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Emerging Collective Behaviors of Animal Groups

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***Abstract*— Many animal groups routinely make consensus decisions jointly with all group members. This paper builds a novel model merging the locally neighboring reciprocal action and alignment together to investigate the mechanisms of consensus decision-making and its robustness. Our model reveals that the shapes of the coherent flocks are limited in a common narrow interval for different group sizes and information structures. Moreover, the coherent groups display a surprising degree of tolerance against errors, however, they simultaneously show an extremely fragile to attacks. Our model and approach discover some novel phenomena and also reveal some underlying mechanisms of the consensus decision-making and its robustness in biological systems.**

I. Introduction

We often watch a flock of birds flying to a specific direction. There is no obvious leader, and individual birds move back and forth within the flock [1-6]. How does the flock move as if it knew exactly where it was going? The fundamental group decision-making dilemma is how to transform individual interests for different outputs into a collective choice for the group as a whole [1-8, 15-21]. A consensus decision is that the individuals choose between two or more mutually exclusive actions with the specific aim of reaching a consensus [5]. This problem has been further investigated mainly for human societies over the past decades. Since human societies cannot normally work without consensus decisions, humans have gradually developed various effective approaches to single out one option from a list of possible choices, such as majority rule. However, the group choice in non-human social animals is less well known, although animal groups also make routine consensus decisions all the time, such as an ant colony has to decide whether or not attack a neighboring colony [1-8, 15-21]. If all group members cannot reach a consensus decision before the animal group splits, then their members will definitely forfeit many of the advantages of group living. Many known examples and an increasing amount of empirical evidences indicate that consensus decisions play an important and key role in the lives of animal groups, such as forage or travel in animal groups. Therefore, it is very interesting to ask two fundamental questions: "What are the underlying mechanisms of consensus decision-making?"; "Which factors have significant influences on the consensus decision?". We will further investigate these two basic questions using a simple model in the following.

In many animal groups, the conflicts of interest are often inevitably generated between group members about the outcome of a consensus decision [1-8, 15-21]. The extent of such conflicts determines the exchange of decision-related information between individuals and the degree of cooperation during decision-making. For little conflict of interest, there are some typical examples of consensus decision, such as a flock of birds navigating to a new forage patch and eusocial insects choosing a new nest site [1-6]. However, many consensus decisions are more likely to involve significant conflicts of interest between at least some of group members, especially for informed individuals. This is because animal groups often have to select between mutually exclusive activities or between moving to different sites. Therefore, consensus decisions involving conflicts of interest need an underlying mechanism to reach a compromise between conflicts.

Sometimes, the environment may be suddenly changed. How do the coherent groups adapt to the new environment in a short response time? Our model demonstrates that the coherent group will collectively select the exact direction of the changed information sources with a high accuracy in a short response time providing that there are enough informed individuals. Many coherent animal groups display a surprising degree of tolerance against errors. For example, the migrating routes of flocks are often slightly revised for avoiding barriers or bad weathers, however, the flocks can exactly arrive at the desired destination and display an unexpected degree of robustness. We also found that the coherent animal groups are extremely fragile to attacks, such as the suddenly big changes of the information sources.

The left paper is organized as follows. A novel consensus decision-making model is introduced in Section II. In Section III, some basic concepts and approaches are presented. In Section IV, several typical examples are then given to further understand the underlying mechanisms of the consensus decision-making. Finally, concluding remarks are drawn in Section V.

II. A Novel Consensus Decision-Making Model

When there are two information sources G_1 and G_2 with angle θ (Fig. 1b), we suppose that the group members modify their own motion based on the local neighboring information:

