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

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15

16 **Abstract**

17 **Whilst fundamental to human societies, voting systems can lead to suboptimal decisions,**

18 **as past climate policies demonstrate. Current systems are harshly criticized for the way**

19 **they consider voters' needs and knowledge. Voting is central in human societies but also**

20 **occurs in animal groups mostly when animals need to choose when and where to move. In**

21 **these societies, animals also consider the needs of the group members and rely on the**

22 **expertise of the most knowledgeable. Recent works in artificial intelligence have sought to**

23 **improve decision-making in human groups, sometimes inspired by animals' decision-**

24 **making systems. We discuss here how our societies could benefit from recent advances in**
25 **ethology and artificial intelligence to improve our collective decision-making system.**

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

27 **Rethinking current voting systems**

28 The voting system is a pillar of our societies. However, voting may sometimes lead to
29 suboptimal or non-representative decisions. This was the case with the election of François
30 Hollande in 2012 ¹ and the election of Donald Trump in 2016 ². These two instances illustrate
31 a first issue of our democracies, the Condorcet paradox (Box 1). Besides, society has become
32 more polarised on many issues, due to the massive use of social networks and influencers ^{3,4},
33 while the political supply has not become more diverse. This combination of high
34 polarisation and low political diversity results in a decrease in citizens' satisfaction with
35 democracy ⁵. In addition, Western democracies suffer from low turnout rates (only one out
36 of two European voters took part in the 2019 European elections,
37 <https://www.europarl.europa.eu/election-results-2019/en/turnout/>), which further
38 weakens the political systems. It is therefore essential to find solutions that ensure citizens'
39 acceptance. The issues that may lead to dissatisfaction with elections or referendums can be
40 summarised in three categories: 1. the **voting systems** (see Glossary), 2. the needs of
41 citizens, and 3. the knowledge on which electors base their decisions. Each of these
42 categories could benefit from recent findings in animal and **artificial intelligence (AI)**.

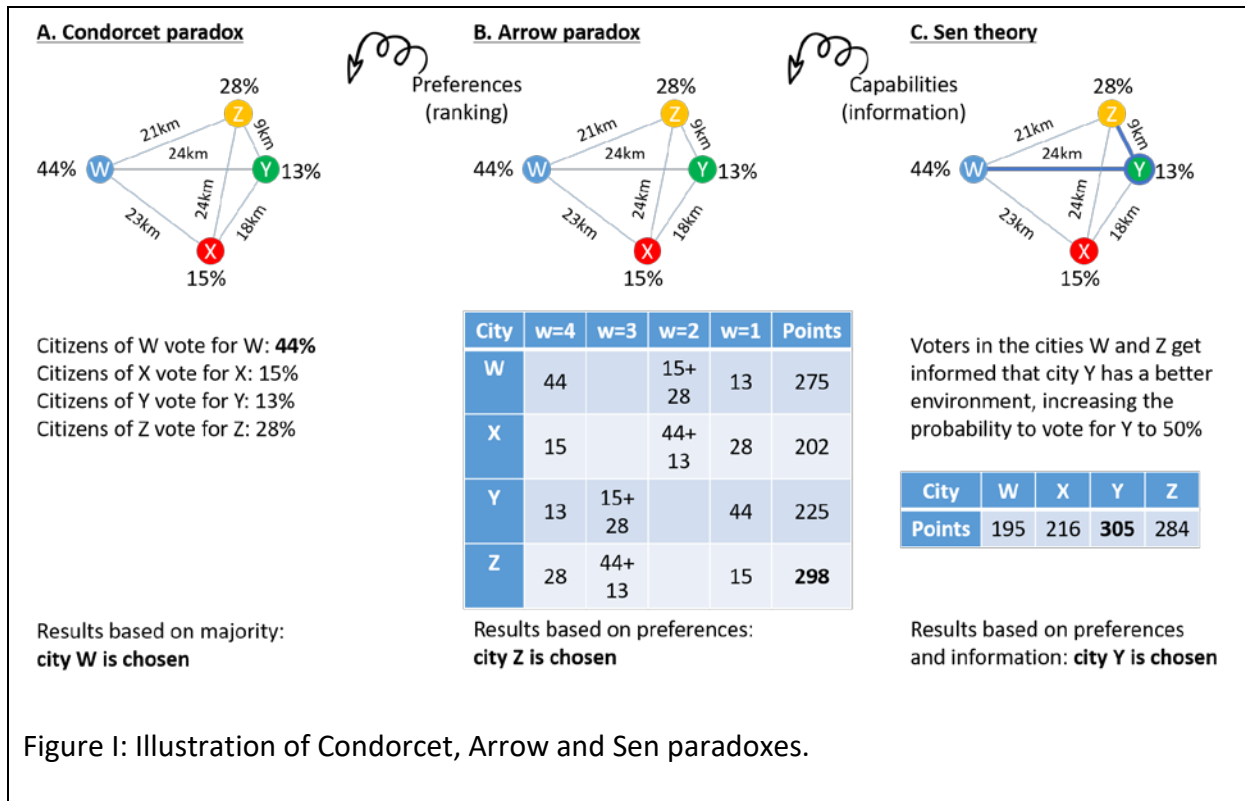
43 Humans are not the only species that use group processes to make important
44 choices. These concepts also exist in other animal societies, in which voting systems are
45 readily used, for instance to decide where to go (Box 2). These decisions can be complex
46 since they involve many (up to thousands) individuals having different needs and
47 information about a complex environment with high conflicts needing resolution and wrong

