Journal of Theoretical Biology 543 (2022) 111094

Contents lists available at ScienceDirect

Journal of Theoretical Biology

journal homepage: www.elsevier.com/locate/yjtbi

An investigation of the role of leadership in consensus decision-making

Cedric Perret [a,b,*], Simon T. Powers [a]

[a] Edinburgh Napier University, 10 Colinton Rd, Edinburgh EH10 5DT, UK
[b] University of Exeter, Penryn TR10 9FE, UK

ARTICLE INFO

Article history:
Received 30 October 2021
Revised 18 February 2022
Accepted 14 March 2022
Available online 24 March 2022

Keywords:
Leadership
Consensus decision-making
Opinion dynamics
Coordination

ABSTRACT

Leadership is a widespread phenomena in social organisms and it is recognised to facilitate coordination between individuals. While the role of leadership in group foraging or swarm movement is well understood, it is not clear if leaders would also benefit more complex forms of coordination. In particular, a number of organisms coordinate by consensus decision-making, where individuals explicitly communicate their opinions until they converge toward a common decision. Taking inspiration from physical sciences, we extend a consensus formation model to integrate leaders, which we define by three traits: persuasiveness, talkativeness, and stubbornness. We use numerical simulations to investigate the effect of the number of leaders and their characteristics on the time a group spends to reach consensus, and the bias in the final decision. We show that having a minority of influential individuals (leaders) and a majority of influenceable individuals (followers) reduces the time to reach consensus, but biases the decision towards the preferences of the leaders. This effect emerges solely from the differences in individuals' personality traits, with the most determinant trait being the talkativeness of the individuals. Overall, we provide a comprehensive investigation of the effects of leaders and their traits on consensus decision-making.

1. Introduction

Leadership describes a phenomena exhibited in many social organisms, where few individuals — leaders — modify the behaviours of other individuals — followers (Smith et al., 2016). Examples of leadership in nature go from group movements guided by a few individuals (Couzin et al., 2005), to the complex hierarchical structures exhibited by human societies (Diefenbach and Sillince, 2011; Day, 2013). A major goal of life sciences research on leadership is to describe and understand the effect of leadership on the functioning of the group and the success of its members. Understanding how leadership traits affect the success of both leaders and followers is particularly important to understand why leadership has emerged. Yet, some roles of leaders are still hard to understand. In particular, leaders are recognised to facilitate group coordination, but it is not clear if and how leaders would do so when groups coordinate by consensus decision-making.

Everyday, social groups have to take collective decisions to coordinate their actions and activities. Examples encompass initiation of group departure in swans (Black, 1988), choice of nest location in bees (Seeley et al., 1999), or collective hunting in humans groups (Alvard and Gillespie, 2004). Some social animals achieved coordination using relatively simple interactions patterns, from which the role of leader results. For instance, coordinated swarm behaviour is the result of a majority of individuals following their neighbours and an individual in the front leading the group.

However, in some organisms, coordination may not be accomplished by interaction rules alone but rather by an active process of consensus decision-making, in which individuals communicate their opinions until they converge toward a common opinion. This form of coordination can be observed on a day-to-day basis in human groups, whether it is in the parliaments of complex states or in the meetings of hunter-gatherers tribes (Von Rueden et al., 2014; Boehm, 2001). Moreover, there are a number of non–human organisms exhibiting consensus decision-making (Conradt and Roper, 2005) using ritualized movement (Seeley et al., 1999), vocalizing (Stewart and Harcourt, 1994), or even sneezing (Walker et al., 2017). Yet, the lack of a mechanistic description of consensus decision-making has limited the investigation of the role of leaders in this process.

Investigation the process of consensus decision-making has often been limited because of its complexity. However, consensus decision-making is a well-known process in physical science, where it has been modelled by opinion formation models. Opinion

* Corresponding author at: Edinburgh Napier University, 10 Colinton Rd, Edinburgh EH10 5DT, UK.

E-mail address: cedric.perret.research@gmail.com (C. Perret).

https://doi.org/10.1016/j.jtbi.2022.111094
0022-5193/

formation models describe the sequence of communication during which individuals transmit their opinions, and provide a stylised representation of the spread of opinions in a population (Castellano et al., 2009).

Famous opinion formation models include the Degroot model (Degroot, 1974) and the voter model (Clifford and Sudbury, 1973; Holley and Liggett, 1975), but they now encompass a large set of models (Castellano et al., 2009) which have been successfully applied in diverse fields, for instance to understand the adoption of innovation (Valente, 1996), the spread of extremism (Deffuant et al., 2002), or the polarisation of opinions (La Rocca et al., 2014) (see (Dong et al., 2018) for a review specific on consensus processes in opinion formation models). Nevertheless, their applications to the topic of leadership in life sciences has been so far limited.

Previous theoretical work have shown that heterogeneity in individuals' personality traits could strongly affect the time a group spends to reach consensus (Mobilia et al., 2007; Galam and Jacobs, 2007; Jalili, 2013; Gavrilets et al., 2016). This could explain the benefit that leaders provide to coordination because the time to reach consensus can be costly, either because time itself carries a cost, e.g. resources get depleted, or because time constraints will force individuals to take a sub-optimal decision (Chittka et al., 2009; Franks et al., 2003), e.g. a quick decision has to be taken during an intergroup conflict.

Nonetheless, it is hard to draw general conclusions on the effect of leaders on consensus decision-making based on previous work. For instance, the presence of stubborn individuals could either slow down the consensus (Mobilia et al., 2007; Galam and Jacobs, 2007), or speed up the consensus (Mayte Pérez-Llanos et al., 2018). Persuasive individuals could allow consensus to be reached quicker, but only if the persuasive individuals can also signal to a high number of individuals (Jalili, 2013; Gavrilets et al., 2016).

The lack of general conclusions from these models is explained by these models focusing on different questions, such as the role of one single perturbing individual like a zealot (Mobilia et al., 2007), or on the effect of diversity of traits on the consensus seeking process (Gavrilets et al., 2016). Thus, there is still the need for a comprehensive investigation of the effect of leaders on consensus decision-making. To fill this gap, this paper aims to (i) clearly demonstrate and quantify the benefit and cost of leaders on consensus decision-making, and (ii) identify under which conditions, that is number of leaders and characteristics of leaders, leadership would provide these benefits and costs. To do so, the analysis and model presented here differs in three points from previous work. First, we consider the three key characteristics previously identified in models and observed in leaders' profiles (Judge et al., 2002): persuasiveness [1], stubbornness and talkativeness, while previous work often focus on a single trait. Second, we divide the group between leaders and followers and consider all possible compositions of groups, rather than the presence of a single leader. This allow us to investigate how multiple leaders interact. Third, we vary independently the traits of leaders to better understand which traits, i.e. persuasiveness, talkativeness and stubbornness, underlie the effects of leadership on consensus decision-making. This allows us to clarify previous results that could appear to draw contradictory conclusions.

