



**HAL**  
open science

# Improving human collective decision-making through animal and artificial intelligence

Cédric Sueur, Christophe Bousquet, Romain Espinosa, Jean-Louis Deneubourg

► **To cite this version:**

Cédric Sueur, Christophe Bousquet, Romain Espinosa, Jean-Louis Deneubourg. Improving human collective decision-making through animal and artificial intelligence. 2021. hal-03299087v2

**HAL Id: hal-03299087**

**<https://hal.science/hal-03299087v2>**

Preprint submitted on 30 Jul 2021 (v2), last revised 30 Aug 2021 (v3)

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Improving human collective decision-making through animal and artificial intelligence**

2 Cédric Sueur<sup>1,2,§,\*</sup>, Christophe Bousquet<sup>3,4,§,\*</sup>, Romain Espinosa<sup>5,6</sup>, Jean-Louis Deneubourg<sup>7</sup>

3 <sup>1</sup> Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France

4 <sup>2</sup> Institut Universitaire de France, Saint-Michel 103, F-75005 Paris, France

5 <sup>3</sup> Laboratoire Cogitamus, <https://www.cogitamus.fr/>

6 <sup>4</sup> Centre de Recherche en Neurosciences de Lyon, CRNL Inserm U1028 - CNRS UMR5292 -

7 UCBLyon1

8 <sup>5</sup> CNRS, CREM – Université Rennes 1, France

9 <sup>6</sup> Rennes School of Business, France

10 <sup>7</sup> Center for Nonlinear Phenomena and Complex Systems (Cenoli) - CP 231, Université Libre

11 de Bruxelles (ULB), Campus Plaine, Boulevard du Triomphe, Building NO - level 5, B-1050,

12 Bruxelles, Belgium.

13 § These authors contributed equally to this work

14 \*Correspondence: [cedric.sueur@iphc.cnrs.fr](mailto:cedric.sueur@iphc.cnrs.fr) (C. Sueur); [chr\\_bousquet@protonmail.com](mailto:chr_bousquet@protonmail.com) (C.

15 Bousquet)

16

17 **Abstract**

18 **Whilst fundamental to human societies, collective decision-making such as voting systems**  
19 **can lead to non-efficient decisions, as past climate policies demonstrate. Current systems**  
20 **are harshly criticized for the way they consider voters' needs and knowledge. Collective**  
21 **decision-making is central in human societies but also occurs in animal groups mostly**  
22 **when animals need to choose when and where to move. In these societies, animals**  
23 **balance between the needs of the group members and their own needs and rely on each**  
24 **individual's (partial) knowledge. We argue that non-human animals and humans share**  
25 **similar collective decision processes, among which are agenda-setting, deliberation and**  
26 **voting. Recent works in artificial intelligence have sought to improve decision-making in**  
27 **human groups, sometimes inspired by animals' decision-making systems. We discuss here**  
28 **how our societies could benefit from recent advances in ethology and artificial intelligence**  
29 **to improve our collective decision-making system.**

30

31 **Keywords: collective decisions, vote, democracy, representativeness, machine learning**

32

33 **Rethinking current voting systems**

34 Collective decision-making processes such as **voting systems** are pillars of our Western  
35 societies <sup>1-6</sup>. However, democratic choices may sometimes lead to non-efficient or non-  
36 representative decisions (see Glossary for definitions of **efficiency** and **representativeness**).

37 This was the case with the election of François Hollande in 2012 <sup>7</sup> and the election of Donald  
38 Trump in 2016 <sup>8</sup>. In the 2012 French presidential elections, François Hollande beat Nicolas  
39 Sarkozy and was elected with 51.62% of votes. However, these two candidates would have  
40 lost in a one-to-one vote to François Bayrou (a third candidate). In fact, Bayrou would have

41 won one-to-one against any other candidate in this election and would therefore have been  
42 a Condorcet candidate (i.e., a candidate with a majority against any other candidate in a  
43 one-to-one vote). Nevertheless, voters' preferences for Bayrou were not strong enough to  
44 qualify him for the second round of elections in a two-round majority system <sup>9</sup>. This example  
45 shows how the choice offered to the voters and the institutions governing that vote are  
46 perhaps as important as the way people vote. As illustrated by Donald Trump's victory over  
47 Hillary Clinton in the 2016 election, another issue affecting the legitimacy of voting results is  
48 the way in which citizens base their choice on media and news sources that were often  
49 unreliable and played on people's fears <sup>10,11</sup>. In the long term, these biased choices lead to  
50 non-efficient decisions that have to be revised frequently. Besides, society and political  
51 parties have become more polarised on many issues, due to the massive use of social  
52 networks and influencers <sup>12,13</sup>, while the political supply has not become more diverse. This  
53 combination of high polarisation and low political diversity results in a decrease in citizens'  
54 satisfaction with democracy <sup>14</sup>. In addition, Western democracies suffer more and more  
55 from low turnout rates <sup>15</sup>, which further weakens the political systems. It is therefore  
56 essential to find solutions that ensure citizens' support. The issues that may lead to  
57 dissatisfaction with elections or referendums can be summarised into three categories: 1.  
58 the voting systems and, more generally, the mechanisms used to aggregate preferences, 2.  
59 the needs and/or desires of citizens, and 3. the knowledge on which voters decide. Each of  
60 these categories could benefit from recent findings in animal and **artificial intelligence (AI)**.

61

## 62 **Recent advances in political science**

63 Political institutions are powerful organisations to articulate multi-level human societies and  
64 to produce decisions that affect large numbers of people. However, to achieve these two

65 goals, most political institutions have excluded ordinary citizens from policy **agenda-setting**  
66 and deliberation, two fundamental yet underestimated aspects of collective decision-making  
67 <sup>16</sup>. Even in representative democracies, ordinary citizens constitutionally have access only to  
68 the final choice, through their vote. In political science, voting generally refers to the choice  
69 of elected representatives by citizens. In most current cases, once the vote is over, the  
70 elected representatives become independent and are in no way bound to deliver their  
71 electoral promises: there is no recall option for the citizens. Over the years, two different  
72 types of disadvantages of voting have been reported. First, it is possible to question the  
73 capacity of the vote to represent society, based on the observation that, sociologically,  
74 elected officials differ greatly from ordinary citizens <sup>17</sup>. However, other forms of  
75 representation are conceivable. For example, statistical research has developed random  
76 sampling techniques that are representative of the general population. While these **sortition**  
77 techniques are widely used for opinion polls, they are still not very popular for choosing  
78 representatives of civil society, although recent experiments in Iceland and France (to name  
79 but two) have taken place <sup>16</sup>. Moreover, under certain conditions, it is possible to consider  
80 the **self-selection** of certain individuals as representative of a desire of similar individuals to  
81 take part in the public debate <sup>16</sup>. Finally, liquid representation is a very recent concept in  
82 political science <sup>18,19</sup> that implies <sup>20</sup>: (i) direct voting on any issue, (ii) flexible proxy voting, (iii)  
83 meta proxy voting and (iv) possible instant recall by each original voter. The other major  
84 form of disadvantage of voting is that it focuses attention on the final choice, while other  
85 dimensions of power are also important to consider. For many political scientists,  
86 representative democracy has come of age and should be either complemented or replaced  
87 by **deliberative democracy** or open democracy <sup>16</sup>. Voting as currently envisaged does not  
88 allow citizens to access the political agenda-setting <sup>21</sup> or deliberation <sup>22</sup> to choose between

89 different options. Yet, these different forms of political participation are increasingly  
90 recognised as crucial and, as we will see later, these two forms also exist in animal groups.

91

## 92 **Taking inspiration from animal collective decisions**

93 Humans are not the only species that uses group processes to make important choices.

94 These concepts also exist in other animal societies, in which voting systems are readily used,

95 for instance to decide where to go (Figure 1). In ethology, voting means that “an animal

96 communicates its individual preference with regard to the collective decision outcome”<sup>23</sup>,

97 and the decision is a sign of an “ecological rationality” and intention, the effectiveness of

98 which is assessed over long evolutionary periods. These voting processes are mostly used to

99 decide about where and when to go for foraging or for resting. Of course, this does not

100 mean that these species have the same mental states as humans but their behaviours

101 suggest certain cognitive capabilities as degrees of theory of mind<sup>24,25</sup>. Empirical studies

102 supported by modelling are able to differentiate simple copying process from true voting

103 decisions involving intentional communication and awareness of mental states of others<sup>26</sup>.

104 Group decision-making is common in the animal kingdom, and has been documented in

105 social insects (honeybees<sup>27</sup> or ants<sup>28–30</sup>), fish<sup>31–34</sup> and mammals (e.g., primates<sup>35,36</sup>,

106 meerkats<sup>37</sup>, African wild dogs<sup>38</sup>, bison<sup>39</sup> and deer<sup>23</sup>). We do not mean here that cognitive

107 processes involved in animal collective decisions are similar to the ones in humans, they

108 differ in degrees. However, animal and human processes are comparable, and this

109 comparison may help to provide insight for the stewardship of human collective behaviour

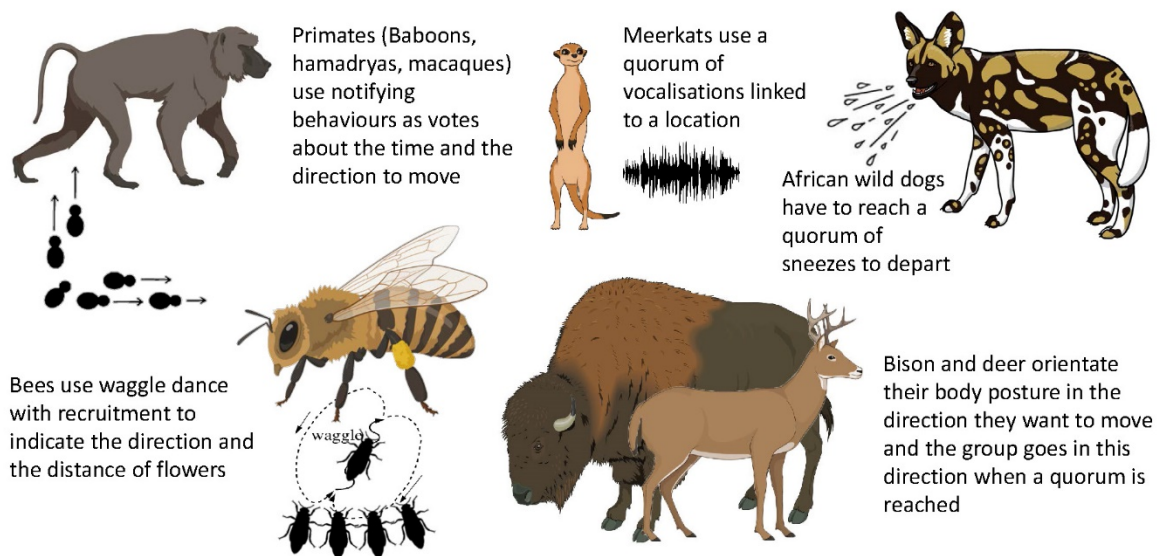
110<sup>40</sup>. Living in groups brings many advantages but animals have to resolve conflicts of interest

111 to maintain their cohesion and these advantages, through collective decisions. Research

112 efforts largely have been directed in relatively stable and cohesive groups. Less well

113 understood is how fission-fusion dynamics mediate the processes and outcomes of collective  
 114 decision making. However, collective decisions also happen in species with fission-fusion  
 115 dynamics as shown in bison or hamadryas baboons and are based on similar concepts than  
 116 the ones applied to cohesive groups (e.g., needs, information, social networks, see <sup>41</sup> for a  
 117 review) but only partial consensus may apply. The difference between stable or cohesive  
 118 groups and groups with fission-fusion dynamics also lies in the way individuals evaluate  
 119 group membership: it is a common rule in animals that if the costs of being in the group  
 120 outweighs the benefits, individuals will leave. It is this rule that partly sets an upper limit to  
 121 the group sizes observed in animals: even in species living in stable groups, fissions are  
 122 observed when a certain group size is reached <sup>42-45</sup>, without necessarily always  
 123 understanding the underlying mechanisms. This could shed new light on the low turnout  
 124 rates observed in elections in Western societies: the benefits of the electoral process for  
 125 some citizens are too low, leading them to desert the ballot box.

