Using an opinion formation model to investigate the effect of leaders on collective decision-making

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The evolution of human social behaviour is a complex topic to formalise in models because it describes processes on different levels of abstraction. These models need to capture individual behaviours or cultural preferences, their effects on group properties and the processes which link the two. Particular real-world scenarios can be formalised on only one level, for instance by describing group properties by lower level individuals decisions and payoffs. However, a large number of scenarios are too complex to be captured by a single level of abstraction. For instance, theorists struggle to model social interactions when a large number of individuals are involved, when individuals are heterogeneous or when the group property lacks a description based on individuals' properties. Agent-based models can fill this gap because they are able to represent complex processes while remaining simple enough to provide valuable knowledge on the system.

One of these unexplored gaps is the collective decision-making process. This process describes how multiple individuals aggregate their opinions into one single decision. It is a critical process by which humans are able to coordinate in order to realise collective tasks or create institutional rules (Ostrom, 1990). It is also a crucial process for evolutionary studies because it links individual preferences i.e. the evolving trait, to group decisions i.e. what affects the reproductive success of the group. Unlike collective decision-making in most social animals, human collective-decision making is actively conducted by individuals using language to communicate, argue and convince. Because of this complexity, collective decision-making is often ignored or assumed in evolutionary models, at the detriment of the explanatory power of the models.

Collective decision-making can be formalised by opinion formation models. Opinion formation models simulate a sequence of discussions between individuals and *a fortiori* the spread of individual opinions within group members. Opinion-formation models are well-known tools to study social dynamics (the most known example is the voter model) (Castellano et al., 2009). Opinion formation models can capture collective decision-making by considering that individuals have agreed on one decision when a number of individuals have close enough opinions i.e. individuals have reached consensus. We illustrate the benefit of such an approach by investigating the role of leaders in collective decision-making.

A manifest trend in human societies is that larger and more productive human groups shift from distributed to centralised decision-making. This transition is best illustrated by the sudden and global transition from egalitarian hunter-gatherer to hierarchical agriculturists at the Neolithic transition 12500 years ago. The mechanisms driving this transition are still not fully understood mainly because leaders often enjoy preferential access to resources and mating partners. Thus, it is not clear why would any individual rationally accept a position of being a follower who might then be exploited. Voluntary theories propose that human groups shifted to social hierarchy in order to reduce the cost of group organisation and the increase in cost of organisation as group size grows. Yet, the investigation of this theory using evolutionary models has been limited because it lacks a mechanistic model describing how leaders would provide such benefit to group organisation.

To fill this gap, we hypothesise that leaders facilitate group organisation because they reduce the time a group spent to reach consensus. The time spent to reach consensus is translated into costs because groups that take too long to reach a decision may lose resources or eventually fail the collective task e.g. no decision taken before a battle starts. Taking inspiration from a previous model (Gavrilets et al., 2016), we develop an agent-based opinion formation model to integrate leaders and followers behaviours. As in previous work (Deffuant et al., 2000), individuals are represented by a continuous opinion on how to realise a collective task e.g. next raid target, plan of an irrigation system or value of a law. At each time step, a speaker shares its opinion to listeners and bring closer their opinion. The individuals repeat the previous step until consensus is reached, i.e. the standard deviation of the preference is less than a threshold. The number of discussion events that occurred to reach consensus is called the time to reach consensus. The novelty

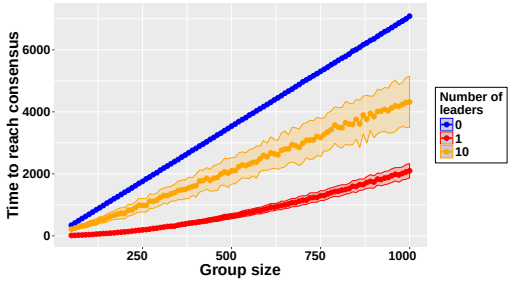

Figure 1: Time to reach consensus as a function of the size of the group for three different types of social organisation: (i) 0 leaders, (ii) 1 leader and (iii) 10 leaders. 100 independent replicates have been realised for each group size and social organisation. The ribbons represents the standard deviation across replicates.

of the model is to explicitly describe individual capacity to influence others. The influence of an individual is defined as the capacity of one individual to modify the opinion of another individual towards its own opinion. At the same time, it modifies the probability that an individual talks to other individuals. Leaders and followers are defined by a fixed influence value with leaders having a higher influence than followers.

We use numerical simulations to investigate the effect of number of leaders on the time to reach consensus for different group sizes. Figure 1 presents the time to reach consensus as a function of group size for three different social organisations, an egalitarian group (no leaders), hierarchy with one leader, and hierarchy with ten leaders. Figure 1 summarises the three main results. First, the presence of influential leaders and influenceable followers reduces the time to reach consensus. Second, the presence of influential leaders and influenceable followers reduces scalar stress i.e. the gradient of consensus time with respect to group size is lower. Third, hierarchy with a single leader provides a higher and more constant benefit to group organisation.

These results confirm the hypothesis of voluntary theories, which state that social hierarchy provides a benefit to group organisation and that this benefit increases as group grows. Our results complete these theories by showing that the difference in individual capacity to influence others is sufficient to explain the organisational benefit of social hierarchy. Indeed, the differential quality of information that leaders might posses, and which might also provides benefit to the group, is not required to get this result. This result provides a mechanistic model of the role of hierarchy in group decision-making that can be applied across a wide range of domains. For instance, it has been successfully integrated to evolutionary models to investigate the evolution of social hierarchy. A first model has demonstrated that the previous result showing that leaders reduce the time to reach consensus and scalar stress can explain how an increase in group size leads to the evolution of leaders and followers behaviour (Perret et al., 2017). A second model has demonstrated that the result showing that single leader hierarchy provides a higher organisational benefit, can explain the evolution of cultural preferences toward institutional hierarchy i.e. leader chosen by the group (Perret et al., 2019).

Evolutionary models and opinion formation models are two fruitful research fields. We believe that cross-fertilisation between the two fields carries high potential for the topic of the evolution of human behaviour. As a first example, the model presented here is one possible version of the opinion formation model with a number of assumptions. Further work could explore how additional factors of collective decision-making e.g. individual knowledge, network structure, multi-layered hierarchy; could modify the effect of hierarchy in organisation and *a fortiori* the evolution of social hierarchy. As a second example, there is a rising interest in the evolution of institutional rules, which can regulate social behaviours in large society. In reality, institutional rules do not evolve but the preferences of individuals on these rules evolve, which are then aggregated by collective-decision making. So far, the collective decision-making has been simplified e.g. majority rule. Modelling the collective decision making would be a further step to understand the dynamics driving how institutional rules change with time.

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