We investigate these questions in an opinion formation model developed by Gavrilets et al. (2016), in which we can vary the number of leaders and their characteristics. We do not integrate the knowledge of individuals or consider that one potential decision is more efficient than another because we want to clearly identify if influential leaders provide a benefit to coordination tasks, where there are multiple choices providing optimal but equal payoffs (Thomas, 1960). We also want to clarify if leaders can provide an intrinsic benefit to the consensus decision-making besides their knowledge or skills. Doing so, we follow the definition of leaders as individuals occupying a special position in the decision-making hierarchy and who have disproportionate influence over group goals and decisions, rather than leaders being more competent individuals (Von Rueden et al., 2014; Mark et al., 2011; Garfield et al., 2019). This is because the role of knowledge in leadership has already been well explored (Gavrilets et al., 2016), and there is evidence that human leaders provide a benefit besides their knowledge (Calvert, 1992; Mark et al., 2011), as shown by post Neolithic leaders in human societies taking decisions on a wide range of topics.

2. Model definition

We use an opinion formation model developed in previous work (Gavrilets et al., 2016). This model consists of a sequence of discussions between individuals until their opinions are close enough, i.e. the group has reached a consensus. Individuals are described by an opinion x. We consider that there is a spectrum of opinion and thus, x is a continuous value defined between $[0, 1]$.

The opinion x describes a generic opinion of an individual on how to realise a collective task, e.g. hunting party direction, time for group departure or value of a law. In addition to the opinion x, individuals are also described by three continuous traits: (i) persuasiveness β, i.e. the capacity of one individual to modify the opinion of another individual towards its own opinion, (ii) stubbornness γ, i.e. the reluctance of an individual to change its opinion, and (iii) talkativeness θ, i.e. the propensity that an individual communicates with another individual whether it is by talking, vocalising or doing ritualised movement. A large part of our analysis is looking at cases where these traits vary together. Empirical evidence demonstrates that these three traits are correlated in leaders' personalities (Judge et al., 2002), and they have been identified in previous models as key factors in explaining how leaders affect consensus time (Gavrilets et al., 2016; Jalili, 2013). Thus, we also define the trait α which is the value of these three traits when they are equal $\beta = \gamma = \theta = \alpha$. α is defined as the individual capacity to influence the collective decision (which is referred to as their influence). To study the effect of social organisation on collective decision-making, we divide individuals into two profiles: leader L, and follower F.

We consider a population of N individuals. At the beginning of the opinion formation model, the values of opinion x are randomly generated. Each time step is defined by one discussion event during which one individual, the speaker, communicates to another individual, the listener. The probability P of an individual i to be chosen as a speaker is an increasing function of its talkativeness θ, as follows:

$$P_i = \frac{(\theta_i)^k}{\sum_{n=1}^{N} (\theta_n)^k}. \tag{1}$$

The parameter k scales how much the probability to talk depends on the talkativeness of an individual (see Fig. 1). A high value means that the probability to talk depends mostly on talkativeness, while a low value means that other parameters are more important in determining the speaker, e.g. there are rules to enforce equal access to speech as in small-scale societies or con-

[1] Some models talk of reputation instead of persuasiveness (Gavrilets et al., 2016; Chen et al., 2016) but both are defined as the weight of the opinion of an individual on the opinion of someone else. This distinction is rather on the determinism of this feature, either being an intrinsic feature, persuasiveness or given by others, reputation

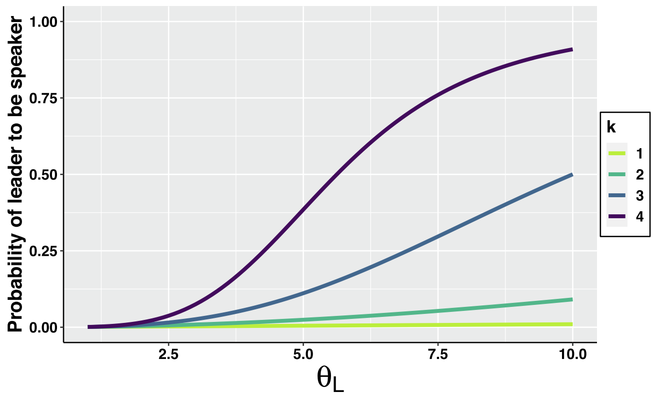

Fig. 1. Probability for a single leader in a group with 999 followers to be chosen as a speaker, as a function of its talkativeness θ_L and the scaling parameter k.

temporary inclusive meetings. In this paper, we use a high $k = 4$ as we want to study the effect of talkativeness in the absence of other factors.

We assume that every individual can be chosen as a listener, i.e. the social network is a complete network, because we are interested in short time-scale decision-making rather than the long time-scale spread of opinions. We also consider that individuals interactions are not limited to individuals with close opinions (as in models with bounded confidence (Deffuant et al., 2002)) because this model describes a consensus-seeking process where individuals are willing to convince each other. During a communication event, a listener v updates its preference to a value x'_v following the equation below, where v represents the listener and u the speaker:

$$x'_v = x_v + r\left(\frac{\beta_u}{\gamma_v}\right)(x_u - x_v). \tag{2}$$

The parameter r represents the base update rate, i.e. how much a listener will update its opinion if the speaker has the same characteristics than itself. We use a ratio relationship between persuasiveness, β, and stubbornness, γ, as in previous work (Gavrilets et al., 2016) because it guarantees the following condition: the change of opinion resulting from a leader communicating to a follower is higher than followers communicating to followers (or leaders to leaders), which is in turn higher than a follower communicating to a leader. The traits β and γ are defined on $[1, \frac{1}{r}]$ so that an individual with the highest persuasiveness β talking to an individual with the lowest stubbornness γ convinces the individual in one event. The talkativeness θ is also defined on $[1, \frac{1}{r}]$ so it can be varied on the same range as the other traits, and thus we can study the effect of influence α summarising the three traits.

The individuals repeat the previous step until consensus is reached, i.e. the standard deviation of the opinions is less than a threshold h. The number of discussion events that occurred to reach consensus is called the time to consensus t^*. Because the opinions are continuous variables, the final decision x^* is the mean of the opinions x at consensus.