126



127

128 Figure 1: Species showing these different voting behaviours, specifically primates <sup>35,36</sup>,

129 meerkats <sup>37</sup>, African wild dogs <sup>38</sup>, honeybees <sup>27</sup>, bison <sup>39</sup> and deer <sup>23</sup>.

130

131 Animal decisions can be complex since they may involve many (up to thousands) individuals  
132 having different needs and information about a complex environment with high conflicts  
133 needing resolution and wrong decisions potentially leading to death. These conflicts of  
134 interests might be due to differential needs of individuals as in primate groups or due to  
135 private information about different sites as in swarming honeybees <sup>46</sup>. Acquiring information  
136 is costly, which is why animals often rely on their groupmates to get informed <sup>47</sup>. By  
137 signalling information and needs within the group, these social species engage in a sort of  
138 deliberation that can take into account the magnitude of each signal as a proxy for individual  
139 motivation (see the part “the needs of citizens for more details”). Over the course of  
140 successive collective decisions, the identities of the individuals sending signals of information  
141 or need vary, thus ensuring a rotation of the group members participating in the agenda-  
142 setting and in the deliberation. Most likely, due to stochastic phenomena in physiological  
143 processes or in information acquisition processes, the identities of the participants in each  
144 collective decision vary randomly, thus basing the selection mechanism on sortition rather  
145 than on election. Animal collective decisions are therefore based on mechanisms of  
146 sortition, agenda-setting and deliberation. Furthermore, these mechanisms have been  
147 selected over many generations to optimise the trade-off between speed and accuracy of  
148 the collective decision and to favour the fitness of individuals belonging to these groups.  
149 Although less studied from this perspective, animal groups with fission-fusion dynamics also  
150 use the same collective decision mechanisms as stable groups, with the additional possibility  
151 for each individual to choose the subgroup that best suits them. In some respects, this could  
152 be similar to liquid representation, although more research is needed to confirm this link.



153 In a nutshell, animal processes and issues such as agenda-setting, deliberation, majority  
154 rules, importance of minorities, uninformed individuals, source of information and  
155 misinformation are very similar to human processes and issues<sup>31,40,48</sup>. Therefore, because of  
156 the strong natural selection increasing the efficiency of animal systems, authors call for  
157 researches on animal systems to improve the decision-making process in human societies,  
158 especially in link with AI<sup>49-53</sup>: bioinspiration for AI may conduct to better understand and  
159 control AI behaviour<sup>54</sup>.

160

### 161 **Taking inspiration from AI**

162 It is important and timely to ask how artificial intelligence and digital technologies can  
163 contribute to strengthening democracy. This link is not straightforward when we see (i) the  
164 development of AI applications in non-democratic countries (China, Russia, among others)<sup>55</sup>  
165 and (ii) the little attention paid to the privacy of their users by the major firms in the sector  
166<sup>56</sup>. AI can help shaping more democratic human collective-decision systems in several ways,  
167 from the establishment of fair voting conditions to the integration of artificial voting agents.  
168 AI can influence decision-making of humans in different contexts (e.g., politics or dating)<sup>57</sup>.  
169 A famous example is an experiment on voting behaviour during the 2010 congressional  
170 election in the U.S., using a sample of 61 million Facebook users<sup>58</sup>. The results showed that  
171 Facebook messages influenced political self-expression and voting behaviour in millions of  
172 people. These results were subsequently replicated during the 2012 U.S. Presidential  
173 election<sup>59</sup>. This example shows at the same time how much AI can be useful and very  
174 dangerous for democracies.

175 Humans benefit from a number of recent advances in AI to improve voting systems. The first  
176 example is an algorithm developed to counter electoral gerrymandering by creating electoral

177 districts that are representative of the global population <sup>60</sup>. By using an algorithm following a  
178 divide-and-conquer approach, it is possible to produce electoral districts' maps that  
179 maximise compactness (to ensure geographical continuity) and minimise population  
180 deviation (to ensure representativeness) <sup>60</sup>. By following these two rules, the algorithm  
181 avoids gerrymandering, thus providing fairer voting conditions, particularly if all stakeholders  
182 participated in developing the rules and in evaluating the resulting maps. Another  
183 perspective is the integration of principles derived from collective animal processes into AI  
184 algorithms <sup>61</sup>. By combining human and AI, the Artificial Swarm Intelligence algorithm <sup>61</sup>  
185 offers promising results: it performs better than humans-only and machine-only setups on a  
186 variety of tasks. The resulting increase in accuracy and acceptance of the collective decision  
187 is attributable to the direct involvement of humans in the decision process.

188 A third approach that requires a democratic debate makes it technically possible for citizens  
189 to be represented by avatars reflecting the preferences of each voter rather than by  
190 politicians <sup>62</sup>. Technically, it will soon be possible to create intelligent e-democracy bots that  
191 can infer the political preferences of their associated human voter. Such bots could then be  
192 allowed to participate in voting processes on the voter's behalf <sup>62</sup>. For example, these bots  
193 could use Natural Language Processing (NLP) to copy the opinion expressed by the politician  
194 deemed closest to the voter's position. This controversial topic could allow citizens to  
195 express themselves on a wide range of issues. Yet this same technique could reinforce vote  
196 manipulation or the abandonment of political life by voters by delegating the expression of  
197 their opinions to a bot. When faced with electoral choices, voters sometimes find it difficult  
198 to distinguish or rank the positions of different political offers on various issues. Analyses by  
199 NLP make it easier to compare the contents of political programmes <sup>63</sup>. This tool provides a  
200 more quantitative representation of political programmes, or an easier means to trace the

201 evolution of a party's positions on a specific topic over time. This leverage could be used to  
202 improve the trade-offs among parties between rounds or in combination with **evaluative**  
203 **voting**<sup>7</sup>. In addition, techniques based on distance analyses between the positions of  
204 stakeholders in successive rounds of deliberation can identify individuals or clusters that  
205 refuse to move towards a consensus<sup>64</sup>. Once these individuals or clusters have been  
206 identified, their weight in the next round of deliberation could, for example, be penalised<sup>64</sup>.  
207 Democratically, this could make sense because participants in a preference aggregation  
208 process who refuse to change their position in response to other stakeholders indicate that  
209 they are not prepared to seek consensus among reasonable perspectives<sup>65</sup>. Without such a  
210 penalisation, small minorities could gain veto power blocking any progress.

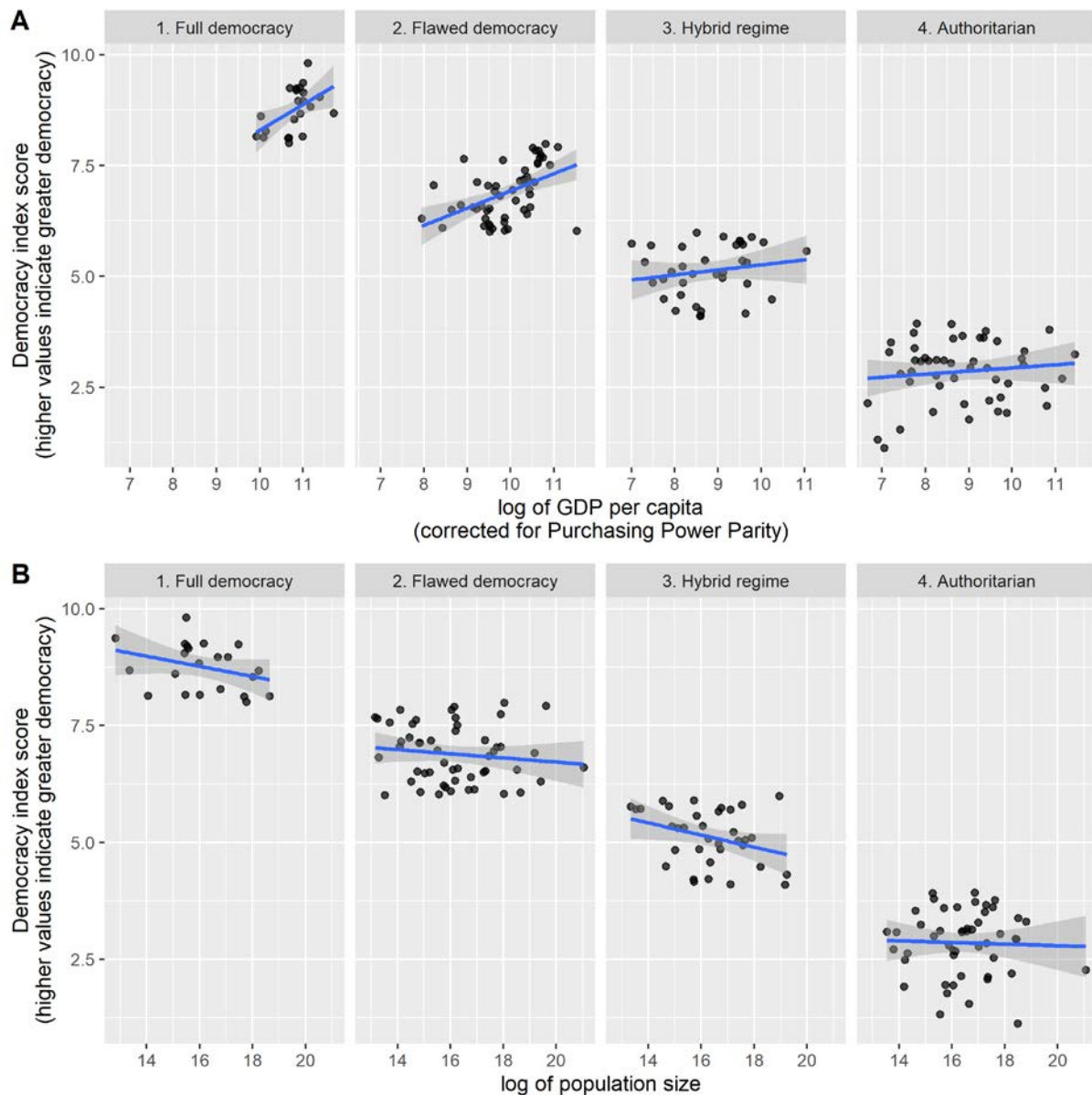
211 AI techniques, such as data mining<sup>66</sup> and synthetic data generation<sup>67,68</sup>, will also be useful in  
212 producing consistent, unbiased and privacy-protecting data<sup>69</sup>. This last point underlines the  
213 importance of the acceptability of AI by the public. While AI is generally viewed positively by  
214 the media<sup>70</sup>, significant concerns about data protection<sup>69</sup> and human employment have  
215 recently emerged. Thus, resistance to AI is stronger among those least inclined to innovation  
216 and most sensitive to data privacy<sup>71</sup>. Finally, AI is very good at identifying patterns in data,  
217 but far less good at predicting complex social outcomes, perhaps because such outcomes are  
218 inherently unpredictable (due to the inevitable reduction of real complexity in algorithms  
219 and to the ability of living beings to react very differently to subtle changes in their  
220 environment)<sup>72</sup>.