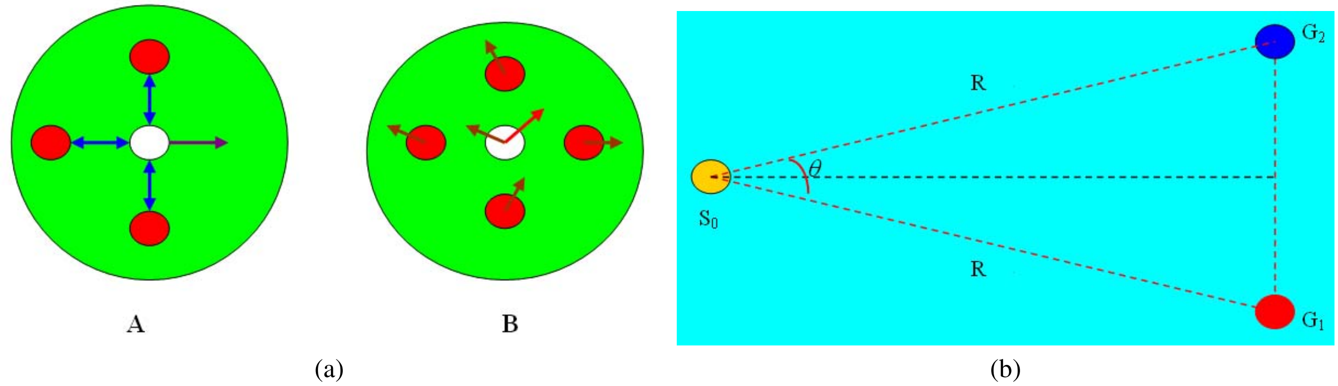


Fig. 1. (a) An illustration of the basic action mechanisms between individuals in the animal groups: A is the reciprocal action and B is the alignment. (b) The sketch map of the animal groups and the information sources, where the golden ball is an animal group, the red and blue balls are two different information sources, respectively.

reciprocal action and alignment (Fig. 1a). Groups are composed of N individuals, including $N_i\,(i = 1, 2)$ informed individuals with preference to $G_i\,(i = 1, 2)$, respectively. Each individual i has a position vector $c_i(t)$, unit direction vector $v_i(t)$, and speed $s_i(t)$ at time t. r_0 and r_1 are the minimum separate distance and the maximum response distance for the group at all times, respectively. $d_{ij}(t)$ is the distance between individuals i and j at time t.

Hereafter, we consider two fundamental actions between individuals in animal groups: reciprocal action and alignment (Fig. 1a). The reciprocal action is characterized by $\frac{1}{n_i}\sum_{j\in\Omega_i, j\neq i}\gamma_{ij}v_{ij}(t)$ (Fig. 1a A), where $v_{ij}(t)$ is the unit vector from $c_i(t)$ to $c_j(t)$, γ_{ij} is the reciprocal coefficient between individuals i and j, and n_i is the number of individuals in neighborhood Ω_i except i. And the alignment is described by $\frac{1}{n_i+1}\sum_{j\in\Omega_i}\delta_i v_j(t)$ (Fig. 1a B), where δ_i is the coupling coefficient of individual i. If there exists an individual j satisfying $d_{ij} \le r_0$, then $\Omega_i = \{\, j \,|\, d_{ij} \le r_0\}$, $\gamma_{ij} = -(r_0 - d_{ij})/r_0$ and $\delta_i = 0$; otherwise $\Omega_i = \{\, j \,|\, r_0 < d_{ij} \le r_1\}$, $\gamma_{ij} = (d_{ij} - r_0)/(r_1 - r_0)$ and $\delta_i = 1$.

Every group member i tends to balance the influence of its reciprocal action with that of its alignment. Thus the desired travel direction of individual i at time $(t + \Delta t)$ is given by

$$h_i(t+\Delta\, t) = \frac{1-\beta_i}{n_i}\sum_{j\in\Omega_i, j\neq i}\gamma_{ij}v_{ij}(t) + \frac{\beta_i}{n_i+1}\sum_{j\in\Omega_i}\delta_i v_j(t)\,, \quad (1)$$

where β_i is the alignment ratio of individual i satisfying $0 \le \beta_i \le 1$. If $\beta_i = 0$, individual i has no desire to align with other individuals in its neighborhood; if $\beta_i = 1$, individual i has no reciprocity with other individuals in its neighborhood. For simplification, suppose that $\beta_i = \beta$ for all individuals i.

