Swarm intelligence in animals and humans

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Electronic media have unlocked a hitherto largely untapped potential for swarm intelligence (SI; generally, the realisation that group living can facilitate solving cognitive problems that go beyond the capacity of single animals) in humans with relevance for areas such as company management, prediction of elections, product development and the entertainment industry. SI is a rapidly developing topic that has become a hotbed for both innovative research and wild speculation. Here, we tie together approaches from seemingly disparate areas by means of a general definition of SI to unite SI work on both animal and human groups. Furthermore, we identify criteria that are important for SI to operate and propose areas in which further progress with SI research can be made.

Introduction to swarm intelligence

Group living enables animals to solve problems that are difficult or impossible for single individuals to resolve. For instance, individuals in groups can catch larger prey more easily or better protect themselves against predators [1]. The recent exploitation of self-organisation theory (see Glossary) in animal behaviour and the resulting study of collective behaviour has prompted the realisation that group living can also facilitate solving cognitive problems that go beyond the capacity of single animals [2,3]: a phenomenon known as swarm intelligence (SI), a term coined by Gerardo Beni [4]. For instance, there are many examples of SI in social insects [2,3] and slime moulds [5] which demonstrate the ability to make speed versus accuracy tradeoffs in decision making and to negotiate mazes, respectively. The underlying perception in most biological (non-human) case studies (particularly in invertebrates) of SI has been that the individual animal is cognitively relatively simple and restricted in what it can achieve, whereas the group collectively is capable of astonishing feats.

In humans, however, there is not only interindividual variation in cognitive abilities, but there are also some individuals that are high performers by any standard [6]. As a result, one emphasis in psychology has focused on assessing if a group can outperform high-performing individuals and on trying to find the limits of what a group of a given size and composition can collectively achieve. In contrast to the recent arrival of SI in the biological sciences, experimental work by psychologists on decision making in human groups stretches back approximately seven decades [6]. One of the first to point out that individuals can benefit from collective decision making was an 18th-century French mathematician, Nicolas de Condorcet [7]. He assumed that each individual can be either right or wrong with a certain probability p. Provided that $p > 50\%$, the chance of a correct collective decision of the group will increase as a function of group size. However, Condorcet's theorem requires that the individuals that have the correct information are in the majority. Therefore, the theorem has more to do with the means by which consensus decisions are made when a majority already has correct information. In 1907, Galton [8] recognised that SI does not require a majority of people who already know the correct answer (in fact, SI does not require anybody to know the correct answer) and was the first researcher to empirically demonstrate SI in humans.

Glossary

Animal personality: often also called the 'behavioural syndrome', refers to the observation that there are correlations between behaviours in different contexts (e.g. a bold individual behaves boldly in different situations).
Biomimetics: the study of nature in search of principles that can find technological application.
Cognitive ability: mental information-processing ability in connection with problem solving.
Collective behaviour: the mechanistic aspect of grouping; mainly used for self-organised grouping behaviour that is usually characterised by synchronised individuals.
Combinatorics: a branch of pure mathematics concerned with counting the number of ways in which a set of given objects can be arranged.
Confusion effect: following multiple moving prey individuals can cause sensory overload in predators, which results in delaying attacks or in reducing attack success.
Consensus decision: agreement among group members on one course of action.
Encounter-dilution effect: if groups are not detected and attacked in proportion to their size, then grouping can result in a reduced per capita predation risk (provided the predator only kills one prey item per attack).
Many eyes effect: predator vigilance generally increases with group size owing to the fact that more individuals are on the look out.
Prediction market: processing of information obtained from interactions of multiple individuals with the aim of predicting developments.
Quorum: a threshold number of individuals that, once reached, will initiate copying in others.
Self organization: individuals follow local behavioural rules, resulting in organised behaviour by the whole group without the need for global control.
Swarm intelligence: two or more individuals independently collect information that is processed through social interaction and provides a solution to a cognitive problem that is not available to single individuals.

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Previous reviews of SI have focused mainly on animal groups [2,3,9] because the literature on humans usually does not use the term 'SI' (but does use terms such as 'group decision making'). However, the human literature has much to offer on this topic and an integration of the SI work on animal and human groups would help further advance this rapidly developing field. To facilitate integration, we propose a general definition of SI. The term 'SI' is often used very loosely (especially in the media) and a clear definition is missing from the literature. In this context, there has been much speculation on the possibilities of SI but little critical assessment to put it into perspective [10].