221

## 222 **The different systems used to aggregate individual preferences**

223 Different systems can be used to aggregate individual preferences, ranging from how  
224 proportional they are (i.e., how the final choice represents the votes) and bearing in mind

225 that heterogeneous preferences and beliefs hinder conflict resolution. A parliament  
226 selecting the proportion of deputies based exactly on the votes for each party is statistically  
227 representative of the political preferences in the population, but one selecting the deputies  
228 based only on the majority voting is not. Moreover, the voting systems may change the final  
229 result according to how preferences of voters are taken into account (see the section “the  
230 needs of citizens”). Human political systems range from authoritarian regimes to full  
231 democracies, depending on the distribution of weights for each individual in society (Fig. 2).  
232 Authoritarian regimes are more likely to emerge and sustain themselves if the despots  
233 manage to secure a relative advantage in fighting ability both in humans and in animals <sup>73,74</sup>.  
234 This fighting advantage may be due to individual traits (strength, personality) but not only.  
235 Securing alliances is important to keep the power <sup>75,76</sup>, which gives prior access to resources  
236 as food <sup>77</sup>, reproduction <sup>78,79</sup>, safe places <sup>80</sup> but also to leadership <sup>81–83</sup>. In democracies, the  
237 most commonly used representation system is the voting system with **majority voting**, for  
238 instance the first-past-the-post rule. Whilst animals do not elect presidents (but see <sup>76</sup> to  
239 choose the dominant male in an animal society), they use democratic (equally shared  
240 consensus) or semi-democratic (partially shared consensus with some individuals having  
241 higher decision weights) systems in their everyday life <sup>23,27,84–86</sup>. Non-human animals do not  
242 have the sophisticated language capacity of humans but this does not mean that they cannot  
243 deliberate and negotiate over different alternatives and vote for them <sup>36,84,85,87</sup>. Recent  
244 empirical studies have shown that the decision-making of social species happens through  
245 the adoption of symbolic systems for consensus construction (vocalisations, movements of  
246 intentions, notifying behaviours, and dances) <sup>88</sup>.  
247



248

249 Figure 2. Relationship of the Democracy Index Score (DIS) (each point represents a country)

250 with the logarithm of the country's Growth Domestic Product per capita, corrected for

251 purchasing power parity (A) and the logarithm of the country's population size (B). Within

252 each regime type, a higher democracy index is more likely when GDP per capita is high

253 (LMM:  $0.19 \pm 0.06$ ,  $t = 2.990$ ,  $p < 0.01$ ) (Fig. 1A). There is also a tendency for countries with

254 smaller populations to be more democratic (LMM:  $-0.08 \pm 0.05$ ,  $t = -1.692$ ,  $p = 0.09$ ) (Fig. 1B).

255 The analysis takes into account the overall regime type of the country by adding this variable

256 as a random effect in the model. Data come from the following websites: Democracy Index

257 (<https://www.eiu.com/topic/democracy-index>), GDP  
258 (<https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD>) and population size  
259 ([https://en.wikipedia.org/wiki/List\\_of\\_countries\\_and\\_dependencies\\_by\\_population](https://en.wikipedia.org/wiki/List_of_countries_and_dependencies_by_population)).  
260 Data and analyses script are available at Zenodo. <http://doi.org/10.5281/zenodo.4703733>  
261  
262 Cases (for instance the first-past-the-post rule) where one alternative is chosen until it is  
263 more popular than another, however small the difference of evidence for the two  
264 alternatives may be are said to derive from the **Race Model** and were proved to be non-  
265 efficient compared to the **Drift-Diffusion Model** (DDM), described at the individual (i.e.,  
266 brain) level or the collective level both in humans and animals<sup>89–92</sup>. The DDM stipulates that  
267 the differences between two alternatives have to reach a threshold and this model,  
268 operating in brain and collective decision processes, is far more efficient than the race model  
269<sup>93,94</sup>. It is adaptive in urgent situations where decision speed is favoured over accuracy<sup>92,94</sup>.  
270 In ants, in emergency situations, individuals decrease their **quorum** threshold and the quality  
271 of a future nest in profit of the decision time, whilst they take time and choose the best nest  
272 in normal conditions by increasing the quorum threshold, which indicates a DDM<sup>30,93</sup>. This  
273 use of different quorums could help to generalise the **Condorcet's jury theorem** to a wider  
274 range of **decision ecologies**<sup>95</sup>. In decision ecology, individuals are prone to two different  
275 types of errors: false positives and false negatives. Yet, in its simplest form, the Condorcet  
276 theorem assumes that both errors are identical. When this assumption is relaxed (when the  
277 probability of a false positive differs from the probability of a false negative), it can be shown  
278 that majority voting becomes non representative and should be replaced by sub- or  
279 supermajority quorums depending on the conditions<sup>95</sup>. Sometimes, in humans, instead of  
280 choosing one of the two alternatives with a small majority, a compromise can be found

281 thanks to a new alternative satisfying a greater majority. This phenomenon has been coined  
282 the **median voter theorem**.

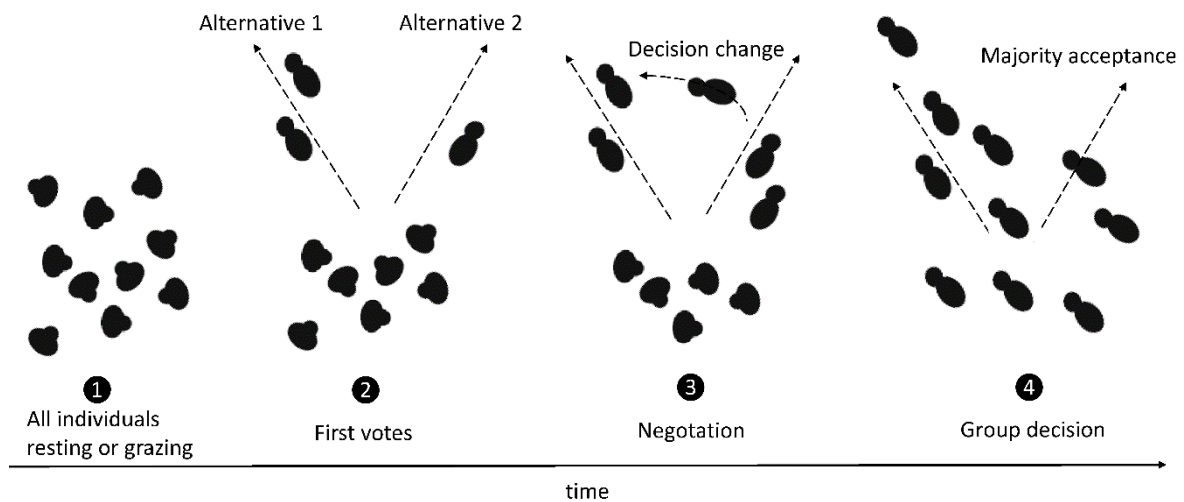
283 Current voting systems could also be improved by creating small, independent groups of  
284 randomly selected voters before deliberation and voting. In this context (called mini-  
285 publics), the deliberation phase is crucial to reduce the partisanship bias observed in other  
286 voting methods. If a large crowd (in which a meaningful deliberation cannot take place  
287 because of its size <sup>16</sup>) is structured into such mini-publics, deliberation and social influence  
288 within groups improve the crowd's collective accuracy <sup>96</sup>: averaging consensus decisions is  
289 then significantly more accurate than aggregating the initial independent opinions. Such  
290 settings have proved to provide better and more robust collective decisions in a variety of  
291 contexts <sup>96-98</sup>. This may also be where fission-fusion groups could have an evolutionary  
292 advantage over stable groups: for instance, for the same number of individuals over a  
293 territory, fission-fusion subgroups may more effectively collect resources than one stable  
294 group. However, this hypothesis still needs to be tested empirically.

295 In animals, the spectrum of weight distributions for individual preferences is also quite  
296 broad. Animals have different needs according to their physiological status, different  
297 knowledge about their environment, and different personality types <sup>99</sup>. These variables may  
298 have synergetic effects to determine which individuals will emerge as a leader <sup>100</sup>. Some  
299 species can be classified as despotic, particularly when there is a large difference in  
300 resource-holding potential within a group <sup>101</sup>. In other species, some group members have a  
301 greater weight in group decisions, especially when these individuals possess a greater  
302 knowledge of the environment that can benefit all group members as in elephants <sup>102</sup>,  
303 bonobos <sup>103</sup> or killer whales <sup>104</sup>. Still, mechanisms are at work to allow most if not all group  
304 members to express their preferences. One such mechanism is to attain a specific number of

305 individuals (a quorum) notifying a preference. For example, African buffalo <sup>105</sup>, wild dogs <sup>38</sup>,  
306 hamadryas baboons <sup>106</sup> or Tonkean macaques <sup>107</sup> are reported to use body orientation to  
307 vote and indicate their preferred direction to achieve a consensus on travel direction, while  
308 golden shiners <sup>108,109</sup> or goats <sup>26</sup> achieve consensus of direction by responding to the  
309 movement cues of their neighbours. In voting processes, long negotiation processes happen  
310 during the collective decision to reach a quorum showing implication of theory of mind,  
311 particularly described in primates <sup>35,36,106</sup>. Generally, a voting process to reach a quorum (i.e.,  
312 a majority) in animals is divided in four steps (Figure 3): initially, all animals are resting or  
313 grazing ❶; then, some individuals stand up and indicate with their body posture or  
314 intentional movements their willingness to move in a specific direction ❷; then, group  
315 members enter in a negotiation (or deliberation) process where some individuals try to  
316 influence others ❸; eventually, all individuals move in the same direction according to the  
317 majority choice ❹. Once this quorum is reached, the probability of deciding for the  
318 proposed alternative sharply shifts, leading to a group consensus. However, supermajority  
319 quorums could be used by a minority to maintain the status quo, without aiming at finding a  
320 consensus. As already mentioned, such an attitude could be identified by detection  
321 algorithms of non-cooperative behaviour, which could then reduce the weight of this  
322 uncooperative minority in the calculation of the consensus degree <sup>64</sup>. A functionally similar  
323 mechanism is present in bees searching for new nests: scouts that indicate a potential nest  
324 decrease the intensity of their dance each time they return to the hive, causing scouts that  
325 found a poorer quality nest to stop dancing faster <sup>110</sup>. Quorum decisions are used to manage  
326 competing needs and information in order to decrease decision errors <sup>95,111</sup>. This solution to  
327 a collective problem can work without needing high cognitive capacities: much of these  
328 collective decisions are the result of relatively simple interaction patterns among group