Considering the information sources, then the final travel direction of individual i at time $(t + \Delta t)$ is described by

$$\bar{h}_i(t + \Delta t) = (1 - \omega_i)\hat{h}_i(t + \Delta t) + \omega_i T_i(t)\,, \quad (2)$$

where $\hat{h}_i(t+\Delta t)$ is the unit vector of $h_i(t+\Delta\, t)$, $T_i(t)$ is the unit vector from $c_i(t)$ to G_1 (or G_2), ω_i is the weight of the preferred goal (information source) of individual i satisfying $0 \le \omega_i \le 1$. If i belongs to the first (or second) set of informed individuals with preference to G_1 (or G_2), then $\omega_i = \omega_1$ (or $\omega_i = \omega_2$); if i is a naive individual, then $\omega_i = 0$. Clearly, for $\omega_i = 0$, individual i has no desire to move to a specific goal; for $0 < \omega_i < 1$, individual i tends to balance its preference to move to goal G_1 (or G_2) with its desire to maintain social interactions with other group members in its neighborhood; for $\omega_i = 1$, individual i moves to a specific goal G_1 (or G_2).

III. Basic Concepts and Approaches

Group direction is described by a characteristic vector from the group centroid evaluated at time $(t_c - k)\Delta t$ to the group centroid evaluated at final time $t_c\Delta t$, where k is the evaluating time step. Our results indicate that the group direction has little relative on k. Here, $k = 50$ for all figures. Group accuracy (Fig. 2) is characterized by $1-\sqrt{1-r}$, the normalized angular deviation of group direction around the average direction of all tests [1-22], where $r = \sqrt{(\sum_{i=1}^{n}\sin\alpha_i)^2 + (\sum_{i=1}^{n}\cos\alpha_i)^2/n}$ is the mean vector length. Normalized average accuracy (Fig. 10) is defined by $1 - \bar{S}/S_0$, where S_0 is the maximum error area and $\bar{S}$ is the average error area bounded by the traveling route and goal trajectory. Group elongation is the ratio between the maximum extended distance along with the group direction and the maximum extended distance along with the perpendicular direction of group direction. Bifurcation angle is the maximum angle θ_b satisfying that if $\theta \le \theta_b$, then the corresponding group will collectively select the average direction of the two preferred goals with tolerance error $\pm 15^0$ and more than 50% probability. Split ratio is the ratio between the split times and the total times. Deflection ratio (Fig. 10) is the ratio between the deflection times and the total times, where the deflection error is 5%.

In each simulation, one randomly generates a set of individuals with positions and orientations. The group density is 1%. The group sizes are given from 10 to 250 which are consistent with the normal sizes of many animal groups, such as birds, fishes, herds. Although the above sizes are also smaller than