Opinion formation models are commonly studied using analytical methods, by which are calculated exact solutions to the system. However, these approaches are difficult in the presence of heterogeneity in the population, which is the case here as individuals have different values of influence. Thus, we implement the model as an individual-based model and use numerical simulations to analyse it. There are two features of the consensus decision-making that leaders could affect and that we measure in the simulations. First, leaders could affect the time the group spends to reach consensus, which is described by t^*. Second, leaders could also bias the final decision. To measure this bias, we consider that the initial opinion of individuals reflects their preferences, and we measure how close the final decision is from the preferences of all individuals. We then look at the distribution of this distance across individuals. More formally, we define the realised influence α_r of an individual i in a simulation run j:

$$\alpha_{r(ij)} = 1 - |x_{ij}(t = 0) - x_j^*| \tag{3}$$

The realised influence of an individual $\alpha_r(i)$ is the average of the realised influence of this individual i across 500 consensus decision-making events. Unlike the influence α, realised influence $\alpha_r(i)$ depends of the influence of other individuals in the group. For instance, a leader would have a high realised influence in a group of followers, but low realised influence in a group with many other leaders. We measure the bias in final decision by the Pearson's moment coefficient of skewness (in short skewness) of the distribution of the realised influence across individuals. A high skewness represents a biased decision, i.e. the decision is close to the preferences of a minority of individuals and far from the preferences of the majority of individuals. A skewness of 0 represents a fair decision, i.e. the decision is equally close to the preferences of all individuals.

We focus on the effect of the following parameters: (i) the number of leaders, and (ii) the influence of leaders α_L. In addition, we study the effect of the consensus threshold h because this parameter controls how global the consensus is. Finally, we vary the three traits independently in a group with one leader to better understand how each trait contributes to the effects of a leader on the consensus decision-making. The influence of followers α_F is set to the minimum value 1 and the influence of leader α_L can vary between $[1, \frac{1}{r}]$. When parameters other than the influence of leaders are varied, the default influence of leaders is set at $\alpha_L = 5$. The other default parameters are for the consensus threshold $h = 0.05$, the base update rate $r = 0.1$ and group size $N = 100$. The results presented are the mean across 500 replicates for each set of parameters presented. The error bars or ribbons represent the standard deviation from the mean rather than the standard error from the mean, because the variance between different runs is important.

3. Results

Fig. 2.A shows the main result: the presence of a minority of influential individuals and a majority of influenceable individuals reduces the time a group spends to reach consensus. Importantly, the differential quality of information that leaders might posses, and which might lead to a group with hierarchy making better decisions, is not required to get this result. Fig. 2.A shows that the shortest time to consensus is obtained in the presence of a single leader, and that the time to consensus is reduced much less in the presence of multiple leaders. In fact, in some cases groups with multiple leaders can spend more time to reach consensus than a group of individuals of equal influence.

The relationship between time to consensus and numbers of leaders can be derived from the formula in (Gavrilets et al., 2016), for the special case when leaders have an extremely high probability of talking.

$$t^* \sim \frac{2N}{r}\left(1 - \frac{1}{N_L}\right), \text{ for } l \geqslant 1 \tag{4}$$

In the absence of leaders, the time to consensus is $t^* \approx \frac{2N}{r}$. We see that adding a single leader strongly speeds up consensus, but this benefit is quickly reduced when more and more leaders are added to the group.

Fig. 2.B gives an illustration of the dynamics of the model. It shows that in the absence of leaders, or with a single leader, individuals' opinions consistently converge. This homogeneous convergence pattern results in low variance in the time to consensus across the different runs, as shown in Fig. 2.A. These results suggest that the long time to consensus in groups of individuals of equal influence is mainly due to a slow convergence. The presence of a single leader speeds up this process as the leader quickly convinces the majority of the group.

Fig. 2.B also shows that the presence of multiple leaders creates a more heterogeneous pattern of convergence. The presence of two leaders results in two clusters of opinions, with the majority of followers switching from one leader to another: leaders alternatively convince individuals from the group but neither leader has enough followers to reach consensus. When more than two leaders are present, the majority of opinions fluctuates between the different leaders. This heterogeneous pattern of convergence results in high variance in the time to consensus between runs as shown in Fig. 2. A. This result shows that the time to consensus in groups with multiple leaders is highly dependent of the leaders' initial opinions. When leaders have similar opinions, they quickly convince the rest of the group, which results in a short time to consensus. But when leaders have diverse opinions, it results in a slow consensus. This effect is illustrated in simulations shown in Supplementary Fig. 1, where the opinions of leaders are set to be the most different from each other. In this case, the time to consensus with multiple leaders is on average worse than the time to consensus in the absence of leaders. This is because multiple leaders: (i) are slower to be convinced, (ii) increase divergence by convincing followers towards extreme opinions, and (iii) convince followers from other leaders. Unlike groups of equals, longer time to consensus in groups with multiple leaders is due to conflict between leaders, rather than a slow convergence.

The previous result considered only the most extreme form of leaders, with leaders having the highest influence $\alpha_L = 10$. We now investigate different values of leaders' influence. Fig. 3 shows that the main result is consistent across different values of leaders' influence α_L: the presence of a minority of influential individuals and a majority of influenceable individuals reduces the time a group spends to reach consensus. Fig. 3 shows that when leaders are less influential, the shortest time to consensus is obtained in presence of multiple leaders, unlike previous results with highly influential leaders in which a single leader has the shortest time to consensus. The detrimental effect of multiple leaders is not observed when leaders have low influence because leaders convince each other relatively quickly. Once their opinions are close, they act as a single strong leader which quickly convinces the rest of the group. Groups with a single leader who has low influence spend more time to reach consensus simply because the leader is less efficient at bringing the opinions of others towards its own. However, across different values of leaders' influence, the shortest time to consensus is obtained in the presence of one single extremely influential leader.

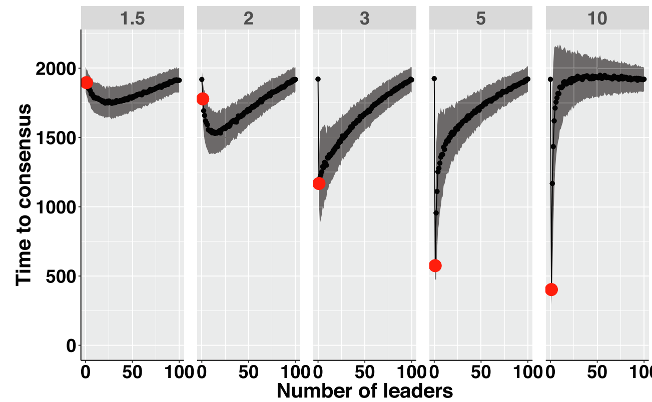

Fig. 3. Time to consensus as a function of number of leaders and the influence of leaders α_L. The time to consensus for a group with a single leader is highlighted in red. The parameters used are $\alpha_F = 1, r = 0.1, h = 0.05, N = 100$.