329 members but not only. Sometimes very high cognitive capacities are involved, but this does  
 330 not change the implication of self-organised rules. Self-organisation principles also rule  
 331 collective decisions in species with high cognitive abilities as primates <sup>112</sup>. In this context,  
 332 group size does not influence behavioural or communication processes involved in the  
 333 collective processes, the system just switches from global to local communication, which  
 334 means that group members do not have a full perception of what happens in the group, but  
 335 they do not need it to decide, as local perception is sufficient <sup>41</sup>. Voting systems in bees,  
 336 macaques or bison are not so different even if species differ in social organisation or  
 337 cognitive capacities. In such 'self-organising systems', multiple individuals following simple  
 338 rules can produce complex collective behaviours without requiring high abilities at the  
 339 individual level <sup>93,113</sup>, which is of great relevance for AI systems used in voting systems.



340

341 Figure 3. Steps of a voting process in animals

342

343 Overall, many studies confirmed that the DDM with a quorum threshold seems to be more  
 344 efficient than simple majority voting. Another difference between collective decisions in  
 345 humans and non-human animals is that the latter do not elect representatives like humans  
 346 do, but decide together throughout the day, as a **participatory democracy**. Besides, non-

347 human animals typically take decisions for short-term aims (those that will occur within  
348 minutes or hours after the decision). There are many multilevel animal societies in which  
349 some individuals have more influence than others at different organisation levels.  
350 Importantly, having a greater weight in the decision does not mean that they are the sole  
351 decision makers. This looks like the participatory democracy (or shared consensus) that  
352 many human citizens request today and seems to be more efficient than a monopolised  
353 leadership (unshared consensus). For instance, in Switzerland, there are seven Councillors  
354 who are indirectly representative of the population but the citizens are invited to vote on  
355 various issues several times a year, which can be done by mail. So, this system can also work  
356 for large sample size and AI can help to pool these votes and avoid errors. However, the  
357 consensus type also depends on the population homogeneity in terms of needs and  
358 knowledge <sup>85,114</sup>. How to take into account different needs and different knowledge of  
359 citizens is of matter and will be developed in the next sections.

360

### 361 **The needs of citizens**

362 Decision makers within a group vary in terms of needs, goals and preferences. Therefore,  
363 choosing an alternative generally only satisfies individuals who vote for this alternative.  
364 Arrow's impossibility theorem stipulates that there is no way to always aggregate all  
365 individual choices within one voting system. However, when within-group choices become  
366 more aligned, as in emergency or wars, more cohesive or coercive systems may become  
367 more acceptable. The current COVID-19 sanitary situation leads us, for example, to accept  
368 coercive decisions such as lockdowns and closures of establishments that are not accepted  
369 in other situations. Previous theoretical studies worked on this homogeneity concept <sup>85,114</sup>:  
370 when animals or humans all have the same needs, there is no issue about preferences

371 pooling and a single leader system is more viable as all individuals are satisfied and the  
372 decisions are taken more rapidly than those made using democratic systems, which require  
373 participants to vote. This is an auto-emergent dictatorship<sup>114</sup>. Collective decision-making in  
374 the non-human animal world cannot escape the notion of dominance. However, true  
375 despotic societies are rare in animal societies, as they are typically not evolutionarily stable  
376 due to the diversity of group members<sup>114</sup>. Aggressive and coercive leaders are strongly  
377 disfavoured<sup>115</sup>. It is clear that this system is not viable when group members differ in their  
378 physiological and social needs and preferences. Moreover, models, confirmed by empirical  
379 data<sup>101</sup>, show that the system collapses if the despot disappears, and a wrong decision taken  
380 by the despot may have strong negative consequences for all individuals<sup>85,114,116</sup>. Conradt  
381 and Roper's model<sup>85</sup> indicates that democratic decisions can evolve when groups have a  
382 heterogeneous composition, but the higher the heterogeneity, the harsher the conflicts and  
383 the more unlikely the conflict resolution. From an evolutionary perspective, animal societies  
384 have managed to resolve these conflicts of interest by giving all members the opportunity to  
385 participate in daily decisions (i.e., to have a say in agenda-setting) but to different extents.  
386 Although dominant individuals can take the role of leader in African wild dogs<sup>38</sup>, meerkats<sup>37</sup>  
387 and baboons<sup>101</sup>, they do not have the exclusive right to decide, but simply a greater weight  
388 in the decision<sup>88</sup>. The alternating of leadership roles among animals can ensure the  
389 expression of individual needs<sup>117</sup>. In this way, voters maintain the leadership purposefully,  
390 which implicitly downplays the social and environmental conditions underlying  
391 egalitarianism<sup>118,119</sup>. Indeed, true egalitarianism may lead to a very long decision time or  
392 even to an absence of consensus. Even if the needs of group members are different,  
393 leadership allows a better group coordination but does not permit other members to  
394 express their intentions. Indeed, in larger human and non-human groups, group members

395 may willingly give leaders greater leeway to make decisions, in view of the functional  
396 benefits of leader-follower relationships in such contexts <sup>115</sup>. For a fully functioning  
397 democracy, some researchers in political science favour a switch from participatory  
398 democracy to deliberative democracy <sup>16,120</sup>. In deliberative human democracies, it is crucial  
399 to allow every citizen to express themselves freely, with a seamless interface between this  
400 public space and the empowered space <sup>121</sup> and to have an equal right to participate in the  
401 public debate, even outside of the electoral process <sup>16</sup>. For instance, the European  
402 Commission regularly launches public consultations to which all stakeholders, including  
403 unions or NGOs, can contribute.

404 In animal groups, leadership can respect the needs of different individuals in a number of  
405 ways. First, the generality dimension of leadership allows it to be split into various sub-  
406 domains <sup>115</sup>. For example, dominant meerkat individuals fight fiercely to secure a  
407 disproportionate share of the reproductive output <sup>122</sup>, but are much less assertive when the  
408 group has to take decisions about changes in daily activities <sup>37,117,123</sup>. Second, the alternating  
409 of leadership roles amongst group members can ensure the expression of individual needs  
410 and leadership. Indeed, studies in sticklebacks <sup>124</sup> and meerkats <sup>117</sup> show that individuals  
411 with conflicting information take turns in leading the group to their respective favourite  
412 location. Another issue with leadership is that it does not safeguard against profiteers  
413 becoming leaders. Humans elect people who propose an electoral platform but who may  
414 want to be leaders for their personal gain and not for the public good. Leaders can be  
415 described as individuals who have a disproportionate level of influence and decision-making  
416 power within their communities, and can distort social relationships to their advantage  
417 <sup>23,119,125</sup>. Even in non-human animals, leaders shape social dynamics through policing <sup>126</sup> or  
418 by embodying culturally appropriate behaviour <sup>127</sup>. In return, leaders are often rewarded

419 with privileges<sup>101,126</sup>. Hence, leadership itself is a frequently contested resource that  
420 individuals compete to obtain and/or maintain. This issue may concern humans<sup>128</sup> and some  
421 vertebrates with theory of mind (see a discussion about Machiavellian intelligence in  
422 primates<sup>129</sup>), but is absent in species such as ants. Machiavellian Intelligence also applies in  
423 the context of strategic votes, which is quite difficult to measure in animals even if studies  
424 on private versus social information may give some cues about decision-making processes<sup>28</sup>.  
425 Are human leaders alpha individuals in a dominance hierarchy<sup>115</sup>? When we look at  
426 presidents or monarchs, this appears to be quite plausible. Work in psychology showed that  
427 dominant appearance traits are chosen by voters in absence of more political information  
428<sup>130,131</sup>. Current knowledge in animal and artificial decision-making can help our societies  
429 improve their public decision-making systems and can provide insight about institutional and  
430 electoral design to select the most appropriate candidates for the offices.

431

### 432 **The knowledge on which citizens base their decisions**

433 Knowledge is important to decide which alternative to vote for. Whilst there is a huge work  
434 on this domain in political science<sup>132,133</sup>, only a few scholars grasped the potential  
435 contribution of animal studies to this field<sup>48,134</sup>. Humans and non-human animals have two  
436 ways to access information: learning by themselves and/or learning from others<sup>28,47</sup>. The  
437 most obvious constraint on majority rules for questions having a correct answer is that the  
438 majority of informants the group relies on need to be right<sup>95,135</sup>. In eusocial insects, groups  
439 seem to identify the best information: even though very few individuals actually possess  
440 relevant information regarding the decision at hand, decisions are still efficient with a mix  
441 between private and social information<sup>28</sup>. In many cases, individuals check and compare  
442 their private and social information before making a decision. Yet we currently observe in

443 human societies many fake news or misinformation voluntarily spread to influence votes for  
444 representatives<sup>12,13</sup>. Misinformation is a clear threat to private and social learning as they  
445 drive the majority towards a non-efficient decision that is beneficial to the group of  
446 manipulators. Many AI algorithms try to identify fake news, particularly during election  
447 periods<sup>8,136,137</sup>.