48 decisions potentially leading to death. Acquiring information is costly, which is why animals
49 often rely on their groupmates to get informed ⁶. By pooling information and needs within
50 the group, these social species seem to solve the paradoxes of majority voting (Box 1), and
51 thus take decisions that ensure group cohesion. Indeed, decision making and rules of
52 interaction are selected for over generations to improve speed and accuracy of decisions
53 and therefore biological fitness of those making such decisions. Because of this strong
54 natural selection increasing the **efficiency** of animal systems, authors call for researches on
55 animal systems to improve the decision-making process in human societies, especially in link
56 with AI ⁷⁻¹¹: bioinspiration for AI may conduct to better understand and control AI behaviour
57 ¹². Nowadays, AI is more and more capable to solve problems of aggregation of individual
58 preferences. Its implementation in human voting processes is now possible, if not inevitable
59 (Box 3). Identifying any similarities and continuities between different species and AI should
60 permit a more unified and informed understanding of group decision-making processes and
61 outcomes in humans and other animals. Whilst it is difficult to know the optimal outcomes
62 in real situations, experimental studies on animals and humans allow assessing this ¹³. This
63 paper seeks to show how animal studies can inspire AI devoted to increase voting system's
64 effectiveness.

65 ***Box 1. Condorcet, Arrow and Sen Paradoxes***

66 The Condorcet paradox (Fig. I.A) stipulates that when asking voters to put four proposals W,
67 Z, X and Y in order of preference, we obtain a cycle (i.e. a majority of participants preferring
68 W to X, a majority preferring X to Y and a majority preferring Y to W). To illustrate this
69 concept, imagine that a new school has to be built and the inhabitants have to choose which
70 of four towns it will be located in (W, X, Y and Z, Fig. I.A). If the referendum has only one
71 round and each citizen votes for his or her own city, city W would be chosen as the location

72 of the new school with 44% of votes. However, if the referendum has two rounds, city W
73 and city Z would make it to the second round, and city Z should be chosen with 56% of votes.
74 If each citizen ranks his or her preferences, we should obtain $W > Z > X > Y$ for city W, $X > Y > W > Z$
75 for city X, $Y > Z > X > W$ for city Y and $Z > Y > W > X$ for city Z. So, whilst W would be chosen for the
76 school in a one-round referendum, Y would be preferred to W three out of four times when
77 dyads are compared. To solve this issue, Arrow proposed classifying proposals instead of
78 choosing the majority. This kind of evaluative vote has been shown experimentally to
79 produce different results from majority voting¹. Here, the top-ranked city receives 4 points
80 (weight w in the table on Fig. I.B), while the second and third-ranked cities receive three and
81 two points respectively. The lowest-ranked study obtains only one point. This ranking system
82 shows city Z to be the chosen location for the school, followed by W, Y and lastly X. Sen (Fig.
83 I.C) considered that although each citizen may have the right to vote, they may not
84 necessarily be able to do so. Sen distinguished the right to vote from the full capability to
85 cast this vote⁶⁷ (Fig. I.C). In Fig. I.C, we presume that citizens were informed that city Y has a
86 better environment (trains and less pollution), and 50% of W and Z citizens preferred their
87 children to go to city Y instead of their own city. In this condition, city Y would be ranked in
88 first position and thus chosen as the location to build the school.