The above results focus on the time to consensus and demonstrate the beneficial side of leaders, which reduces the time that a group spend to reach consensus. However, the final decision resulting from the consensus is also important, and could be affected by the presence of influential individuals. To investigate this effect, Fig. 4 presents the skewness of the distribution of realised influence, i.e. how far the final decision is from the initial opinion of an individual. A higher skewness represents a strong bias of the decision towards a minority of individuals. Fig. 4 shows that leaders bias the decision: a minority of influential individuals and a majority of influenceable individuals leads to a high skewness of the distribution of realised influence. This result is consis-

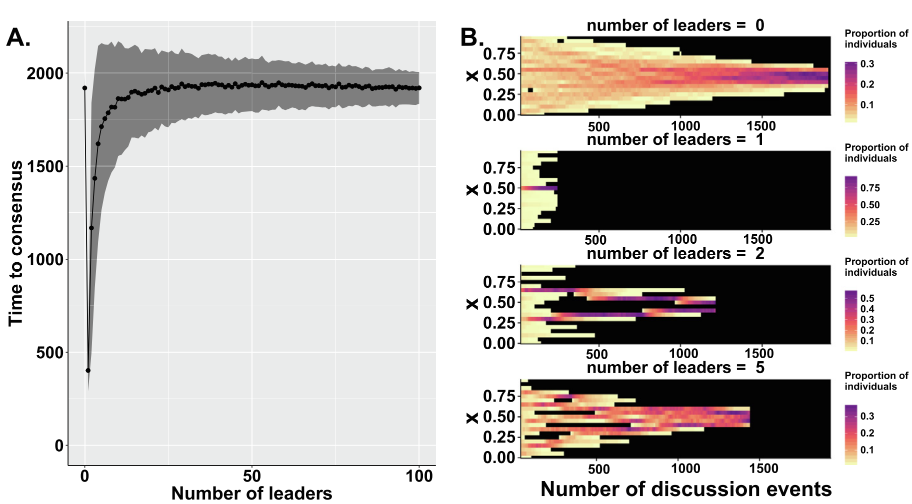

Fig. 2. A. Time to consensus as a function of numbers of leaders. The influence of leaders is equal to $\alpha_L = 10$. B. Density distribution of individual opinion as a function of number of discussion events for different numbers of leaders: from top to bottom 0, 1, 2, 5. For illustration, the difference between the opinions of leaders are set to be maximum and equidistant. The plot represents results for a single run. The parameters used are $\alpha_F = 1, r = 0.1, h = 0.05, N = 100$. The black area represents opinions that no individuals currently hold.

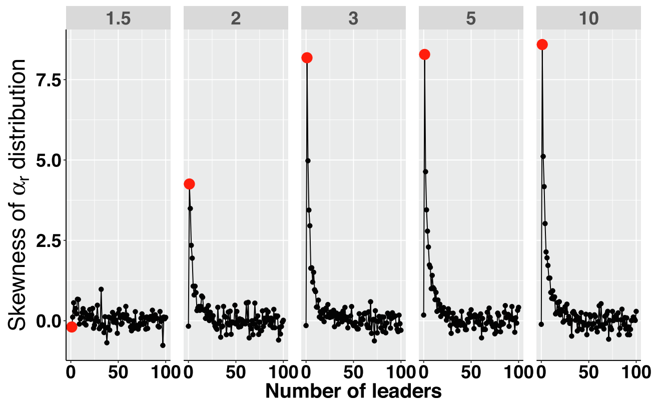

Fig. 4. Skewness of the distribution of realised influence α_r as a function of the number of leaders, and the influence of leaders α_L. The skewness for a group with single leader is highlighted in red. The parameters used are $\alpha_F = 1, r = 0.1, h = 0.05, N = 100$.

tent across different values of leaders' influence, except when leaders have very limited influence ($\alpha_L = 1.5$). The highest bias is obtained for groups with one single leader. This is because influential individuals efficiently propagate their opinions (due to their high persuasiveness and talkativeness), and maintain their initial opinions longer than followers (due to their stubborness). Ultimately, leaders are able to pull the final decision toward their own preferences. In conclusion, the results show that there is a trade-off between time to consensus and fairness of the decision, i.e. how representative the decision is of the opinions of all group members.

We consider here that only global consensus is possible, i.e. the whole group agrees on the decision. Nonetheless, we can vary the consensus threshold h to allow for a more or less strict consensus, i.e. divergent opinions are more or less accepted. Supplementary Fig. 2 shows that a higher consensus threshold reduces the time to consensus, in particular in absence of leaders or in presence of multiple leaders. Yet, the main results are consistent across different values of consensus threshold h: the presence of a minority of influential leaders results in shorter time to consensus, but a biased decision. The consensus threshold has a limited effect on the skewness of the distribution of the realised influence. This is because a higher consensus threshold leads to an early end to the consensus process, but by this time the decision is already biased. Indeed, influential individuals quickly bring the opinions of others towards their own, and the late stage of the consensus process consists of the leader convincing the last remaining individual.

We now vary the traits independently to understand how each trait contribute to the effects of leaders on consensus decision-making. Fig. 5 shows that the time to consensus is highly reduced when the leader is both persuasive (high β_L) and talkative (high θ_L) (first row). In other words, the interaction between talkativeness and persuasiveness is the main factor reducing time to consensus. For instance, when talkativeness is high (right column), an increase in persuasiveness results in a strong decrease in the time to consensus. When talkativeness of leaders is equal to followers (left column), an increase in the persuasiveness of the leader does not appear to affect the time to consensus. This result shows that talkativeness θ_L is a crucial trait, and that the effect of persuasiveness of leaders β_L depends on the talkativeness. This is because talkativeness sets how much a leader communicates and thus, how much a leader exerts its persuasiveness on others.

An intuition behind this result can be obtained using the formula for time to consensus considering that individuals are equal in talkativeness, shown in (Gavrilets et al., 2016). This formula states that the time to consensus is proportional to $\frac{1}{\beta H(1/\alpha)}$ with H defined as the harmonic mean. If we consider that persuasiveness and stubbornness are equal, that is $\beta = \alpha$, this formula reduces to 1 and the time to consensus becomes independent of the persuasiveness and stubbornness of individuals. In other words, the benefit for adding a persuasive individual is exactly cancelled by the addition of a stubborn individual. Talkativeness tilts the balance by