448 To comply with the Condorcet theorem, votes should be independent from each other.  
449 However, the heavy reliance on social information in humans is at odds with this  
450 assumption. Therefore, trusting others may have consequences at the individual level<sup>138</sup>,  
451 but also at the group level. At the individual level, this is what Amartya Sen called the  
452 'capability to vote': although it is good to vote, it is better when one has the knowledge to  
453 vote well<sup>139</sup>, meaning to be sure to have all the information for each alternative in order to  
454 make a choice representative of one's needs. At the group level, the sum of knowledge leads  
455 to the emergence of the 'wisdom of crowds' for humans and 'swarm intelligence' for non-  
456 human animals<sup>48,140</sup>, both of which sometimes fail<sup>31,138,141</sup>. As already mentioned, several  
457 vote-pooling mechanisms can efficiently improve outcome accuracy, both when voters  
458 cannot communicate<sup>97,98</sup> and when communication is allowed<sup>96</sup>. Theoretical and empirical  
459 works suggest that collective decisions can be more accurate than individual decisions.  
460 However, homogeneity of individual traits may lead to non-efficient collective decisions<sup>142</sup>  
461 as group members all search for or have the same information and needs reinforcing the  
462 probability to take wrong decisions, whilst diversity of individual traits conducts to diversity  
463 of information and diversity of alternatives. In fish, social insects, birds and humans, two or  
464 more individuals independently collect information that is processed through social  
465 interactions, providing a solution to a cognitive problem that is not available to single  
466 individuals<sup>48</sup>. Different studies have attempted to identify who should be trusted and which

467 decision is the best when faced with the choice between one expert and ten non-experts.  
468 Collective decisions are almost always preferred to individual ones <sup>143,144</sup>. However, it is not  
469 necessary to know who has the best information as the combination of individual behaviours  
470 and social interactions lead to the emergence of effective systems <sup>113</sup>.  
471 Importantly, two phenomena may prevent individuals or algorithms from correctly assessing  
472 a situation: misinformation (or lack of information) and biases. Currently, fake news and  
473 misinformation appears to be on the rise and poses a threat to democracy, particularly when  
474 elected politicians and activist groups interact to relay such news <sup>145</sup>. This type of  
475 misinformation could be mitigated by providing citizens with a better understanding of how  
476 to differentiate between fake and real news. However, sometimes, fake news can also  
477 convince well-informed people through other cognitive mechanisms (confirmation bias,  
478 desirability bias <sup>146</sup>). In such cases, algorithms relying on advanced AI can detect fake news  
479 from real information in social media posts <sup>147</sup> or in video speeches <sup>148</sup> and can propose, as  
480 Twitter, to consider reading a link before sharing it or warn about specific content (violent,  
481 unsure). This better identification also comes from research on animal and human  
482 communication, particularly facial expressions <sup>149,150</sup>.  
483 Nowadays, humans are connected to many other people directly or indirectly through  
484 Facebook and other social media, people who they know as friends or family members or  
485 who they do not know but with whom they share similar interests. These connections form a  
486 social network which can be embedded into the real and the virtual world. Since the  
487 development of these social media, the number of relationships a human has increased,  
488 thus reducing the six degrees of separation <sup>151</sup> to three and half <sup>152</sup>. However, this booming  
489 of relationships may lead to different decision biases. Specific connections in social networks  
490 may lead information that is considered untrue by the majority to be excessively over-

491 trusted by voters who only have access to these connections. This social effect, called the  
492 'majority illusion', is derived from the 'friendship paradox'. It leads individuals to  
493 systematically overestimate the prevalence of a piece of information, manipulating  
494 evidences in the DDM, which may accelerate the spread of fake news and the ultimate  
495 choice of an unsuitable alternative <sup>153,154</sup>. Such so-called 'small world' networks <sup>151</sup> lead to  
496 partial views of the world. To our knowledge, only one study has shown this effect in non-  
497 human animals <sup>155</sup>. This is maybe the most difficult issue to control when trying to take  
498 individual and collective decisions.

499

#### 500 **Future perspectives about using animal and artificial intelligence**

501 Human social adaptations evolved in the context of small hunter-gatherer groups solving  
502 local problems through vocalizations and gestures. Now humans face complex challenges  
503 from pandemics to climate change and communicate on dispersed networks connected by  
504 digital technologies and social media <sup>40</sup>. We are not ready for this, cognitively speaking,  
505 facing numerous biases, but decentralised systems exist in animal societies and we can use  
506 their decision-making processes via AI to increase the efficiency of our collective decisions <sup>40</sup>.  
507 Moreover, AI can also help to predict and understand how people make decisions even at  
508 large scale <sup>156</sup>. Then a strong link in the future research, between human collective decisions,  
509 AI and animal behaviour has to be made.

510 Numerous instances, such as policies on climate change, show that majority voting may lead  
511 to non-efficient collective decisions. We identified several research frameworks that could  
512 enhance the effectiveness of human collective-decision system:

513 1. Animal studies have shown that collective rules evolve to achieve efficient  
514 decisions. Many of these results inspired AI to help reach better democratic decisions.



515 Continuing to think about a diffusion model with an appropriate difference threshold  
516 between alternatives and with an appropriate quorum <sup>89,93</sup> would increase effectiveness of  
517 human systems. We have to create systems in which minorities can attempt different  
518 strategies that search through the solution space. We need to “rethink democracy” not as an  
519 all-or-nothing system <sup>157</sup>, with always opposite alternatives where one wins and one loses  
520 but to build integrative solutions leading to unified societies as defined in deliberative or  
521 open democracies <sup>16</sup>. As Seeley says in *Honeybee Democracy* <sup>27</sup>, “It often pays a group to  
522 *argue* things carefully through to find the best solution to a tough problem” (p. 2). This is  
523 where applying the DDM might be useful to balance between accuracy and speed of the  
524 collective decision.

525           2. A second aim would be to increase participatory and deliberative democracy and  
526 AI helping it. The frequencies and the weights of decisions of each member in non-human  
527 animal groups or in small human groups are much higher than those observed in large  
528 human societies, as these groups decide on a daily basis: non-human animals or hunter-  
529 gatherers appear to hold referendums every day. A more participatory democracy in large  
530 human societies resembling those we observe in animal societies could result in greater  
531 satisfaction of citizens but also more efficient decisions due to a greater accumulation of  
532 knowledge <sup>28,143</sup>. Indeed, from our animal roots, the current decrease in voter turnout is not  
533 surprising, because current voting systems prevent ordinary citizens from participating in  
534 agenda-setting and deliberation phases, two important facets of animal collective decision  
535 making. Agenda-setting should therefore be given back to citizens, for instance via sortition-  
536 based assemblies or mini-publics <sup>16</sup>.

537           3. Third, we need to better understand how our connections affect the quality of  
538 information we get and as a consequence the efficiency of our decisions. The digital age and

539 the rise of social media have accelerated changes to our social systems, with poorly  
540 understood functional consequences. We can gain a better picture of how our individual or  
541 collective decisions are constructed through the study of the real or imaginative links we  
542 make between the information provided by TV, social networks, social media and influential  
543 people <sup>31</sup>. As humans we tend to think that we have control over our decisions and  
544 knowledge, but recent events in elections have shown this to be untrue. Collective  
545 behaviour reveals how large-scale higher-order properties of the group feedback to  
546 influence individual behaviour, which in turn can influence the behaviour of the group, and  
547 so on. Many voting processes are self-organized in the animal kingdom and we should admit  
548 that this is also the case in humans <sup>31,111</sup>.

549

#### 550 **Concluding remarks**

551 Identifying these animal collective solutions shaped by selection over millions of years and  
552 implementing them into AI algorithms devoted to democracy is likely to increase the stability  
553 of our political systems in achieving larger consensus and reducing polarization. However, AI  
554 can also be dangerous <sup>146,148</sup> and several scientists appeal to more and more develop the  
555 research field in AI ethics <sup>158-160</sup>. More research on efficient collective decisions in algorithms  
556 and animals has to be done focusing on the outcomes and their effectiveness. Indeed,  
557 humans are limited by their cognitive capacities, some biases and their mental dimensions,  
558 leading to higher polarization of societies and mental block to think about new voting  
559 systems. As animals do not think as we do, behavioural experiments on multiple species and  
560 modelling can help to get out of these human dimensions, and to find new ones <sup>161,162</sup>. This  
561 could improve humanity and yield novel bioinspired technologies.

562

563 **Glossary**

564 **Agenda-setting:** Ability to participate in the definition of the issues and/or options open to a  
565 vote.

566 **Artificial intelligence:** Set of algorithms and processes enabling artificial agents to perceive  
567 their environment or to process data in order to respond in an optimised way to a given  
568 problem.

569 **Condorcet's jury theorem:** The Condorcet's jury Theorem implies that the choice made by a  
570 group using the majority voting rule will be better than the individual choices of the  
571 members of that group, provided that the members of the group have more than a 1 in 2  
572 chance of being correct. One of its postulates is that individuals can only make one type of  
573 mistake, which is not always true.

574 **Condorcet winner criterion:** The Condorcet criterion for a voting system is that it chooses  
575 the beats-all winner when one exists.

576 **Decision ecology:** Concept encompassing all dimensions influencing decision making. It takes  
577 the types of error individuals do as the starting point for understanding decision-making and  
578 suggests that decisions need to be understood within their context.

579 **Deliberative democracy:** Form of democracy in which deliberation and negotiation are  
580 central to decision-making. It adopts elements of both consensus decision-making and  
581 majority rule.

582 **Drift-Diffusion Model:** The DDM stipulates that a choice should be made as soon as the  
583 difference between the evidence (information) supporting the winning alternative (drift 1)  
584 and the evidence supporting the losing alternative (drift 2) exceeds a threshold. The DDM  
585 implements a test called the sequential probability ratio test which optimizes the speed of  
586 decision-making for a required accuracy.

587 **Efficiency:** In the context of voting, efficiency relies on a decision that maximizes the  
588 difference between the benefits and the costs. These benefits and costs can be measured in  
589 two ways: first, the time to take a decision, which can increase costs if it is too long; second  
590 the representativeness of the decision. Usually, there is a trade-off between the decision  
591 time and the representativeness. This trade-off reflects the decision efficiency<sup>94,163</sup>. Time to  
592 take a decision often reflects the quantity of information or evidence one can get to take a  
593 decision. A short decision time indicates low quantity and quality of information conducting  
594 to higher probability of wrong decision. With efficient decisions, the divide between  
595 competing participants is likely to decrease and such decisions are therefore more likely to  
596 be implemented for longer periods of time<sup>22,120</sup>. As a corollary, efficient decisions are  
597 generally more representative of the diversity of the group<sup>120</sup>.

598 **Evaluative voting:** Each alternative open to voting can be evaluated independently by each  
599 voter. The scale for evaluating alternatives may vary.

600 **Majority voting:** A decision is taken as soon as a number of votes equals to  $(N/2) + 1$  of the  $N$   
601 votes cast.

602 **Median voter theorem:** Proposition relating to direct ranked preference voting put forward  
603 by Duncan Black<sup>164</sup>. It states that if opinions are distributed along a one-dimensional  
604 spectrum, then any voting method which satisfies the **Condorcet winner criterion** will  
605 produce a winner close to the median voter.

606 **Participatory democracy:** Participatory democracy tends to advocate more involved forms  
607 of citizen participation and greater political representation than representative democracy.

608 **Quorum:** Minimum number of group members necessary to observe a drastic change in  
609 group behaviour or to validate a group decision. Majority voting is a special case of quorum.  
610 50% for a quorum makes sense when only two alternatives are proposed, which is rare in

611 animal societies as researchers count all animals even those which do not have opinions.  
612 50% majority is present in humans but removing individuals with no opinion. If we consider  
613 individuals who do not vote or do white vote, the majority does not reach 50%. For instance,  
614 if only 60% of the population vote, then the real quorum is 30% ( $60\% \times 50\%$ ). Sub-majority  
615 quorums refer to cases where the collective decision is taken as soon as a threshold of less  
616 than 50% is reached. Symmetrically, super-majority quorums refer to cases where the  
617 collective decision is taken as soon as a threshold of more than 50% is reached.

618 **Race Model:** The Race Model stipulates that a choice should be made as soon as the  
619 evidence supporting the winning alternative exceeds a threshold.