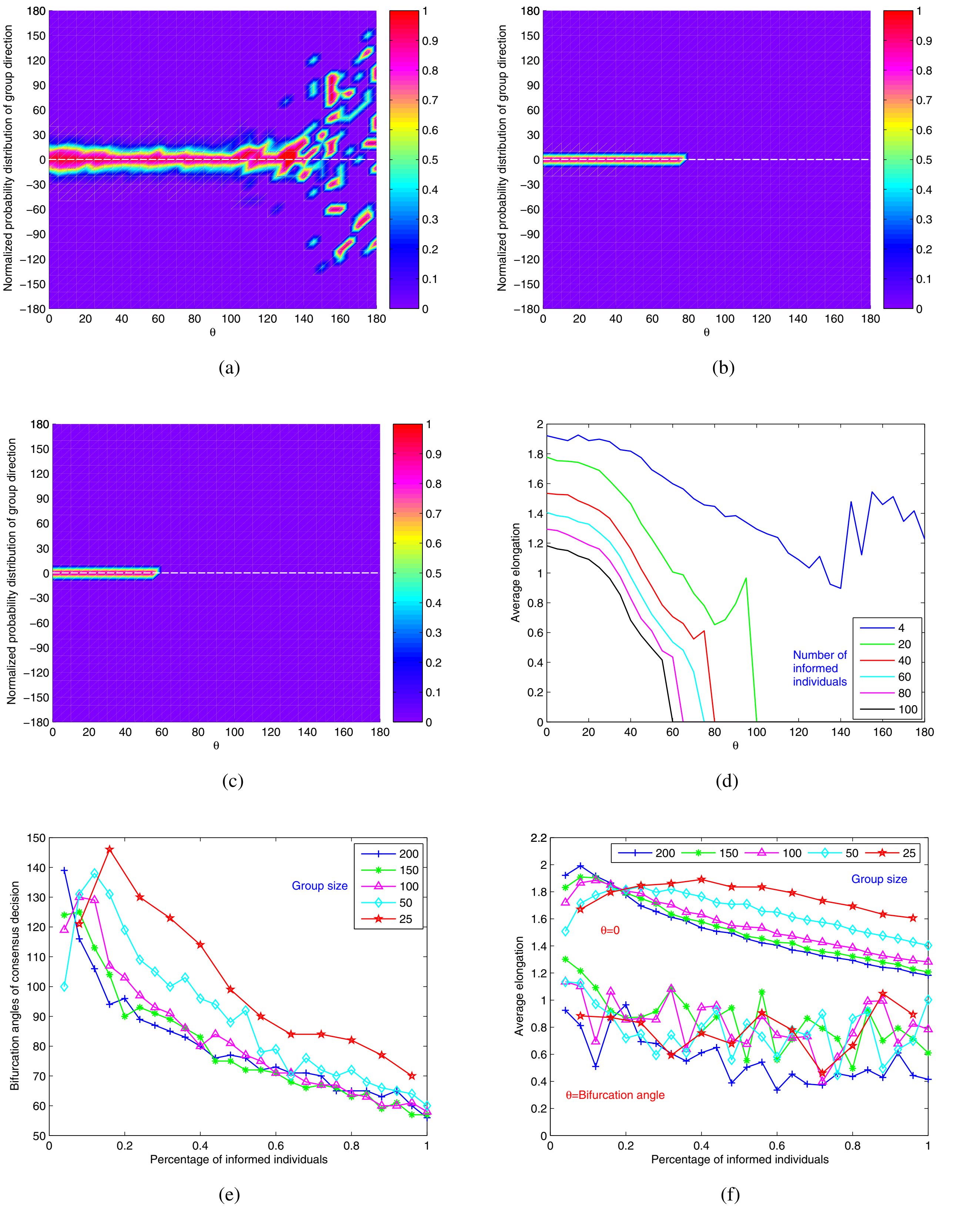


Fig. 2. The influence of the proportion of informed individuals on consensus decision. (a)-(c) The normalized probability distribution of the group direction ((a): $N = 200$, $N_1 = 4$; (b): $N = 200$, $N_1 = 48$; (c): $N = 200$, $N_1 = 100$). (d) The average elongation of the group for different number of informed individuals ($N = 200$). (e) The bifurcation angles of consensus decision of the group with different group sizes. (f) The average elongations of the group with different group sizes. Parameters $r_0 = 1$, $r_1 = 6$, $\Delta t = 0.1$, $s_i(t) = 1/s$, $\beta = 0.6$, $\omega_1 = \omega_2 = 0.5$, $N_1 = N_2$.

the large animal groups such as honeybee swarms, our model shows that the results have little relative on the absolute group sizes. Here, the total running time steps are 1,000 and 8,000 for Figs. 2 and 10, respectively. All simulations are independently repeated 400 times and the final results are the average of these replicates. The total computer processing time is about seven months 24h every day based on a IBM T43 1.86GHz personal computer.

Since all animal movements involve random factors [1-8,15-21], such as animal feeling and possible errors, one introduces four random angles $\xi_i (1 \leq i \leq 4)$ created by the circular wrapped gaussian distributions $WN(\mu_i, \sigma_i)(1 \leq i \leq 4)$ to characterize the uncertainty of two information sources, difference of individual identification, and motion randomness of animals, respectively. For the uncertainty of two information sources $G_j (j = 1, 2)$, one does the following rotations: $T_i'(t) = T_i(t)(\cos(\xi_j) + i \sin(\xi_j))\,(j = 1, 2)$ and then replicates $T_i(t)$ by $T_i'(t)$ in (2), respectively. For the difference of individual identification, one rotates the preferred goal vector $T_i'(t)$ to $T_i''(t) = T_i'(t)(\cos(\xi_3) + i \sin(\xi_3))$ and then replicates $T_i'(t)$ by $T_i''(t)$ in (2). For the motion randomness of animals, one rotates the final travel direction vector $\bar{h}_i(t + \Delta t)$ to $\bar{h}_i'(t + \Delta t) = \bar{h}_i(t + \Delta t)(\cos(\xi_4) + i \sin(\xi_4))$. Denote the angle between $v_i(t)$ and $\bar{h}_i'(t + \Delta t)$ be $\phi_i(t)$. If $|\phi_i(t)| \leq \theta\,\Delta t$, then $v_i(t + \Delta t) = \bar{h}_i'(t + \Delta t)$; otherwise, $v_i(t + \Delta t) = v_i(t)(\cos(\mathrm{sgn}(\phi_i(t))\theta\Delta\,t) + i \sin(\mathrm{sgn}(\phi_i(t))\theta\Delta\,t))$, where θ is the maximum turning ratio. Here, $\theta = 2$. Thus the new position vector of individual i is described by $c_i(t + \Delta t) = c_i(t) + v_i(t + \Delta t)\Delta t\, s_i(t)$. In the simulations, one considers many possible uncertain reasons. Here, for simplification, most results are attained based on the given parameters $\mu_i = 0(1 \leq i \leq 4)$, $\sigma_i = 0(1 \leq i \leq 3)$, and $\mu_4 = 0.01$ except the specific explanations.