89

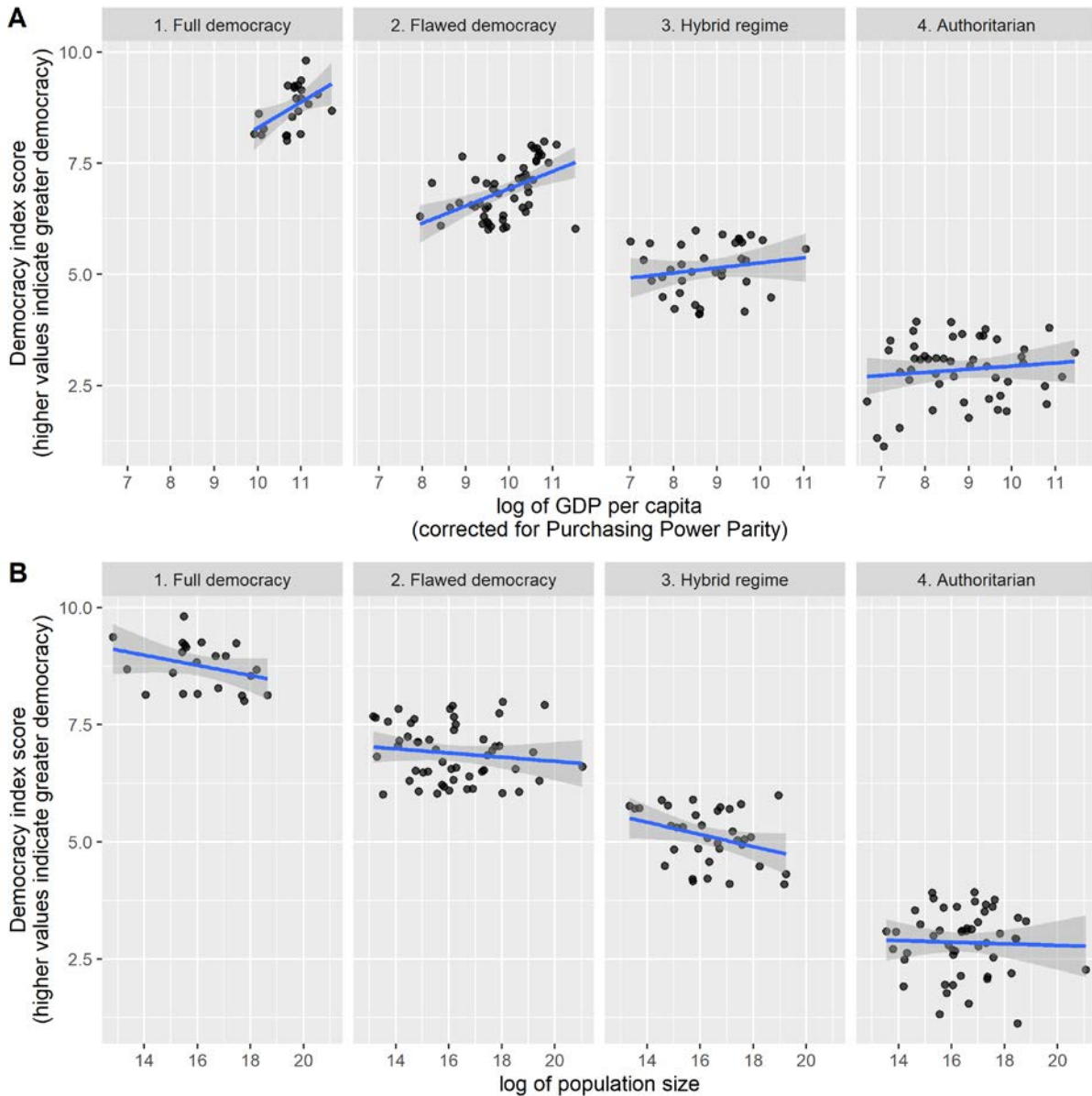
90 Figure I: Illustration of Condorcet, Arrow and Sen paradoxes.

91

92 **The different systems used to aggregate individual preferences**

93 Different systems can be used to aggregate individual preferences, bearing in mind
 94 that heterogeneous preferences and beliefs hinder conflict resolution. Human political
 95 systems range from authoritarian regimes to full democracies, depending on the distribution
 96 of weights for each individual in society (Fig. 1). Authoritarian regimes are more likely to
 97 emerge and sustain themselves if the despots manage to secure a relative advantage in
 98 fighting ability^{14,15}. In democracies, the most commonly used representation system is the
 99 voting system with majority voting. For this system to be efficient, members of the majority
 100 should be competent and benevolent¹⁶. Furthermore, voters' opinions should be formed
 101 independently, without influence¹⁶. However, many voting cases in history have shown that
 102 these assumptions are not met in practice, leading to suboptimal decisions or ineffective
 103 leadership for our societies. This is why some political researchers recommend banning
 104 polls, which lead to a change in voter behaviour known as the "bandwagon effect"¹⁷ and are

105 criticised because they are flawed in many ways¹⁸. Besides, one may question the validity of
 106 a vote and the satisfaction of voters when the relative size of the majority is low. The Brexit
 107 48/52% conundrum is a perfect example¹⁹. However a strong majority (90/10%) also shows
 108 a democracy fallacy²⁰.
 109



110
 111 Figure 1. Relationship of the Democracy Index Score (DIS) (each point represents a country)
 112 with the logarithm of the country's Growth Domestic Product per capita, corrected for
 113 purchasing power parity (A) and the logarithm of the country's population size (B). Within
 114 each regime type, a higher democracy index is more likely when GDP per capita is high
 115 (LMM: 0.19 ± 0.06 , $t = 2.990$, $p < 0.01$) (Fig. 1A). There is also a tendency for countries with
 116 smaller populations to be more democratic (LMM: -0.08 ± 0.05 , $t = -1.692$, $p = 0.09$) (Fig. 1B).

