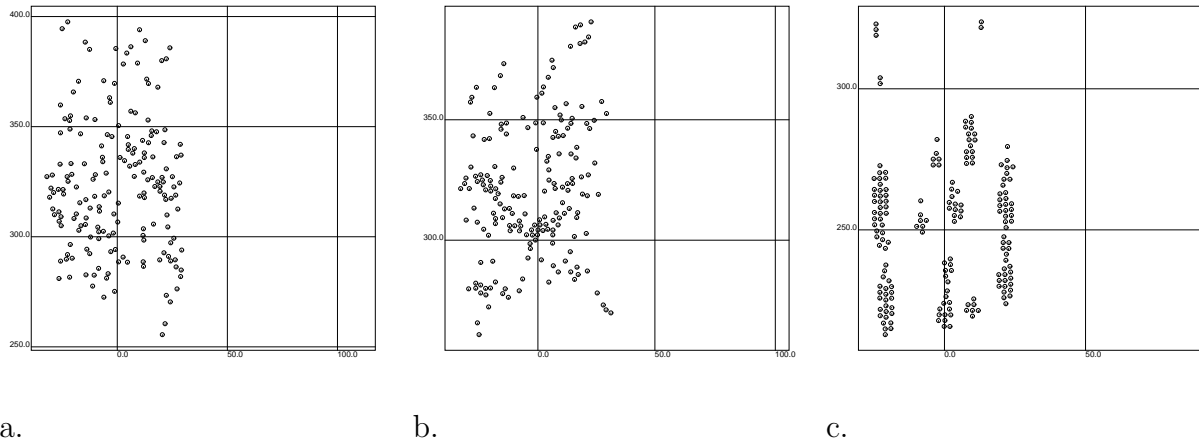


Figure 13: The effects of a $\pm 10\%$ speed variation in a) neutral, b) speed-matching, and c) centering models. The herds were elongated, but otherwise resembled herds without speed variation.