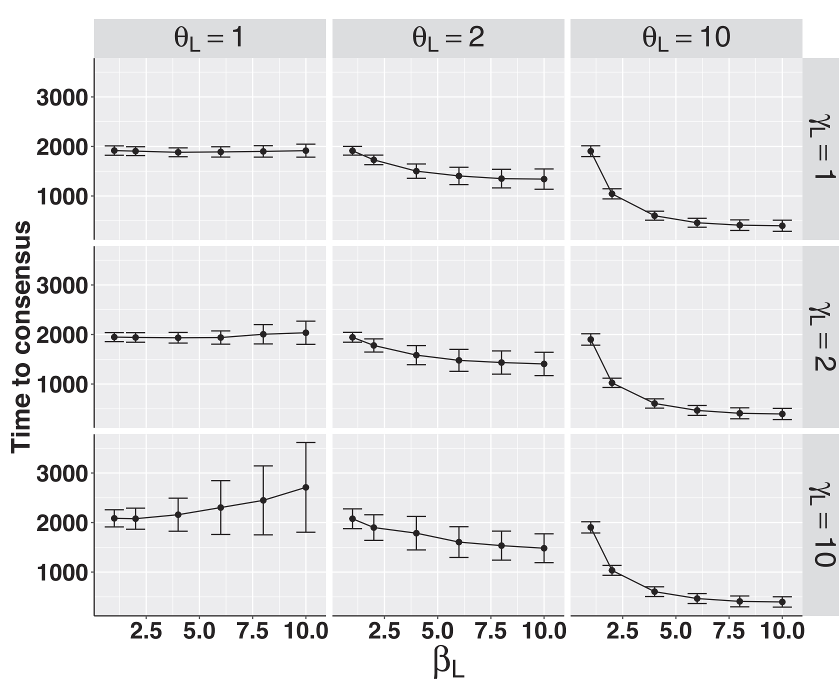

Fig. 5. Time to consensus as a function of leader persuasiveness β_L, talkativeness θ_L and stubbornness γ_L in a group with a single leader. The parameters used are $\alpha_F = 1, r = 0.1, h = 0.05, N = 100$.

increasing the number of times an individual talks (which amplifies the benefits of persuasiveness) compared to the number of times an individual is talked to (which decreases the cost of stubbornness).

Fig. 5 shows that modifying the stubbornness γ_L of the leader has a limited effect on the time to consensus, especially when leaders are already very talkative. We find similar results in Supplementary Fig. 3, which shows that adding leaders who are talkative, persuasive but easy to persuade, still reduces the time to consensus. This is because when the leader is talkative, the consensus decision-making consists mostly of the leader convincing others, rather than individuals convincing the leader. Nonetheless, the stubborness γ_L increases the variance between runs when the talkativeness of the leader is low and when persuasiveness of the leader is high (bottom left panel). This is because a stubborn and persuasive leader is (i) longer to be convinced, but (ii) can also bring back other individuals to its opinion, even when this is far from the emerging consensus.

Fig. 6 shows how the three traits of the leader bias the final decision. The results show that the level of talkativeness of the leader θ_L strongly affects the bias in decision. For instance, groups with very talkative leader (right column) has a very skewed distribution of realised influence independently of the persuasiveness or stubborness of the leader. As previously, persuasiveness β_L and talkativeness θ_L interact. For instance, when talkativeness is moderate (middle column), an increase in persuasiveness strongly increases the bias in the final decision. This result is explained by the same reason as before: a group with a highly talkative individual reaches consensus because the influential individual convinces the rest of the group and pulls their opinions towards its own. Finally, an increase in stubborness γ_L has a limited effect in the bias of the decision, even when talkativeness and persuasiveness are low. This is because the group can still reach consensus even when one individual has an extreme opinion, and thus the presence of a stubborn individual does not pull the final decision towards an extreme.

4. Discussion

Consensus decision-making is a pervasive method for social groups to coordinate (Conradt and Roper, 2005). It has the benefit that it can be used to coordinate a wide range of collective tasks, unlike context specific coordination such as swarm movement. Yet, it can also carry costs. For instance, a long time to reach consensus can lead to individuals abandoning the task for better alternatives (Skyrms, 2003), or even fission of the group (Krause and Ruxton, 2002). Leaders could limit this risk by speeding up the consensus decision-making. Yet, the absence of a mechanistic model of consensus decision-making has limited the investigation of the effect of leaders. To fill this gap, we used an opinion formation model which integrates heterogeneity in individuals' capacity to influence. We use numerical simulations to investigate the qualitative effects of the number of leaders and their communication traits on the consensus time and the final decision.

First, our results show that the presence of influential leaders and influenceable followers reduces the time a group spends to reach consensus. In other words, the benefit of leadership on consensus decision-making can emerge from the difference in individuals' capacity to influence others. This result is in line with previous work in game theory, which shows that a dimorphism in leader–follower behaviours could facilitate coordination (Johnstone and Manica, 2011), and also shows that this conclusion can be extended to species using communication to coordinate rather than copying others' behaviour. Second, our results show that a single highly influential leader is the most efficient in terms of consensus time, but that leaders with limited influence are preferred when multiple leaders are present. This suggests that social groups would favour strong leaders only in particular conditions, i.e. when they are able to enforce the presence of a single leader, such as in leadership based on conditional behaviours or by design e.g. institutional leadership (Perret et al., 2019). On the other side, the influence of leaders in many social organisms could be limited considering that multiple leaders are likely in nature, because of

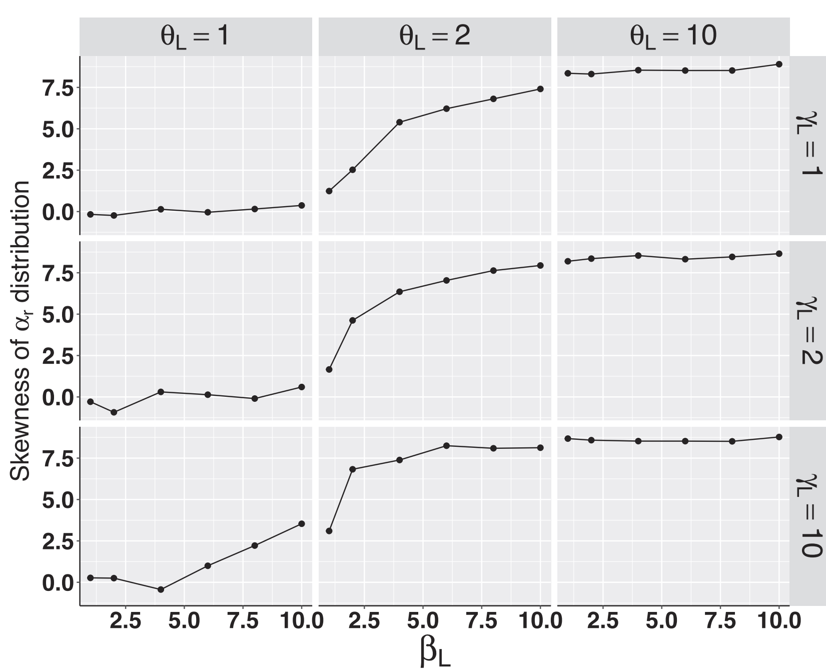

Fig. 6. Skewness of the distribution of realised influence as a function of leader persuasiveness β_L, talkativeness θ_L and stubborness γ_L in a group with a single leader. The parameters used are $\alpha_F = 1, r = 0.1, h = 0.05, N = 100$.

the variations in individual leader traits resulting from evolutionary processes.