117 The analysis takes into account the overall regime type of the country by adding this variable
118 as a random effect in the model. Data come from the following websites: Democracy Index
119 (<https://www.eiu.com/topic/democracy-index>), GDP
120 (<https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD>) and population size
121 (https://en.wikipedia.org/wiki/List_of_countries_and_dependencies_by_population).
122 Data and analyses script are available at Zenodo. <http://doi.org/10.5281/zenodo.4703733>
123

124

125 This model—where one alternative is chosen until it is more popular than another,
126 however small the difference may be—is called the **Race Model** and was proved to be
127 suboptimal compared to the **Drift-Diffusion Model** (DDM) ^{21–24}. The DDM stipulates that the
128 differences between two alternatives have to reach a threshold and this model, operating in
129 brain and collective decision processes, is far more efficient than the race model ^{25,26}. It is
130 adaptive in urgent situations where decision speed is favoured to accuracy ^{24,26}. This model
131 should replace majority voting in order to solve the issue of proportionality. For instance, the
132 Belgian Parliament chose a two-thirds supermajority quorum ²⁷. This use of different
133 quorums could help to generalise the **Condorcet jury theorem** to a wider range of decision
134 ecologies ²⁸. In decision ecology, individuals are prone to two different types of errors: false
135 positives and false negatives. Yet, in its simplest form, the Condorcet theorem assumes that
136 both errors are identical. When this assumption is relaxed (when the probability of a false
137 positive differs from the probability of a false negative), it can be shown that majority voting
138 becomes suboptimal and should be replaced by sub- or supermajority quorums depending
139 on the conditions ²⁸. Current voting systems could also be improved by creating independent
140 small groups of voters and pooling votes within each group, either by majority rule or
141 another rule. Such settings have proved to provide better and more robust collective
142 decisions in a variety of contexts ^{13,29,30}.

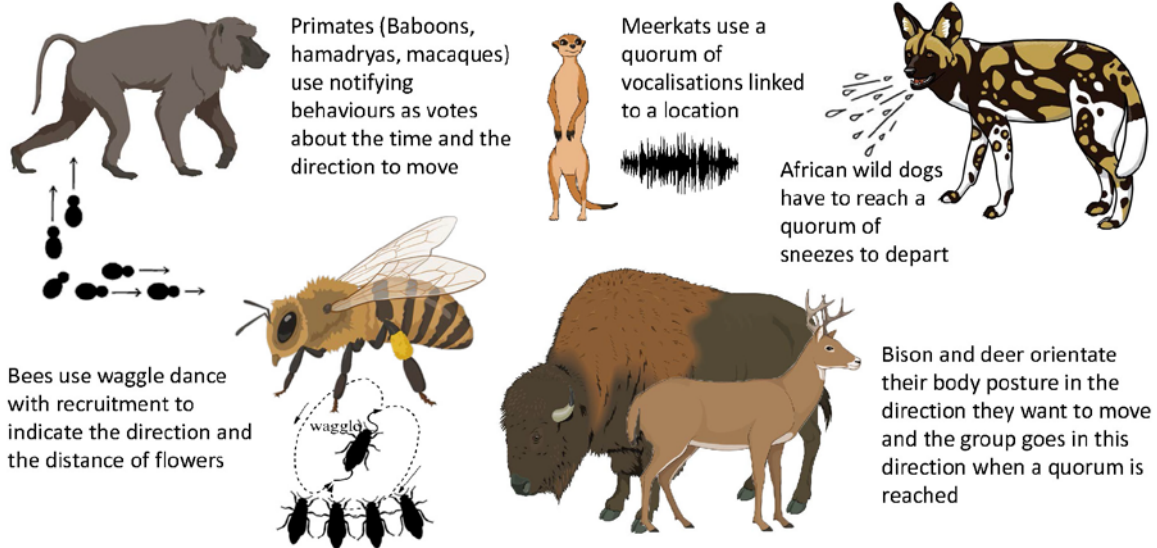
143 In animals, the spectrum of weight distributions for individual preferences is also
144 quite broad. Animals have different needs according to their physiological status, different
145 knowledge about their environment and different personality types³¹. These variables may
146 have synergetic effects to determine which individuals will emerge as a leader³². Some
147 species can be classified as despotic, particularly when there is a large difference in
148 resource-holding potential within a group³³. In other species, some group members have a
149 greater weight in group decisions, especially when these individuals possess a greater
150 knowledge of the environment that can benefit all group members. Still, mechanisms are at
151 work to allow most if not all group members to express their preferences. One such
152 mechanism is to attain a specific number of individuals (a quorum) notifying a preference
153 (Box 2). Once this quorum is reached, the probability of deciding for the proposed
154 alternative sharply shifts, leading to a group consensus. However, supermajority quorums
155 could be used by a minority to maintain the status quo, without aiming at finding a
156 consensus. Such an attitude could be detected by non-cooperative behaviour detection
157 algorithms, which could then reduce the weight of this uncooperative minority in the
158 calculation of consensus degree³⁴. Quorum decisions are used to manage competing needs
159 and information in order to decrease decision errors^{28,35}. This solution to a collective
160 problem can work without needing high cognitive capacities: much of these collective
161 decisions are the result of relatively simple interaction patterns among group members. In
162 such 'self-organising systems', multiple individuals following simple rules can produce
163 complex collective behaviours without requiring high abilities at the individual level^{25,36},
164 which is of great relevance for AI systems used in voting systems.
165