620 **Representativeness:** State or quality of a decision to be representative of the group or  
621 individual needs according to the level we consider (group or individual).

622 **Self-selection:** Selection mechanism relying on individuals selecting themselves to influence  
623 collective decisions; in humans, self-selection is present in all candidates for elections or  
624 participants in a demonstration; in non-human animals, self-selection is present when  
625 individuals produce signals that are evaluated during the voting process.

626 **Sortition:** Selection mechanism relying on a (stratified) random sampling of participants; in  
627 humans, sortition is a recognised method for producing interpretable opinion polls.

628 **Voting system:** Mechanism by which individual preferences are pooled together in order to  
629 reach a group decision.

630

631 **Twitter accounts:** @cedrisueur, @EspinosaRomain, @KrisAnathema

632

633 **Acknowledgements**

634 We thank Herrade Igersheim, Julien Navarro and José Kobielski for their help about concepts  
635 detailed in this paper.

636

637 **Conflicts of interest**

638 The authors declare no competing interests

639

640 **Authors contribution**

641 CS and CB wrote a first version of the paper. RE and JLD reviewed, commented and  
642 enhanced the different versions. All authors read and agreed with the final version.

643

644 **References**

- 645 1. Arrow, K. J. A difficulty in the concept of social welfare. *J. Polit. Econ.* **58**, 328–346 (1950).
- 646 2. Bergson, A. An Economic Theory of Democracy. (1958).
- 647 3. Enelow, J. M. & Hinich, M. J. A general probabilistic spatial theory of elections. *Public Choice* **61**,
- 648 101–113 (1989).
- 649 4. Hinich, M. J. & Munger, M. C. The dynamics of issue introduction: A model based on the politics
- 650 of ideology. *Math. Comput. Model.* **48**, 1510–1518 (2008).
- 651 5. Riker, W. H. & Ordeshook, P. C. A Theory of the Calculus of Voting. *Am. Polit. Sci. Rev.* **62**, 25–42
- 652 (1968).
- 653 6. Saari, D. G. Complexity and the geometry of voting. *Math. Comput. Model.* **48**, 1335–1356
- 654 (2008).
- 655 7. Baujard, A., Igersheim, H., Lebon, I., Gavrel, F. & Laslier, J.-F. Who’s favored by evaluative
- 656 voting? An experiment conducted during the 2012 French presidential election. *Elect. Stud.* **34**,
- 657 131–145 (2014).
- 658 8. Gunther, R., Beck, P. A. & Nisbet, E. C. “Fake news” and the defection of 2012 Obama voters in
- 659 the 2016 presidential election. *Elect. Stud.* **61**, 102030 (2019).
- 660 9. Van der Straeten, K., Laslier, J.-F. & Blais, A. Vote au pluriel: how people vote when offered to
- 661 vote under different rules. *PS Polit. Sci. Polit.* **46**, 324–328 (2013).
- 662 10. Davenport, C. & Landler, M. Trump administration hardens its attack on climate science. *N. Y.*
- 663 *Times* **27**, (2019).
- 664 11. Jotzo, F., Depledge, J. & Winkler, H. US and international climate policy under President Trump.
- 665 (2018).
- 666 12. Golub, B. & Jackson, M. O. Naive learning in social networks and the wisdom of crowds. *Am.*
- 667 *Econ. J. Microecon.* **2**, 112–49 (2010).
- 668 13. Kurvers, R. H. *et al.* Strategic dishonesty trumps truth-telling in competition for social influence.
- 669 *PsyArXiv Prepr.* (2020) doi:10.31234/osf.io/vpzg5.

- 670 14. Hoerner, J. M. & Hobolt, S. B. Unity in diversity? Polarization, issue diversity and satisfaction  
671 with democracy. *J. Eur. Public Policy* 1–20 (2019) doi:10.1080/13501763.2019.1699592.
- 672 15. Kostelka, F. & Blais, A. The generational and institutional sources of the global decline in voter  
673 turnout. *World Polit.* (2021).
- 674 16. Landemore, H. *Open democracy: reinventing popular rule for the twenty-first century.*  
675 (Princeton University Press, 2020).
- 676 17. Fox, R. L. & Lawless, J. L. To run or not to run for office: explaining nascent political ambition.  
677 *Am. J. Polit. Sci.* **49**, 642–659 (2005).
- 678 18. Tullock, G. *Toward a mathematics of politics.* (Ann Arbor: University of Michigan Press, 1967).
- 679 19. Miller, J. C. A program for direct and proxy voting in the legislative process. *Public Choice* **7**,  
680 107–113 (1969).
- 681 20. Blum, C. & Zuber, C. I. Liquid democracy: potentials, problems, and perspectives. *J. Polit. Philos.*  
682 **24**, 162–182 (2016).
- 683 21. Bachrach, P. & Baratz, M. S. Two faces of power. *Am. Polit. Sci. Rev.* **56**, 947–952 (1962).
- 684 22. List, C., Luskin, R. C., Fishkin, J. S. & McLean, I. Deliberation, single-peakedness, and the  
685 possibility of meaningful democracy: evidence from deliberative polls. *J. Polit.* **75**, 80–95 (2013).
- 686 23. Conradt, L. & Roper, T. J. Consensus decision making in animals. *Trends Ecol. Evol.* **20**, 449–456  
687 (2005).
- 688 24. Boureau, Y.-L., Sokol-Hessner, P. & Daw, N. D. Deciding How To Decide: Self-Control and Meta-  
689 Decision Making. *Trends Cogn. Sci.* **19**, 700–710 (2015).
- 690 25. Bayne, T. *et al.* What is cognition? *Curr. Biol.* **29**, R608–R615 (2019).
- 691 26. Sankey, D. W. E. *et al.* Consensus of travel direction is achieved by simple copying, not voting, in  
692 free-ranging goats. *R. Soc. Open Sci.* **8**, 201128.
- 693 27. Seeley, T. D. *Honeybee democracy.* (Princeton University Press, 2010).
- 694 28. Czaczkes, T. J., Grüter, C., Jones, S. M. & Ratnieks, F. L. Synergy between social and private  
695 information increases foraging efficiency in ants. *Biol. Lett.* **7**, 521–524 (2011).



- 696 29. Buffin, A., Goldman, S. & Deneubourg, J. L. Collective regulatory stock management and  
697 spatiotemporal dynamics of the food flow in ants. *FASEB J.* **26**, 2725–2733 (2012).
- 698 30. Franks, N. R., Dornhaus, A., Fitzsimmons, J. P. & Stevens, M. Speed versus accuracy in collective  
699 decision making. *Proc. R. Soc. Lond. B Biol. Sci.* **270**, 2457–2463 (2003).
- 700 31. Kao, A. B. & Couzin, I. D. Decision accuracy in complex environments is often maximized by  
701 small group sizes. *Proc. R. Soc. Lond. B* **281**, 20133305 (2014).
- 702 32. Burns, A. L. J., Herbert-Read, J. E., Morrell, L. J. & Ward, A. J. W. Consistency of Leadership in  
703 Shoals of Mosquitofish (*Gambusia holbrooki*) in Novel and in Familiar Environments. *PLoS ONE*  
704 **7**, e36567 (2012).
- 705 33. Ward, A. J. W., Herbert-Read, J. E., Sumpter, D. J. T. & Krause, J. Fast and accurate decisions  
706 through collective vigilance in fish shoals. *Proc. Natl. Acad. Sci.* **108**, 2312–2315 (2011).
- 707 34. Reeb, S. G. Can a minority of informed leaders determine the foraging movements of a fish  
708 shoal? *Anim. Behav.* **59**, 403–409 (2000).
- 709 35. Strandburg-Peshkin, A., Farine, D. R., Couzin, I. D. & Crofoot, M. C. Shared decision-making  
710 drives collective movement in wild baboons. *Science* **348**, 1358–1361 (2015).
- 711 36. Sueur, C., Deneubourg, J.-L. & Petit, O. From the first intention movement to the last joiner:  
712 macaques combine mimetic rules to optimize their collective decisions. *Proc. R. Soc. Lond. B*  
713 **278**, 1697–1704 (2011).
- 714 37. Bousquet, C. A. H., Sumpter, D. J. T. & Manser, M. B. Moving calls: a vocal mechanism  
715 underlying quorum decisions in cohesive groups. *Proc. R. Soc. Lond. B* **278**, 1482–1488 (2011).
- 716 38. Walker, R. H., King, A. J., McNutt, J. W. & Jordan, N. R. Sneeze to leave: African wild dogs  
717 (*Lycaon pictus*) use variable quorum thresholds facilitated by sneezes in collective decisions.  
718 *Proc. R. Soc. Lond. B* **284**, 20170347 (2017).
- 719 39. Ramos, A., Petit, O., Longour, P., Pasquaretta, C. & Sueur, C. Collective decision making during  
720 group movements in European bison, *Bison bonasus*. *Anim. Behav.* **109**, 149–160 (2015).

- 721 40. Bak-Coleman, J. B. *et al.* Stewardship of global collective behavior. *Proc. Natl. Acad. Sci.* **118**,  
722 (2021).
- 723 41. Sueur, C. *et al.* Collective decision-making and fission–fusion dynamics: a conceptual  
724 framework. *Oikos* **120**, 1608–1617 (2011).
- 725 42. Ménard, N. & Vallet, D. Dynamics of fission in a wild Barbary macaque group (*Macaca*  
726 *sylvanus*). *Int. J. Primatol.* **14**, 479–500 (1993).
- 727 43. Henzi, S., Lycett, J. & Piper, S. Fission and troop size in a mountain baboon population. *Anim.*  
728 *Behav.* **53**, 525–535 (1997).
- 729 44. Okamoto, K. & Matsumura, S. Group fission in moor macaques (*Macaca maurus*). *Int. J.*  
730 *Primatol.* **22**, 481–493 (2001).
- 731 45. Manno, T. G., Dobson, F. S., Hoogland, J. L. & Foltz, D. W. Social group fission and gene  
732 dynamics among black-tailed prairie dogs (*Cynomys ludovicianus*). *J. Mammal.* **88**, 448–456  
733 (2007).
- 734 46. Marshall, J. A. Optimal voting in groups with convergent interests. in (2011).
- 735 47. Duboscq, J., Romano, V., MacIntosh, A. & Sueur, C. Social Information Transmission in Animals:  
736 Lessons from Studies of Diffusion. *Front. Psychol.* **7**, (2016).
- 737 48. Krause, J., Ruxton, G. D. & Krause, S. Swarm intelligence in animals and humans. *Trends Ecol.*  
738 *Evol.* **25**, 28–34 (2010).
- 739 49. Dorigo, M., Theraulaz, G. & Trianni, V. Reflections on the future of swarm robotics. *Sci. Robot.*  
740 **5**, eabe4385 (2020).
- 741 50. Hassabis, D., Kumaran, D., Summerfield, C. & Botvinick, M. Neuroscience-Inspired Artificial  
742 Intelligence. *Neuron* **95**, 245–258 (2017).
- 743 51. Zador, A. M. A critique of pure learning and what artificial neural networks can learn from  
744 animal brains. *Nat. Commun.* **10**, 3770 (2019).
- 745 52. Aral, S. & Eckles, D. Protecting elections from social media manipulation. *Science* **365**, 858–861  
746 (2019).