IV. Numerical Simulations

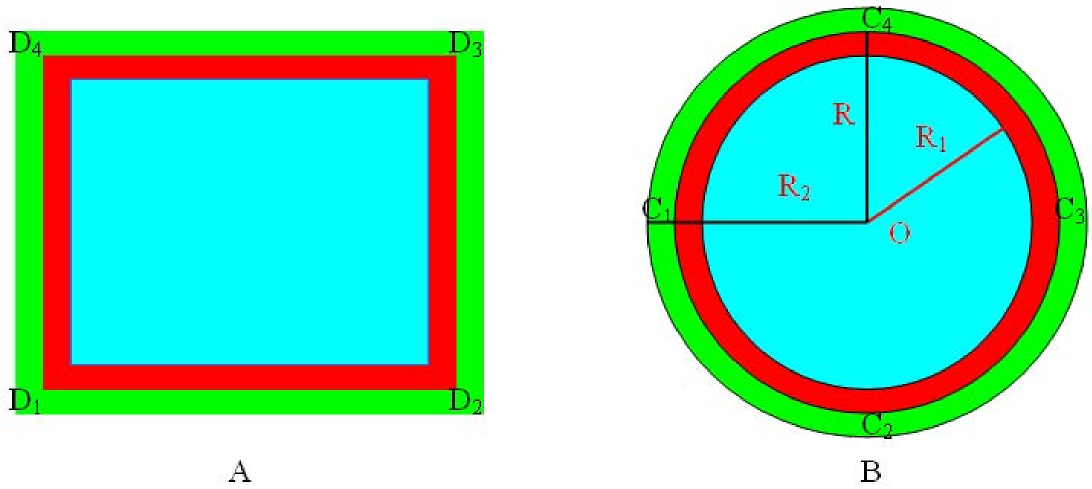
The angle θ of the information sources G_1 and G_2 characterizes the extent of the conflicts between informed individuals of the group. Bifurcation angles (see Basic concepts) characterize the maximum ability of a group to reach a consensus decision between group members. The larger the bifurcation angle the stronger ability to make a consensus decision for a group. Here we further investigated the influence of several main factors on consensus decisions for different group sizes, including the proportions of informed (Fig. 2) and naive individuals, the group alignment ratio, the weights and their difference of preferred goals of the informed individuals, the difference between the numbers of the informed individuals with different weights of preferred goals, the distance between the informed individuals, the variation and its varying forms (Fig. 3) of the information sources. We discovered that the shapes of the coherent animal groups are limited in a common narrow interval for different group sizes and information structures, that is, the average elongation (see Basic concepts) of a coherent group is approximately varying from 0.5 to 2.5 (Figs. 2d, 2f). In general, a coherent group formed into a long shape (average elongation > 1) is much more stable than the same coherent group formed into a broad shape (average elongation < 1) (Fig. 2f). This is one of the key reasons why the flocks of birds, ducks or geese often form into a long shape when traveling or foraging.

For a fixed group size, we found that the larger the proportion of informed individuals the easier to reach a consensus decision for a group with a little conflict of interest (small angle θ) between informed individuals (Figs. 2a-c, 2e), however, the larger the proportion of informed individuals the more difficult to reach a consensus decision for a group with a significant conflict (large angle θ, Figs. 2a-c, 2e). Moreover, the more informed individuals the smaller the average elongation (Fig. 2d). Normally, the large groups have much larger average elongation than the small groups with the same proportion of informed individuals for a little conflict (Fig. 2f), however, the large groups have much smaller average elongation than the small groups with the same proportion of informed individuals for a significant conflict (Fig. 2f).