166 **Box 2: Voting behaviours in animals**

167 Living in groups bring many advantages but animals have to resolve conflict of interests to
168 maintain their cohesion and these advantages, through collective decisions. These conflicts
169 of interests might be on needs of individuals as in primate groups or on information about
170 different sites as in honeybees swarming⁸⁹. Whilst animals do not elect president (but see⁹⁰
171 to choose the dominant male in an animal society), they use democratic systems in their
172 everyday life^{40,86,91}. Non-human animals do not have the sophisticated language capacity of
173 humans but this does not mean that they cannot deliberate and negotiate over different
174 alternatives and vote for them^{40,49,91,92}. Group decision-making is common in the animal
175 kingdom, and occurs in social insects, fish and mammals (Fig. II). Recent empirical studies
176 have shown that the decision-making of social species happens through the adoption of
177 symbolic systems for consensus construction (vocalisations, movements of intentions,
178 notifying behaviours and dances)⁴⁵. In ethology, voting means that “an animal
179 communicates its individual preference with regard to the decision outcome”⁵⁰ and the
180 decision is a sign of an “ecological rationality” and intention, the effectiveness of which is
181 assessed over long evolutionary periods. These voting processes are mostly used to decide
182 about where and when to go for foraging or for resting. Whilst it is difficult to find a
183 compromise between two proposed directions, it is possible to satisfy the Condorcet winner
184 criterion with an average of voters about the time to go (i.e. the **mean voter theorem**). Of
185 course, this does not mean that these species have the same mental states as humans but
186 their behaviours suggest certain cognitive capabilities as degrees of theory of mind^{93,94}.
187 Quorum decisions, which include the majority vote as a particular case, allow the
188 maintenance of group cohesion, the enhancement of decision accuracy compared with
189 single individuals, and improved decision speed³⁵. Whilst the quorum number might be

190 quite low (three in capuchin monkeys ⁹⁵ or meerkats ⁴⁴, or about 30% of the group in deer ⁵⁰
191 or macaques ⁴⁹), it generally represents the most pressing needs and information for at least
192 some members of the society.

193



194

195 Figure II: Species showing these different voting behaviours, specifically primates ^{49,99},
196 meerkats ⁴⁴, African wild dogs ⁴³, honeybees ⁸⁶, bison ¹⁰⁰ and deer ⁵⁰.

197

198 Indeed, humans benefit from a number of recent advances in AI to improve voting
199 systems (Box 3). The first example is an algorithm developed to counter electoral
200 gerrymandering by creating electoral districts that are representative of the global
201 population ³⁷. Another perspective is the integration of principles derived from collective
202 animal processes into AI algorithms ³⁸. A third approach that requires a democratic debate
203 makes it technically possible for citizens to be represented by avatars reflecting the
204 preferences of each voter rather than by politicians ³⁹.

205 Overall, many studies confirmed that the DDM with a quorum threshold seems to be
206 more efficient than simple majority voting. Another difference between collective decisions
207 in humans and non-human animals is that the latter do not elect representatives like
208 humans do, but decide together throughout the day, as a **participatory democracy**. Besides,
209 non-human animals typically take decisions for short-term aims (those that will occur within
210 minutes or hours after the decision). There are many multilevel animal societies in which
211 some individuals have more influence than others at different organisation levels.
212 Importantly, having a greater weight in the decision does not mean that they are the sole
213 decision makers. This looks like the participatory democracy (or shared consensus) that
214 many human citizens request today and seems to be more efficient than a monopolised
215 leadership (unshared consensus), but the consensus type depends on the population
216 homogeneity in terms of needs and knowledge ^{40,41}.