- 747 53. Mezza-Garcia, N. Bio-inspired Political Systems: Opening a Field. in *Proceedings of the European*  
748 *Conference on Complex Systems 2012* (eds. Gilbert, T., Kirkilionis, M. & Nicolis, G.) 785–812  
749 (Springer International Publishing, 2013). doi:10.1007/978-3-319-00395-5\_97.
- 750 54. Rahwan, I. *et al.* Machine behaviour. *Nature* **568**, 477–486 (2019).
- 751 55. Fatima, S., Desouza, K. C., Denford, J. S. & Dawson, G. S. What explains governments interest in  
752 artificial intelligence? A signaling theory approach. *Econ. Anal. Policy* **71**, 238–254 (2021).
- 753 56. Durand, C. *Technoféodalisme - Critique de l'économie numérique*. (Zones, 2020).
- 754 57. Agudo, U. & Matute, H. The influence of algorithms on political and dating decisions. *PLOS ONE*  
755 **16**, e0249454 (2021).
- 756 58. Bond, R. M. *et al.* A 61-million-person experiment in social influence and political mobilization.  
757 *Nature* **489**, 295–298 (2012).
- 758 59. Jones, J. J., Bond, R. M., Bakshy, E., Eckles, D. & Fowler, J. H. Social influence and political  
759 mobilization: Further evidence from a randomized experiment in the 2012 U.S. presidential  
760 election. *PLoS One* **12**, e0173851 (2017).
- 761 60. Levin, H. A. & Friedler, S. A. Automated congressional redistricting. *J. Exp. Algorithmics* **24**, 1–24  
762 (2019).
- 763 61. Metcalf, L., Askay, D. A. & Rosenberg, L. B. Keeping humans in the loop: pooling knowledge  
764 through artificial swarm intelligence to improve business decision making. *Calif. Manage. Rev.*  
765 **61**, 84–109 (2019).
- 766 62. Perez, O. Collaborative e-rulemaking, democratic bots, and the future of digital democracy.  
767 *Digit. Gov. Res. Pract.* **1**, 1–13 (2020).
- 768 63. Merz, N., Regel, S. & Lewandowski, J. The Manifesto Corpus: a new resource for research on  
769 political parties and quantitative text analysis. *Res. Polit.* **3**, 2053168016643346 (2016).
- 770 64. Ding, R.-X. *et al.* Large-scale decision-making: characterization, taxonomy, challenges and  
771 future directions from an artificial intelligence and applications perspective. *Inf. Fusion* **59**, 84–  
772 102 (2020).

- 773 65. Landemore, H. & Page, S. E. Deliberation and disagreement: problem solving, prediction, and  
774 positive dissensus. *Polit. Philos. Econ.* **14**, 229–254 (2015).
- 775 66. Duan, Y., Edwards, J. S. & Dwivedi, Y. K. Artificial intelligence for decision making in the era of  
776 Big Data – evolution, challenges and research agenda. *Int. J. Inf. Manag.* **48**, 63–71 (2019).
- 777 67. El Emam, K., Mosquera, L. & Hoptroff, R. *Practical synthetic data generation: balancing privacy  
778 and the broad availability of data.* (O’Reilly Media, 2020).
- 779 68. Rankin, D. *et al.* Reliability of supervised machine learning using synthetic data in health care:  
780 model to preserve privacy for data sharing. *JMIR Med. Inform.* **8**, e18910 (2020).
- 781 69. Lane, J. *Democratizing our data: a manifesto.* (MIT Press, 2020).
- 782 70. Fast, E. & Horvitz, E. Long-term trends in the public perception of artificial intelligence. *ArXiv  
783 Prepr.* arXiv:1609.04904 (2016).
- 784 71. Lobera, J., Fernández Rodríguez, C. J. & Torres-Albero, C. Privacy, values and machines:  
785 predicting opposition to artificial intelligence. *Commun. Stud.* **71**, 448–465 (2020).
- 786 72. Jensen, P. *Your life in numbers: modeling society through data.* (Copernicus, 2021).
- 787 73. Summers, K. The evolutionary ecology of despotism. *Evol. Hum. Behav.* **26**, 106–135 (2005).
- 788 74. Hemelrijk, C. K. An individual-orientated model of the emergence of despotic and egalitarian  
789 societies. *Proc. R. Soc. Lond. B* **266**, 361–369 (1999).
- 790 75. Chapais, B. Alliances as a means of competition in primates: Evolutionary, developmental, and  
791 cognitive aspects. *Am. J. Phys. Anthropol.* **38**, 115–136 (1995).
- 792 76. Waal, F. de. *Chimpanzee Politics: Power and Sex Among Apes.* (JHU Press, 2007).
- 793 77. King, A., Douglas, C., Huchard, E., Isaac, N. & Cowlshaw, G. Dominance and Affiliation Mediate  
794 Despotism in a Social Primate. *Curr. Biol.* **18**, 1833–1838 (2008).
- 795 78. Hodge, S. J., Manica, A., Flower, T. P. & Clutton-Brock, T. H. Determinants of reproductive  
796 success in dominant female meerkats. *J. Anim. Ecol.* **77**, 92–102 (2008).
- 797 79. Wroblewski, E. E. *et al.* Male dominance rank and reproductive success in chimpanzees, Pan  
798 troglodytes schweinfurthii. *Anim. Behav.* **77**, 873–885 (2009).

- 799 80. Schein, M. W. & Fohrman, M. H. Social dominance relationships in a herd of dairy cattle. *Br. J.*  
800 *Anim. Behav.* **3**, 45–55 (1955).
- 801 81. Kindleberger, C. P. Dominance and Leadership in the International Economy: Exploitation,  
802 Public Goods, and Free Rides. *Int. Stud. Q.* **25**, 242–254 (1981).
- 803 82. Peterson R.O., Jacobs A.K., Drummer T.D., Mech L.D. & Smith D.W. Leadership behavior in  
804 relation to dominance and reproductive status in gray wolves, *Canis lupus*. *Can. J. Zool.* **80**,  
805 1405–1412 (2002).
- 806 83. Sueur, C., MacIntosh, A. J. J., Jacobs, A. T., Watanabe, K. & Petit, O. Predicting leadership using  
807 nutrient requirements and dominance rank of group members. *Behav. Ecol. Sociobiol.* **67**, 457–  
808 470 (2013).
- 809 84. List, C. Democracy in animal groups: a political science perspective. *Trends Ecol. Evol. Pers. Ed.*  
810 **19**, 168–169 (2004).
- 811 85. Conradt, L. & Roper, T. J. Group decision-making in animals. *Nature* **421**, 155–158 (2003).
- 812 86. Sueur, C. & Petit, O. Shared or unshared consensus decision in macaques? *Behav. Process.* **78**,  
813 84–92 (2008).
- 814 87. Pennisi, A. & Giallongo, L. Animal biopolitics: how animals vote. *Int. J. Semiot. Law - Rev. Int.*  
815 *Sémiot. Jurid.* **31**, 491–499 (2018).
- 816 88. King, A. J. & Sueur, C. Where next? Group coordination and collective decision making by  
817 primates. *Int. J. Primatol.* **32**, 1245–1267 (2011).
- 818 89. Bogacz, R. Optimal decision-making theories: linking neurobiology with behaviour. *Trends Cogn.*  
819 *Sci.* **11**, 118–125 (2007).
- 820 90. Ratcliff, R., Smith, P. L., Brown, S. D. & McKoon, G. Diffusion decision model: current issues and  
821 history. *Trends Cogn. Sci.* **20**, 260–281 (2016).
- 822 91. Tavares, G., Perona, P. & Rangel, A. The Attentional Drift Diffusion Model of Simple Perceptual  
823 Decision-Making. *Front. Neurosci.* **11**, (2017).

- 824 92. Pirrone, A., Stafford, T. & Marshall, J. A. When natural selection should optimize speed-  
825 accuracy trade-offs. *Front. Neurosci.* **8**, 73 (2014).
- 826 93. Marshall, J. A. *et al.* On optimal decision-making in brains and social insect colonies. *J. R. Soc.*  
827 *Interface* **6**, 1065–1074 (2009).
- 828 94. Pelé, M. & Sueur, C. Decision-making theories: linking the disparate research areas of individual  
829 and collective cognition. *Anim. Cogn.* **16**, 543–556 (2013).
- 830 95. Marshall, J. A., Kurvers, R. H., Krause, J. & Wolf, M. Quorums enable optimal pooling of  
831 independent judgements in biological systems. *eLife* **8**, e40368 (2019).
- 832 96. Navajas, J., Niella, T., Garbulsky, G., Bahrami, B. & Sigman, M. Aggregated knowledge from a  
833 small number of debates outperforms the wisdom of large crowds. *Nat. Hum. Behav.* **2**, 126–  
834 132 (2018).
- 835 97. Almaatouq, A. *et al.* Adaptive social networks promote the wisdom of crowds. *Proc. Natl. Acad.*  
836 *Sci. U. S. A.* **117**, 11379–113686 (2020).
- 837 98. Kurvers, R. H., Herzog, S. M., Hertwig, R., Krause, J. & Wolf, M. Pooling decisions decreases  
838 variation in response bias and accuracy. *iScience* **24**, 102740 (2021).
- 839 99. Wolf, M. & Weissing, F. J. Animal personalities: consequences for ecology and evolution. *Trends*  
840 *Ecol. Evol.* **27**, 452–461 (2012).
- 841 100. Bousquet, C. A. H., Ahr, N., Sueur, C. & Petit, O. Determinants of leadership in groups of female  
842 mallards. *Behaviour* **154**, 467–507 (2017).
- 843 101. King, A. J., Douglas, C. M. S., Huchard, É., Isaac, N. J. B. & Cowlshaw, G. Dominance and  
844 affiliation mediate despotism in a social primate. *Curr. Biol.* **18**, 1833–1838 (2008).
- 845 102. McComb, K. *et al.* Leadership in Elephants: The Adaptive Value of Age. *Proc. R. Soc. B Biol. Sci.*  
846 **278**, 3270–3276 (2011).
- 847 103. Tokuyama, N. & Furuichi, T. Leadership of old females in collective departures in wild bonobos  
848 (*Pan paniscus*) at Wamba. *Behav. Ecol. Sociobiol.* **71**, 55 (2017).