Third, our results show that the presence of influential leaders and influenceable followers biases the decision towards the preferences of the leaders. This bias can ultimately affect the fitness of individuals, as groups often have to decide between mutually exclusive activities, and individuals differ in their preferences for how activities should be carried out, e.g. travel destination, type of food, or timing (Conradt and Roper, 2005). This bias could also be detrimental as it limits the inflow of information from the followers. This can be harmful if followers possess knowledge that leaders lack (Koriat, 2012), or because followers often have more accurate knowledge by being closer to the ground (Ostrom, 1990). A promising development to study the cost of bias is through the use of information cascade models, which simulate how information is transmitted within a social network (Jalili and Perc, 2017).

Fourth, our results show that talkativeness is the crucial characteristic explaining the two effects of leaders on consensus decision-making: a reduction in time to consensus and a bias in the final decision. In addition, our results show that the effect of persuasiveness of leaders is highly dependant on their talkativeness.

The work presented here shows that opinion formation models can provide a mechanistic model that describes the role of leadership in consensus decision-making, and that can be applied across a wide range of domains. Consensus decision-making has often been ignored or simplified in models of leadership in life sciences. For instance, previous models studying animal (Conradt and Roper, 2003) or human leadership (Powers and Lehmann, 2014) considered only despotic (one leader) or democratic (majority rule) groups. Yet, these are two extremes on a range of possible forms of social organisation, and a wide range of forms of leadership can be observed in nature (Von Rueden et al., 2014; Walker et al., 2017). This diversity can be integrated into opinion formation models, and allows a more thorough investigation of the evolution of leadership, as shown recently for the evolution of human leadership (Perret et al., 1928). The model presented here can similarly be tailored to investigate leadership in non–humans species that appear to use consensus processes to take collective decisions, e.g. bees, swans, and wild dogs (Conradt and Roper, 2005).

Our work expands on previous research in social dynamics. In particular, a previous opinion formation model investigated the effect of persuasiveness, stubbornness and talkativeness (called reputation in their models) on consensus decision-making (Gavrilets et al., 2016). However, this prior work has two differences with the model and analysis presented here. First, their mathematical approximation focuses on the effect of population change in a single trait. For instance, they show that an increase in the mean persuasiveness of a group always reduces the time to consensus, because individuals convince each other faster. We complete their work by looking at cases where these traits covary as observed in nature. We showed that in these conditions, consensus time is reduced only when a small number of individuals are present and thus, we find back the benefit of leadership. Second, their simulations focus on the variability in the traits rather than their distribution. Thus, their results showing a benefit of leadership is limited by one of their shortest simulations being obtained when there was only one persuasive, stubborn and talkative individual. Our findings confirm this result and provide a more thorough exploration. Finally, our results broaden their conclusion by showing that this effect is dependant of the number of leaders and the difference of influence between leaders and followers. In particular, we show that multiple influential leaders can have a limited benefit, because leaders persuade each others' followers, creating conflict of interest between a large proportion of the group.

We considered here a complete network and only global consensus, i.e. all the group agrees. Despite both being conservative assumptions, they are two unlikely features of real world situations. Jalili, 2013 develops an continuous opinion formation considering local consensus and looked at the effect of the distribution of persuasion (called social power) within different network structures. This model shows that when persuasion is asymmetrically distributed with the most connected individuals having the highest social power, the consensus is largely improved with the largest cluster at the end of consensus moving from 30 to 85 percent of the total. Yet, this result does not hold on other network structures in which there are not large differences in the number of social links. In brief, their results suggest that a minority of talkative and persuasive individuals also facilitates consensus decision-making when local consensus is considered. Further work could integrate network structure to investigate the effect of hierarchy and group size as defined here on the time to consensus. However, this requires a good representation of the social structure of individuals during consensus decision-making, which can be more dynamic than the social network observed in long-term interactions.

The model developed here predicts a relationship between the distribution of individuals' capacity to influence and the time that a group spend to reach consensus. Previous work (Kearns et al., 2009) has investigated how network structure and incentives affect human groups to reach a consensus before a given time limit using behavioural economics experiments. Their results support our predictions that groups with a minority of individuals with large influence (in their case, well-connected individuals) more often reach consensus. Our results also predict that (i) talkativeness is the most important characteristic of leaders, and (ii) that persuasiveness is important when leaders are talkative. These predictions fit with experiments on human groups. First, it has been shown that the most talkative individuals are recognised as leaders (the "babble hypothesis") (Bass, 1947; Sorrentino and Boutillier, 1975). Second, this conclusion has been latter refined with experiments that show that the quality of communication is also important, but depends on the talkativeness of the individual communicating (Riecken, 1958; Jones et al., 2007). More broadly, the difficulty of measuring the distribution of individual capacity to influence others has limited experimental measures. However, further tests of our predictions could be done with developing methods to measure influence of individuals in animal groups (Strandburg-Peshkin et al., 2018; Richardson et al., 2018). Influence can also be measured a*posteriori* from transcripts of human communication, where one can measure the impact of an individual's speech on the content of further communications (for instance, see Barron et al., 2018).

In conclusion, our model supports the hypothesis that leadership provides a benefit to group organisation (Calvert, 1992). Our results complete this hypothesis by showing that the difference in individual capacity to influence is sufficient to explain the organisational benefit of social hierarchy. How much does this benefit, i.e. taking faster decisions, rather than a competency benefit, i.e. taking better decisions, explain the emergence of leaders? When faced with a task which can be solved by an optimal course of action, and given that competences are easy to assess, it is likely that the emergence of leaders would be driven by their capacities to take the right decision. (Gavrilets et al., 2016). This fits with the type of leadership observed in small-scale societies where skills are well-known by all (Garfield et al., 2019). However, when the best solution for a task is not obvious or when there are multiple optimal solutions, when time is pressing, or when competences of individuals are hard to assess, the benefit brought by leaders on time to consensus could be the main driver behind the emergence of leadership. For instance, permanent and influential leaders are observed in large-scale human societies where group size limits the assessment of competences, the number of collective tasks can be very high, and tasks do not have an obvious solution (the payoff of a new rule regulating markets is hard to measure, for example). Promising future work would consist in adding concrete tasks to this decision-making model to better identify which benefit is likely to drive the emergence of leadership. More broadly, merging the body of work on leadership in life sciences and opinion formation in physical sciences should be a fertile ground for further research. We have shown here that opinion formation models can provide a in-depth description of the consensus decision-making, and connect individual characteristics to group functioning. More than providing new understanding, these models also carry potential for managing group coordination. For instance, theoretical work has proposed algorithms to maximise the spread of information within groups (AskariSichani and Mahdi, 2015). Likewise, work focusing on how bacteria regulate their virulence using collective decision-making by quorum sensing could also provide new ways to control it (Rutherford and Bassler, 2012).

Data availability statement

The code is available online at "https://github.com/CedricPerret" in the project "ConsensusModTraits".