217

218 **The needs of citizens**

219 Decision makers within a group vary in terms of needs, goals and preferences.
220 Therefore, choosing an alternative generally only satisfies individuals who vote for this
221 alternative. Arrow's impossibility theorem stipulates that there is no way to always
222 aggregate all individual choices within one voting system. However, when within-group
223 choices become more aligned, as in emergency or wars, more cohesive or coercive systems
224 may become more acceptable. Previous theoretical studies worked on this homogeneity
225 concept ^{40,41}: when animals all have the same needs, a single leader system is more viable as
226 all individuals are satisfied and the decisions are taken more rapidly than those made using
227 democratic systems, which require participants to vote. This is an auto-emergent
228 dictatorship ⁴¹. However, it is clear that this system is not viable when group members differ

229 in their physiological and social needs and preferences. Moreover, models, confirmed by
230 empirical data³³, show that the system collapses if the despot disappears, and a wrong
231 decision taken by the despot may have strong negative consequences for all individuals^{40–42}.
232 Conradt and Roper's model⁴⁰ indicate that democratic decisions can evolve when groups
233 have a heterogeneous composition. The higher the heterogeneity, the harsher the conflicts
234 and the more unlikely the conflict resolution. From an evolutionary perspective, animal
235 societies have managed to resolve these conflicts of interest by giving all members the
236 opportunity to participate in daily decisions but to different extents. Although dominant
237 individuals can take the role of leader in African wild dogs⁴³, meerkats⁴⁴ and baboons³³,
238 they do not have the exclusive right to decide, but simply a greater weight in the decision⁴⁵.
239 The alternating of leadership roles among animals can ensure the expression of individual
240 needs⁴⁶. For a fully functioning democracy, some researchers in political science favour a
241 switch from participatory democracy to **deliberative democracy**^{20,47}. In deliberative human
242 democracies, it is crucial to allow every citizen to express themselves freely, with a seamless
243 interface between this public space and the empowered space⁴⁸ and to have an equal right
244 to participate in the public debate, even outside of the electoral process⁴⁷. For instance, the
245 European Commission regularly launches public consultations to which all stakeholders,
246 including unions or NGOs, can contribute.

247 A parallel with deliberative democracy can be drawn in animal societies in such a way
248 that the preferences of almost all members are also taken into account through the
249 expression of notifying behaviours (Box 2). Choices are not only based on the number of
250 voters but also on the number of voting behaviours per individual, a cue about motivation
251^{43,45,49}. An individual may show several notifying behaviours as if it could vote several times
252 or have a vote with a higher weight than other individuals. Through these notifying

253 behaviours, animals negotiate, change their mind and reach a consensus ⁴⁹. This type of
254 decision-making is in accordance with the Borda count, an election method in which voters
255 rank options in order of preference (Box 1).

256 Another issue with leadership is that it does not safeguard against profiteers
257 becoming leaders. Humans elect people who propose an electoral platform but who may
258 want to be leaders for their personal gain and not for the public good. Leaders can be
259 described as individuals who have a disproportionate level of influence and decision-making
260 power within their communities, and can distort social relationships to their advantage ⁵⁰⁻⁵².
261 Even in non-human animals, leaders shape social dynamics through policing ⁵³ or by
262 embodying culturally appropriate behaviour ⁵⁴. In return, leaders are often rewarded with
263 privileges ^{33,53}. Hence, leadership itself is a frequently contested resource that individuals
264 compete to obtain and/or maintain. This issue may concern humans and some vertebrates
265 with theory of mind (see a discussion about Machiavellian intelligence in Primates ⁵⁵), but is
266 absent in species such as ants. Machiavellian Intelligence also applies in the context of
267 strategic votes, which is quite difficult to measure in animals even if studies on private
268 versus social information may give some cues about decision-making processes ⁵⁶. Are
269 human leaders alpha individuals in a dominance hierarchy ⁵⁷? When we look at our
270 presidents or monarchs, this appears to be quite plausible. Work in psychology showed that
271 dominant appearance traits are chosen by voters in absence of more political information
272 ^{58,59}. Current knowledge in animal and artificial decision-making can help our societies
273 improve their public decision-making systems and can provide insight about institutional and
274 electoral design to select the most appropriate candidates for the offices.

275

276 **The knowledge on which citizens base their decisions**

277 Knowledge is important to decide which alternative to vote for. Whilst there is a huge
278 work on this domain in political science^{60,61}, only a few scholars grasped the potential
279 contribution of animal studies to this field.^{62,63} Humans and non-human animals have two
280 ways to access information: learning by themselves and/or learning from others^{6,56}. The
281 most obvious constraint on majority rules for questions having a correct answer is that the
282 majority of informants the group relies on need to be right^{16,28}. In eusocial insects, groups
283 seem to identify the best information: while very few individuals actually possess relevant
284 information regarding the decision at hand, decisions are still efficient with a mix between
285 private and social information⁵⁶. In many cases, individuals check and compare their private
286 and social information before making a decision. Yet we currently observe in human
287 societies many fake news voluntarily spread to influence votes for representatives^{3,4}. Fake
288 news is a clear threat to private and social learning as they drive the majority towards a
289 suboptimal decision that is beneficial to the group of manipulators. Many AI algorithms try
290 to identify fake news, particularly during election periods^{2,64,65}.