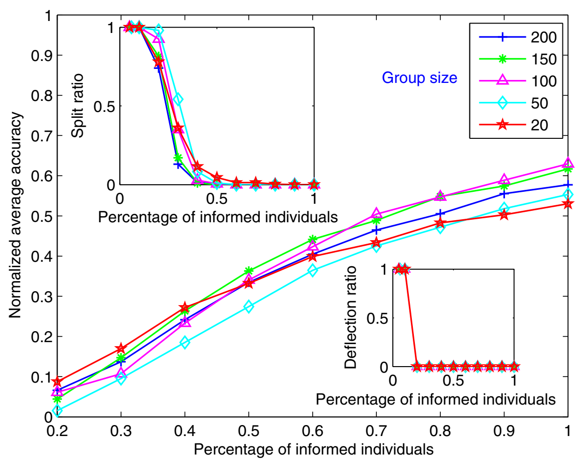
We found that the coherent groups display an unexpected degree of robustness again errors and also show an extremely fragile to attacks (that is, to the suddenly big changes of the information sources). For example, for a given 5% error e_r and 20% informed individuals, the animal groups can circle around a circle ($R = 100$) with more than 99% normalized average accuracy (see Basic concepts) and the lower split and deflection ratios (see Basic concepts) for different group sizes (Figs. 3a, 3c); however, the same groups can circle around a square ($R = 100$) with only less than 10% normalized average accuracy and the very high split and deflection ratios (Figs. 3a-b). The key reason is that the circle is very smooth (small changes) but the square has four right angle changes (big changes). Therefore, the coherent animal groups have an inertia and are rather robust again errors but extremely fragile to attacks (Achilles's heel [11] in the animal groups).

V. Conclusions

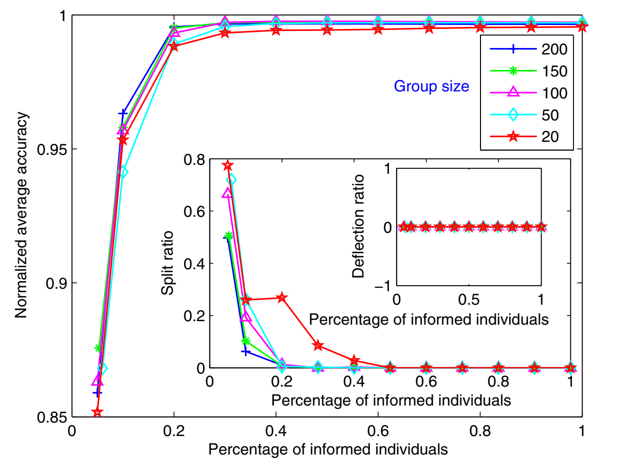
Our model reveals some underlying mechanisms and novel phenomena of the consensus decision-making and its robustness in animal groups. Also, our model demonstrates that some simple rules (only reciprocal action and alignment) can emerge complex intelligent, such as complex communication and consensus decision-making in no-human social animals. We found that the coherent animal groups almost keep the similar shapes and collectively select the exact direction of the changed information sources in a short response time when the informed source is unexpectedly changed provided that there are enough informed individuals. In particular, we discovered that the coherent groups have an inertia and display a surprising degree of robustness again errors and also an extreme fragility to attacks. Our model also provides some new insights into the evolution of cooperation, communication and consensus decision-making in humans. In fact, the flocks of birds and autos on a freeway have some common characteristics. We hope that our model and approach can be extended to describe other multi-agent information systems, such as the



(a)



(b)



(c)

Fig. 3. The influence of the varying forms of information sources on consensus decision. (a) An illustration of the rectangle and circle routes: A is the rectangle route and B is the circle route. (b)-(c) The normalized average accuracy, split and deflection ratios for the rectangle and circle routes, respectively. Parameters as for Fig. 2, $N_2 = 0$, $e_r = 5\%$, $R = 100$, $R_1 = 95$, $R_2 = 105$.

grouping robots, navigating systems, power systems, complex network systems [12-14], and communication systems.

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