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We thank the reviewers for their helpful comments. We thank an anonymous reviewer for suggesting the analytical approximations. We thank Guillaume St-Onge, Zohar Neu, and Andrea Santoro for their helpful comments and input during a related project at the Complex Systems Summer School 2018.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jtbi.2022.111094.

References

Alvard, Michael S.,Gillespie, Allen, 2004. Good lamalera whale hunters accrue reproductive benefits. In Socioeconomic Aspects of Human Behavioral Ecology: Vol 23, pages 225–247. Emerald Group Publishing Limited, 2004. doi:10.1016/S0190-1281(04)23009-8..

AskariSichani, Omid, Jalili, Mahdi. Influence maximization of informed agents in social networks. Applied Mathematics and Computation, 254: 229–239, 2015. ISSN 00963003. doi:10.1016/j.amc.2014.12.139..

Barron, Alexander T.J., Huang, Jenny, Spang, Rebecca L., Dedeo, Simon, 2018. Individuals, institutions, and innovation in the debates of the French Revolution. PNAS 115 (18), 4607–4612. https://doi.org/10.1073/pnas.1717729115.

Bass, Bernard M., 1947. An analysis of the leaderless group discussion. J. Appl. Psychol. 33 (6), 527–533. https://doi.org/10.1037/h0058164. ISSN 0021-9010.

Black, Jeffrey M., 1988. Preflight Signalling in Swans: A Mechanism for Group Cohesion and Flock Formation. Ethology 79 (2), 143–157. https://doi.org/10.1111/j.1439-0310.1988.tb00707.x. ISSN 01791613.

Boehm, Christopher, 2001. Hierarchy in the forest: The evolution of egalitarian behavior. Harvard University Press, Cambridge.

Calvert, Randall, 1992. Leadership and its basis in problems of social coordination. Int. Political Sci. Rev. 13 (1), 7–24. https://doi.org/10.1177/019251219201300102. ISSN 0192-5121.

Claudio Castellano, Santo Fortunato, and Vittorio Loreto. Statistical physics of social dynamics. Reviews of Modern Physics, 81 (2): 591–646, 10 2009. ISSN 00346861. doi:10.1103/RevModPhys.81.591..

Shuwei Chen, David H. Glass, and Mark McCartney. Characteristics of successful opinion leaders in a bounded confidence model. Physica A: Statistical Mechanics and its Applications, 449: 426–436, 2016. ISSN 03784371. doi:10.1016/j.physa.2015.12.107..

Lars Chittka, Peter Skorupski, and Nigel E. Raine. Speed-accuracy tradeoffs in animal decision making. Trends in Ecology & Evolution, 24 (7): 400–407, 7 2009. ISSN 0169–5347. doi:10.1016/J.TREE.2009.02.010..

P. Clifford and A. Sudbury. A model for spatial conflict. Biometrika, 60 (3): 581–588, 1973. ISSN 00063444. doi:10.2307/2335008..

L. Conradt and T.J. Roper. Group decision-making in animals. Nature, 421 (6919): 155–158, 1 2003. ISSN 0028–0836. doi:10.1038/nature01294..

Larissa Conradt and Timothy J. Roper. Consensus decision making in animals. Trends in Ecology & Evolution, 20 (8): 449–456, 8 2005. ISSN 0169–5347. doi:10.1016/J.TREE.2005.05.008..

Iain D. Couzin, Jens Krause, Nigel R. Franks, and Simon A. Levin. Effective leadership and decision-making in animal groups on the move. Nature, 433 (7025): 513–516, 2 2005. ISSN 0028–0836. doi:10.1038/nature03236..

David V Day. The Oxford handbook of leadership and organizations, volume 50. Oxford University Press, 2013. ISBN 0199755612. doi:10.5860/choice.50-6860..

Guillaume Deffuant, Frédéric Amblard, Gérard Weisbuch, and Thierry Faure. How can extremism prevail? A study based on the relative agreement interaction model. Journal of Artificial Societies and Social Simulation, 5 (4): 1–26, 2002. ISSN 14607425..

Morris H. Degroot. Reaching a Consensus. Journal of the American Statistical Association, 69 (345): 118–121, 3 1974. ISSN 0162–1459. doi:10.1080/01621459.1974.10480137..

Thomas Diefenbach and John A.A. Sillince. Formal and informal hierarchy in different types of organization. Organization Studies, 32 (11): 1515–1537, 2011. ISSN 01708406. doi:10.1177/0170840611421254..

Yucheng Dong, Min Zhan, Gang Kou, Zhaogang Ding, and Haiming Liang. A survey on the fusion process in opinion dynamics. Information Fusion, 43: 57–65, 9 2018. ISSN 1566–2535. doi:10.1016/J.INFFUS.2017.11.009..

Nigel R. Franks, Anna Dornhaus, Jon P. Fitzsimmons, and Martin Stevens. Speed versus accuracy in collective decision making. Proceedings of the Royal Society B: Biological Sciences, 270 (1532): 2457–2463, 2003. ISSN 14712970. doi:10.1098/rspb.2003.2527..

Serge Galam and Frans Jacobs. The role of inflexible minorities in the breaking of democratic opinion dynamics. Physica A: Statistical Mechanics and its Applications, 381: 366–376, 7 2007. ISSN 03784371. doi:10.1016/j.physa.2007.03.034..

Zachary H. Garfield, Robert L. Hubbard, and Edward H. Hagen. Evolutionary models of leadership. Human Nature, pages 1–36, 2 2019. ISSN 1045–6767. doi:10.1007/s12110-019-09338-4. url:http://link.springer.com/10.1007/s12110-019-09338-4..

Zachary H. Garfield, Christopher von Rueden, and Edward H. Hagen. The evolutionary anthropology of political leadership. Leadership Quarterly, 30 (1): 59–80, 2019. ISSN 10489843. doi:10.1016/j.leaqua.2018.09.001..

Sergey Gavrilets, Jeremy Auerbach, and Mark Van Vugt. Convergence to consensus in heterogeneous groups and the emergence of informal leadership. Scientific Reports, 6, 2016. doi:10.1038/srep29704..

Richard A. Holley and Thomas M. Liggett. Ergodic theorems for weakly interacting infinite systems and the voter model. The Annals of Probability, 3 (4): 643–663, 8 1975. ISSN 0091–1798. doi:10.1214/aop/1176996306..

Mahdi Jalili. Social power and opinion formation in complex networks. Physica A: Statistical Mechanics and its Applications, 392 (4): 959–966, 2 2013. ISSN 0378–4371. doi:10.1016/J.PHYSA.2012.10.013..

Mahdi Jalili and Matja++ Perc. Information cascades in complex networks. Journal of Complex Networks, 5 (5): 665–693, 10 2017. ISSN 2051–1310. doi:10.1093/COMNET/CNX019. url:https://academic.oup.com/comnet/article/5/5/665/3930936..