291 To comply with the Condorcet theorem, votes should be independent from each
292 other. However, the heavy reliance on social information in humans is at odds with this
293 assumption. Therefore, trusting others may have consequences at the individual level⁶⁶, but
294 also at the group level. At the individual level, this is what Sen called the ‘capability to vote’
295 (Box 1): although it is nice to vote, it is better when you have the knowledge to vote well⁶⁷.
296 At the group level, the sum of knowledge leads to the emergence of the ‘wisdom of crowds’
297 for humans and ‘swarm intelligence’ for non-human animals^{62,68}, both of which sometimes
298 fail^{66,69,70}. As already mentioned, several vote-pooling mechanisms can efficiently improve
299 outcome accuracy, both when voters cannot communicate^{13,30} and when communication is

300 allowed ²⁹. Theoretical and empirical works suggest that collective decisions can be more
301 accurate than individual decisions (although homogeneity of individual traits may lead to
302 suboptimal decisions ⁷¹). In fish, social insects, birds and humans, two or more individuals
303 independently collect information that is processed through social interactions, providing a
304 solution to a cognitive problem that is not available to single individuals ⁶². Different studies
305 have attempted to identify who should be trusted and which decision is the best when faced
306 with the choice between one expert and ten non-experts. Collective decisions are almost
307 always preferred to individual ones ^{72,73}. However, it is not necessary to know who has the
308 best information as the combination of individual behaviours and social interactions lead to
309 the emergence of effective systems ³⁶.

310 Importantly, two phenomena may prevent individuals or algorithms from correctly
311 assessing a situation: misinformation (or lack of information) and biases. In order to fight
312 against misinformation, AI algorithms should be developed to produce consistent, unbiased
313 and privacy-protecting publicly available data ⁷⁴. Currently, fake news appears to be on the
314 rise and poses a threat to democracy, particularly when elected politicians and activist
315 groups interact to relay such news ⁷⁵. This type of misinformation could be mitigated by
316 providing citizens with a better understanding of how to differentiate between fake and real
317 news. However, sometimes, fake news can also convince well-informed people through
318 other cognitive mechanisms (confirmation bias, desirability bias ⁷⁶). In such cases, algorithms
319 relying on advanced AI can detect fake news from real information in social media posts ⁷⁷ or
320 in video speeches ⁷⁸. This better identification also comes from research on animal and
321 human communication, particularly facial expressions ^{79,80}.

322 Specific connections in social networks may lead information that is considered
323 untrue by the majority to be excessively over-trusted by voters who only have access to

324 these connections. This social effect, called the ‘majority illusion’, is derived from the
325 ‘friendship paradox’. It leads individuals to systematically overestimate the prevalence of a
326 piece of information, manipulating evidences in the DDM, which may accelerate the spread
327 of fake news and the ultimate choice of an unsuitable alternative^{81,82}. Such so-called ‘small
328 world’ networks⁸³ lead to partial views of the world. To our knowledge, only one study has
329 shown this effect in non-human animals⁸⁴. This is maybe the most difficult issue to control
330 when trying to take individual and collective decisions.

331 ***Box 3: AI and voting systems***

332 AI can help shaping human voting systems in several ways, from the establishment of fair
333 voting conditions to the integration of artificial voting agents. For instance, by using an
334 algorithm following a divide-and-conquer approach, it is possible to produce electoral
335 districts’ maps that maximise compactness (to ensure geographical continuity) and minimise
336 population deviation (to ensure representativeness)³⁷. By following these two goals, the
337 algorithm avoids gerrymandering, thus providing fairer voting conditions.

338 Representativeness in redistricting and publicly available datasets can also be enhanced by
339 more advanced techniques, such as Natural Language Processing (NLP) and mining of Big
340 Data, to produce consistent, unbiased and privacy-protecting data⁷⁴.

341 When faced with electoral choices, voters sometimes find it difficult to distinguish or rank
342 the positions of different political offers on various issues. Analyses by NLP make it easier to
343 compare the contents of political programmes⁹⁶. This tool provides a more quantitative
344 representation of political programmes, or an easier means to trace the evolution of a
345 party’s positions on a specific topic over time. This leverage could be used to improve the
346 trade-offs among parties between rounds or in combination with evaluative voting¹.