- 849 104. Brent, L. J. *et al.* Ecological knowledge, leadership, and the evolution of menopause in killer  
850 whales. *Curr. Biol.* **25**, 746–750 (2015).
- 851 105. Prins, H. H. T. *Ecology and behaviour of the African buffalo: social inequality and decision*  
852 *making.* (Springer, 1996).
- 853 106. Kummer, H. *Social Organization of Hamadryas Baboons. A Field Study.* (1968).
- 854 107. Sueur, C., Deneubourg, J.-L. & Petit, O. Sequence of quorums during collective decision making  
855 in macaques. *Behav. Ecol. Sociobiol.* **64**, 1875–1885 (2010).
- 856 108. Herbert-Read, J. E. *et al.* Inferring the rules of interaction of shoaling fish. *Proc. Natl. Acad. Sci.*  
857 **108**, 18726–18731 (2011).
- 858 109. Katz, Y., Tunstrøm, K., Ioannou, C. C., Huepe, C. & Couzin, I. D. Inferring the structure and  
859 dynamics of interactions in schooling fish. *Proc. Natl. Acad. Sci.* **108**, 18720–18725 (2011).
- 860 110. Seeley, T. D. Consensus building during nest-site selection in honey bee swarms: the expiration  
861 of dissent. *Behav. Ecol. Sociobiol.* **53**, 417–424 (2003).
- 862 111. Sumpter, D. J. T. & Pratt, S. C. Quorum responses and consensus decision making. *Philos. Trans.*  
863 *R. Soc. B Biol. Sci.* **364**, 743–753 (2009).
- 864 112. Sueur, C. & Deneubourg, J.-L. Self-Organization in Primates: Understanding the Rules  
865 Underlying Collective Movements. *Int. J. Primatol.* **32**, 1413–1432 (2011).
- 866 113. Couzin, I. D., Krause, J., Franks, N. R. & Levin, S. A. Effective leadership and decision-making in  
867 animal groups on the move. *Nature* **433**, 513–516 (2005).
- 868 114. Sueur, C. Viability of decision-making systems in human and animal groups. *J. Theor. Biol.* **306**,  
869 93–103 (2012).
- 870 115. Smith, J. E. *et al.* Leadership in mammalian societies: emergence, distribution, power, and  
871 payoff. *Trends Ecol. Evol.* **31**, 54–66 (2016).
- 872 116. Hooper, P. L., Kaplan, H. S. & Boone, J. L. A theory of leadership in human cooperative groups. *J.*  
873 *Theor. Biol.* **265**, 633–646 (2010).

- 874 117. Bousquet, C. A. H. & Manser, M. B. Resolution of experimentally induced symmetrical conflicts  
875 of interest in meerkats. *Anim. Behav.* **81**, 1101–1107 (2011).
- 876 118. Van Vugt, M., Hogan, R. & Kaiser, R. B. Leadership, followership, and evolution: some lessons  
877 from the past. *Am. Psychol.* **63**, 182 (2008).
- 878 119. King, A. J. Follow me! I'm a leader if you do; I'm a failed initiator if you don't? *Behav. Processes*  
879 **84**, 671–674 (2010).
- 880 120. Dryzek, J. S. *et al.* The crisis of democracy and the science of deliberation. *Science* **363**, 1144–  
881 1146 (2019).
- 882 121. Dryzek, J. S. & Stevenson, H. Global democracy and earth system governance. *Ecol. Econ.* **70**,  
883 1865–1874 (2011).
- 884 122. Hodge, S. J., Manica, A., Flower, T. P. & Clutton-Brock, T. H. Determinants of reproductive  
885 success in dominant female meerkats. *J. Anim. Ecol.* **77**, 92–102 (2008).
- 886 123. Gall, G. E., Strandburg-Peshkin, A., Clutton-Brock, T. & Manser, M. B. As dusk falls: collective  
887 decisions about the return to sleeping sites in meerkats. *Anim. Behav.* **132**, 91–99 (2017).
- 888 124. Harcourt, J. L., Sweetman, G., Manica, A. & Johnstone, R. A. Pairs of fish resolve conflicts over  
889 coordinated movement by taking turns. *Curr. Biol.* **20**, 156–160 (2010).
- 890 125. Bourjade, M. & Sueur, C. Shared or unshared consensus for collective movement? Towards  
891 methodological concerns. *Behav. Processes* **84**, 648–652 (2010).
- 892 126. Flack, J. C., Girvan, M., De Waal, F. B. & Krakauer, D. C. Policing stabilizes construction of social  
893 niches in primates. *Nature* **439**, 426–429 (2006).
- 894 127. Canteloup, C., Hoppitt, W. & van de Waal, E. Wild primates copy higher-ranked individuals in a  
895 social transmission experiment. *Nat. Commun.* **11**, 1–10 (2020).
- 896 128. Riker, W. H., Riker, W. H. & Riker, W. H. *The art of political manipulation*. vol. 587 (Yale  
897 University Press, 1986).
- 898 129. Whiten, A. & Byrne, R. W. *Machiavellian intelligence II - Extensions and evaluations*. vol. 2  
899 (Cambridge University Press, 1997).



- 900 130. Olivola, C. Y. & Todorov, A. Elected in 100 milliseconds: Appearance-Based Trait Inferences and  
901 Voting. *J. Nonverbal Behav.* **34**, 83–110 (2010).
- 902 131. Alexander, D. & Andersen, K. Gender as a Factor in the Attribution of Leadership Traits. *Polit.*  
903 *Res. Q.* **46**, 527–545 (1993).
- 904 132. Brown, M. B. *Science in democracy: Expertise, institutions, and representation*. (MIT Press,  
905 2009).
- 906 133. Collins, H., Evans, R., Durant, D. & Weinel, M. Introduction: Pluralist Democracy, Populism and  
907 Expertise. in *Experts and the Will of the People* 1–9 (Springer, 2020).
- 908 134. Conradt, L. & List, C. Group decisions in humans and animals: a survey. *Philos. Trans. R. Soc. B*  
909 *Biol. Sci.* **364**, 719–742 (2009).
- 910 135. Mercier, H. & Morin, O. Majority rules: how good are we at aggregating convergent opinions?  
911 *Evol. Hum. Sci.* **1**, e6 (2019).
- 912 136. Ozbay, F. A. & Alatas, B. Fake news detection within online social media using supervised  
913 artificial intelligence algorithms. *Phys. Stat. Mech. Its Appl.* **540**, 123174 (2020).
- 914 137. KAPLAN, A. Artificial intelligence, social media, and fake news: Is this the end of democracy?  
915 *MEDIA Soc.* 149 (2020).
- 916 138. Giraldeau, L., Valone, T. J. & Templeton, J. J. Potential disadvantages of using socially acquired  
917 information. *Philos. Trans. R. Soc. B Biol. Sci.* **357**, 1559–1566 (2002).
- 918 139. Sen, A. K. *The idea of justice*. (Harvard University Press, 2009).
- 919 140. Nagy, M. *et al.* Synergistic Benefits of Group Search in Rats. *Curr. Biol.* **0**, (2020).
- 920 141. Chamley, C. Rational herds. *Camb. Univ. Press Camb.* **3**, 20 (2004).
- 921 142. Jolles, J. W., King, A. J. & Killen, S. S. The role of individual heterogeneity in collective animal  
922 behaviour. *Trends Ecol. Evol.* **35**, 278–291 (2020).
- 923 143. Katsikopoulos, K. V. & King, A. J. Swarm intelligence in animal groups: when can a collective  
924 out-perform an expert? *PLoS ONE* **5**, e15505 (2010).

- 925 144. Kurvers, R. H. *et al.* Boosting medical diagnostics by pooling independent judgments. *Proc. Natl.*  
926 *Acad. Sci. U. S. A.* **113**, 8777–8782 (2016).
- 927 145. Tollefson, J. Tracking QAnon: how Trump turned conspiracy-theory research upside down.  
928 *Nature* **590**, 192–193 (2021).
- 929 146. Lazer, D. M. *et al.* The science of fake news. *Science* **359**, 1094–1096 (2018).
- 930 147. Ozbay, F. A. & Alatas, B. Fake news detection within online social media using supervised  
931 artificial intelligence algorithms. *Phys. Stat. Mech. Its Appl.* **540**, 123174 (2020).
- 932 148. Kaur, S., Kumar, P. & Kumaraguru, P. Deepfakes: temporal sequential analysis to detect face-  
933 swapped video clips using convolutional long short-term memory. *J. Electron. Imaging* **29**,  
934 033013 (2020).
- 935 149. Crivelli, C. & Fridlund, A. J. Facial displays are tools for social influence. *Trends Cogn. Sci.* **22**,  
936 388–399 (2018).
- 937 150. Lisetti, C. L. & Schiano, D. J. Automatic facial expression interpretation: Where human-  
938 computer interaction, artificial intelligence and cognitive science intersect. *Pragmat. Cogn.* **8**,  
939 185–235 (2000).
- 940 151. Milgram, S. The small world problem. *Psychol. Today* **1**, 60–67 (1967).
- 941 152. Edunov, S., Diuk, C., Filiz, I. O., Bhagat, S. & Burke, M. Three and a half degrees of separation.  
942 *Res. Facebook* **694**, (2016).
- 943 153. Jackson, M. O. The friendship paradox and systematic biases in perceptions and social norms. *J.*  
944 *Polit. Econ.* **127**, 777–818 (2019).
- 945 154. Lerman, K., Yan, X. & Wu, X.-Z. The ‘majority illusion’ in social networks. *PLoS ONE* **11**,  
946 e0147617 (2016).
- 947 155. Pasquaretta, C. *et al.* How social network structure affects decision-making in *Drosophila*  
948 *melanogaster*. *Proc. R. Soc. Lond. B* **283**, 20152954 (2016).

- 949 156. Peterson, J. C., Bourgin, D. D., Agrawal, M., Reichman, D. & Griffiths, T. L. Using large-scale  
950 experiments and machine learning to discover theories of human decision-making. *Science* **372**,  
951 1209–1214 (2021).
- 952 157. Bollen, K. A. & Jackman, R. W. Democracy, stability, and dichotomies. *Am. Sociol. Rev.* 612–621  
953 (1989).
- 954 158. Miorandi, D., Maltese, V., Rovatsos, M., Nijholt, A. & Stewart, J. *Social collective intelligence -*  
955 *Combining the powers of humans and machines to build a smarter society.* (Springer, 2014).
- 956 159. Jobin, A., Ienca, M. & Vayena, E. The global landscape of AI ethics guidelines. *Nat. Mach. Intell.*  
957 **1**, 389–399 (2019).
- 958 160. Hagendorff, T. The ethics of AI ethics: An evaluation of guidelines. *Minds Mach.* **30**, 99–120  
959 (2020).
- 960 161. De Waal, F. *Are we smart enough to know how smart animals are?* (WW Norton & Company,  
961 2016).
- 962 162. Meijer, E. *When Animals Speak: Toward an Interspecies Democracy.* (NYU Press, 2019).
- 963 163. Sueur, C., King, A. J., Pelé, M. & Petit, O. Fast and accurate decisions as a result of scale-free  
964 network properties in two primate species. in *Proceedings of the European conference on*  
965 *complex systems 2012* (eds. Gilbert, T., Kirilionis, M. & Nicolis, G.) 579–584 (2013).
- 966 164. Black, D. On the rationale of group decision-making. *J. Polit. Econ.* **56**, 23–34 (1948).
- 967