Rufus A. Johnstone and Andrea Manica. Evolution of personality differences in leadership. Proceedings of the National Academy of Sciences, 108 (20): 8373–8378, 2011. ISSN 0027–8424. doi:10.1073/pnas.1102191108..

Eric E. Jones and Janice R. Kelly. Contributions to a group discussion and perceptions of leadership: Does quantity always count more than quality? Group Dynamics: Theory, Research, and Practice, 11 (1): 15–30, 2007. ISSN 1930–7802. doi:10.1037/1089-2699.11.1.15..

Timothy A. Judge, Joyce E. Bono, Remus Ilies, and Megan W. Gerhardt. Personality and leadership: A qualitative and quantitative review. Journal of Applied Psychology, 87 (4): 765–780, 2002. ISSN 0021–9010. doi:10.1037//0021-9010.87.4.765..

Michael Kearns, Stephen Judd, Jinsong Tan, and Jennifer Wortman. Behavioral experiments on biased voting in networks. Proceedings of the National Academy of Sciences, 106 (5): 1347–52, 2 2009. ISSN 1091–6490. doi:10.1073/pnas.0808147106..

A. Koriat. When Are Two Heads Better than One and Why? Science, 336 (6079): 360–362, 4 2012. ISSN 0036–8075. doi:10.1126/science.1216549. url:http://www.sciencemag.org/cgi/doi/10.1126/science.1216549..

Krause, Jens, Ruxton, Graeme D., 2002. Living in groups. Oxford University Press, ISBN 0198508182.

Mobilia, M., Petersen, A., Redner, S., 2007. On the role of zealotry in the voter model. J. Stat. Mech.: Theory and Experiment 2007 (08), 8. https://doi.org/10.1088/1742-5468/2007/08/p08029.

Ostrom, Elinor, 1990. Governing the commons. Cambridge University Press.

Mayte Pérez-Llanos, Juan P. Pinasco, Nicolas Saintier, and Analia Silva. Opinion formation models with heterogeneous persuasion and zealotry. SIAM Journal

on Mathematical Analysis, 50 (5): 4812–4837, 2018. ISSN 10957154. doi:10.1137/17M1152784..
Perret, Cedric, Hart, Emma, Powers, Simon T., 2019. Being a leader or being the leader: The evolution of institutionalised hierarchy. In: Proceedings of the 2019 Conference on Artificial Life. MIT Press.
Cedric Perret, Emma Hart, and Simon T. Powers. From disorganized equality to efficient hierarchy: how group size drives the evolution of hierarchy in human societies. Proceedings of the Royal Society B: Biological Sciences, 287 (1928): 20200693, 2020. ISSN 14712954. doi:10.1098/rspb.2020.0693..
Simon T. Powers and Laurent Lehmann. An evolutionary model explaining the Neolithic transition from egalitarianism to leadership and despotism. Proceedings of the Royal Society B: Biological Sciences, 281 (1791), 2014. ISSN 14712954. doi:10.1098/rspb.2014.1349..
Thomas O. Richardson, Charles Mullon, James A.R. Marshall, Nigel R. Franks, and Thomas Schlegel. The influence of the few: A stable 'oligarchy' controls information flow in house-hunting ants. Proceedings of the Royal Society B: Biological Sciences, 285 (1872), 2018. ISSN 14712954. doi:10.1098/rspb.2017.2726..
Riecken, Henry W., 1958. The effect of talkativeness on ability to influence group solutions of problems. Sociometry 21 (4), 309–321.
La Rocca, C.E., Braunstein, L.A., Vazquez, F., 2014. The influence of persuasion in opinion formation and polarization. Europhysics Letters 106, 40004. https://doi.org/10.1209/0295-5075/106/40004.
Steven T. Rutherford and Bonnie L. Bassler. Bacterial quorum sensing: Its role in virulence and possibilities for its control. Cold Spring Harbor perspectives in medicine, 2 (11), 11 2012. ISSN 2157–1422. doi:10.1101/cshperspect.a012427..
Schelling, Thomas C., 1960. The strategy of conflict. Harvard University Press, ISBN 9780674840317.
Thomas D. Seeley and Susannah C. Buhrman. Group decision making in swarms of honey bees. Behavioral Ecology and Sociobiology, 45 (1): 19–31, 1999. ISSN 03405443. doi:10.1007/s002650050536..
Brian Skyrms. The stag hunt and the evolution of social structure. Cambridge University Press, 2003. ISBN 9781139165228. doi:10.1017/CBO9781139165228..
Jennifer E. Smith, Sergey Gavrilets, Monique Borgerhoff Mulder, Paul L. Hooper, Claire El Mouden, Daniel Nettle, Christoph Hauert, Kim Hill, Susan Perry, Anne E. Pusey, Mark van Vugt, and Eric Alden Smith. Leadership in mammalian societies: Emergence, distribution, power, and payoff. Trends in Ecology and Evolution, 31 (1): 54–66, 1 2016. ISSN 01695347. doi:10.1016/j.tree.2015.09.013..
Richard M Sorrentino and Robert G Boutillier. The effect of quantity and quality of verbal interaction on ratings of leadership ability. Journal of Experimental Social Psychology, 11 (5): 403–411, 9 1975. ISSN 0022–1031. doi:10.1016/0022-1031(75)90044-X..
Stewart, Kelly J., Harcourt, Alexander H., 1994. Gorillas' vocalizations during rest periods: Signals of impending departure? Behaviour 130 (1), 29–40.
Ariana Strandburg-Peshkin, Danai Papageorgiou, Margaret C Crofoot, and Damien R Farine. Inferring influence and leadership in moving animal groups. Philosophical Transactions of the Royal Society B: Biological Sciences, 373, 2018. doi:10.1098/not..
ThomasW. Valente. Network models of the diffusion of innovations. Computational and Mathematical Organization Theory, 2 (2), 1996. ISSN 1381–298X. doi:10.1007/BF00240425..
Mark Van Vugt, Anjana. Ahuja, and Mark Van Vugt. Naturally selected: The evolutionary science of leadership. HarperBusiness, 2011. ISBN 0061963836..
Christopher Von Rueden, Michael Gurven, Hillard Kaplan, and Jonathan Stieglitz. Leadership in an egalitarian society. Human Nature, 25 (4): 538–566, 2014. ISSN 10456767. doi:10.1007/s12110-014-9213-4..
Reena H. Walker, Andrew J. King, J. Weldon McNutt, and Neil R. Jordan. Sneeze to leave: African wild dogs (Lycaon pictus) use variable quorum thresholds facilitated by sneezes in collective decisions. Proceedings of the Royal Society B: Biological Sciences, 284 (1862), 2017. ISSN 14712954. doi:10.1098/rspb.2017.0347..