347 Technically, it will soon be possible to create intelligent e-democracy bots that can infer the
348 political preferences of their associated human voter. Such bots could then be allowed to
349 participate in voting processes on the voter's behalf ³⁹. For example, these bots could use
350 NLP to copy the opinion expressed by the politician deemed closest to the voter's position.
351 This controversial topic could allow citizens to express themselves on a wide range of issues.
352 Yet this same technique could reinforce vote manipulation or the abandonment of political
353 life by voters by delegating the expression of their opinions to a bot.
354 By combining human and AI, the Artificial Swarm Intelligence algorithm ³⁸ offers promising
355 results: it performs better than humans-only and machine-only setups on a variety of tasks.
356 The resulting increase in accuracy and acceptance of the collective decision is attributable to
357 the direct involvement of humans in the decision process.
358 This last point underlines the importance of the acceptability of AI by the public. While AI is
359 generally viewed positively by the media ⁹⁷, significant concerns about data protection ⁷⁴ and
360 human employment have recently emerged. Thus, resistance to AI is stronger among those
361 least inclined to innovation and most sensitive to data privacy ⁹⁸.

362

363

364 **Concluding remarks and future perspectives**

365 Numerous instances, such as policies on climate change, show that majority voting
366 fall short and frequently lead to suboptimal collective decisions. We identified several
367 research frameworks enhancing human voting system effectiveness (see Outstanding
368 Questions):

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

371 Continuing to think about a diffusion model with an appropriate difference threshold
372 between alternatives and with an appropriate quorum ^{21,25} would increase effectiveness of
373 human systems. We have to create systems in which minorities can attempt different
374 strategies that search through the solution space. We need to “rethink democracy” not as an
375 all-or-nothing system ⁸⁵, with always opposite alternatives where one wins and one loses but
376 to build integrative solutions leading to unified societies as defined in deliberative
377 democracy. As Seeley says in *Honeybee Democracy* ⁸⁶, “It often pays a group to *argue* things
378 carefully through to find the best solution to a tough problem” (p. 2). This is where applying
379 the DDM might be useful to balance between accuracy and speed of the collective decision.

380 2. A second aim would be to increase participatory and deliberative democracy and
381 AI helping it. The frequencies and the weights of decisions of each member in non-human
382 animal groups are much higher than those observed in human societies, as animal decisions
383 are on a daily basis: non-human animals appear to hold referendums every day. A more
384 participatory democracy resembling those we observe in animal societies could result in
385 greater satisfaction of citizens but also more efficient decisions due to a greater
386 accumulation of knowledge ^{56,72}.

387 3. Third, we need to better understand how our connections affect the quality of
388 information we get and as a consequence the efficiency of our decisions. We can gain a
389 better picture of how our individual or collective decisions are constructed through the study
390 of the real or imaginative links we make between the information provided by TV, social
391 networks, social media and influential people ⁶⁹. As humans we tend to think that we have
392 control over our decisions and knowledge, but recent events in elections have shown this to
393 be untrue. Many voting processes are self-organized in the animal kingdom and we should
394 admit that this is also the case in humans ^{35,69}.

395 Identifying these animals collective solutions shaped by selection over millions of
396 years and implementing them into AI algorithms devoted to democracy is likely to increase
397 the stability of our political systems in achieving larger consensus and reducing polarization.
398 More research on efficient collective decisions in algorithms and animals has to be done
399 focusing on the outcomes and their effectiveness. Indeed, humans are limited by their
400 cognitive capacities, some biases and their mental dimensions, leading to higher polarization
401 of societies and mental block to think about new voting systems. As animals do not think as
402 we do, behavioural experiments on multiple species and modelling can help to get out of
403 these human dimensions, and to find new ones^{87,88}. This could improve humanity and yield
404 novel bioinspired technologies.

405

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

407

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411

412 **Conflicts of interest**

413 The authors declare no competing interests

414

415 **Authors contribution**

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

418

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- 614

615 **Glossary**

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

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

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

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

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

634 **Efficiency:** In the context of voting, optimality relies on a decision that maximizes the
635 difference between the benefits and the costs.

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

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

640 **Mean voter theorem:** proposition relating to direct ranked preference voting put forward by
641 Duncan Black. It states that if opinions are distributed along a one-dimensional spectrum,
642 then any voting method which satisfies the **Condorcet winner criterion** will produce a
643 winner close to the median voter.

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

646 **Quorum:** Minimum number of group members necessary to observe a drastic change in
647 group behaviour or to validate a group decision. Majority voting is a special case of quorum.
648 50% for a quorum makes sense when only two alternatives are proposed, which is rare in animal
649 societies as researchers count all animals even those which do not have opinions. 50% majority is
650 present in humans but removing individuals with no opinion. If we consider individuals who do not
651 vote or do white vote, the majority does not reach 50%. For instance, if only 60% of the population
652 vote, then the real quorum is 30% ($60\% \times 50\%$).

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

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