Our review has three main aims: (i) to provide a general definition of SI; (ii) to address not only the possibilities but also the limitations of SI; and (iii) to integrate SI work on animal groups and human groups.

A definition of SI

We propose an overarching definition of SI that covers phenomena observed in both animals and humans: two or more individuals independently, or at least partially independently, acquire information and these different packages of information are combined and processed through social interaction, which provides a solution to a cognitive problem in a way that cannot be implemented by isolated individuals.

Essentially, SI is a mechanism that individuals can use to overcome some of their own cognitive limitations. Therefore, owing to individual variation in cognitive abilities in animal (and human) populations, some individuals might solve a cognitive problem only through joining a group and using SI; whereas others might be able to do this alone through insight. Our focus is on the questions of how and when SI is used rather than on the issue of whether SI always provides an exclusive solution to cognitive problems that cannot be solved by single individuals. However, whenever SI enables grouping individuals to solve a cognitive problem, then the way in which this is done (information processing through interaction) is unique to grouping and cannot be implemented by singletons (even if they are capable of solving the problem in other ways). The terminology in the literature can be confusing and different names are applied: such as SI, collective intelligence and collective cognition. We consider these all to be essentially the same phenomena, and refer to them as SI.

What SI is not

The above criteria make clear that (by our definition) not all kinds of grouping and/or collective behaviour should be regarded as evidence of SI. A flock of birds or a crowd of humans in which individuals simply stay together through social attraction are not examples of SI. The fact that animals group and show collective behaviours, including consensus decision making [11,12], only tells us that decisions are made in a social context and that animals have evolved forms of decision making that can result in agreement but are not a conclusive indication of SI. After all, grouping is known to be advantageous for many reasons other than increased cognitive abilities (e.g. reduced predation [1]). It is probable, however, that whenever individuals live in groups, there is a potential for SI. It needs to be evaluated on a case-by-case basis whether and how this potential is utilised (and it will be interesting to re-examine some of the recent work on cockroach collective behaviour [13,14] and human pedestrian behaviour [15] to look for SI evidence). SI is not different in this regard from individual cognition, where criteria such as brain size (relative to body size) and structure might give us some approximate idea of the cognitive potential that animals might have. However, the ultimate test of the abilities of single animals usually comes in the form of the particular types of problem that require a solution.

Possibilities and limitations of SI

Media articles often suggest that SI (or 'the wisdom of the crowds' [10]) could be the answer to every decision-making or forecasting problem in modern society. The difference between areas in which SI can and cannot contribute is, however, easily illustrated by a simple example. At a biomimetics exhibition in Berlin, Germany, we presented the general public with two tasks. In the first problem, following Galton [8], they needed to estimate the number of marbles in a large glass jar. For the second problem, they had to estimate how many times a coin needs to be tossed for the probability that the coin shows heads (and not tails) on all occasions to be roughly as small as that of winning the German lotto. For the first problem, the collective estimate came within 1.5% of the real value (Figure 1): an impressive performance of SI (despite the high variance of the individual guesses). In the second case, however, the collective guess was poor (Figure 1). For a person with a background in combinatorics, this second task involves only a quick calculation that always arrives at the correct answer of 24 coin tosses. Clearly, expert knowledge would be superior here.

An interesting difference is that between imprecision and bias in this context. For the marbles, the individual estimate is imprecise and uncorrelated guesses can result in a close approximation of the real value. In the second case, there is a huge systematic bias preventing useful information extraction. Most real-life problems will have components of both imprecision and bias, and the general rule would be that the greater the imprecision component (relative to the bias component), the greater the potential for SI solutions.

SI overview

The current SI debate suffers from two problems; a lack of clear criteria to recognize SI and confusion over commonalities and differences in human SI and animal SI. Here, we give examples of ways to apply our definition to case studies and we group SI into different categories that make clear where the parallels are between SI in humans and animals. The first category covers cases in which SI is utilized via direct social interactions in both humans and animals; whereas the second category only applies to human cases that involve different forms of electronic information processing for SI purposes.

Direct interaction

Both animal and human groups can gain SI advantages through direct social interactions for a range of cognitive

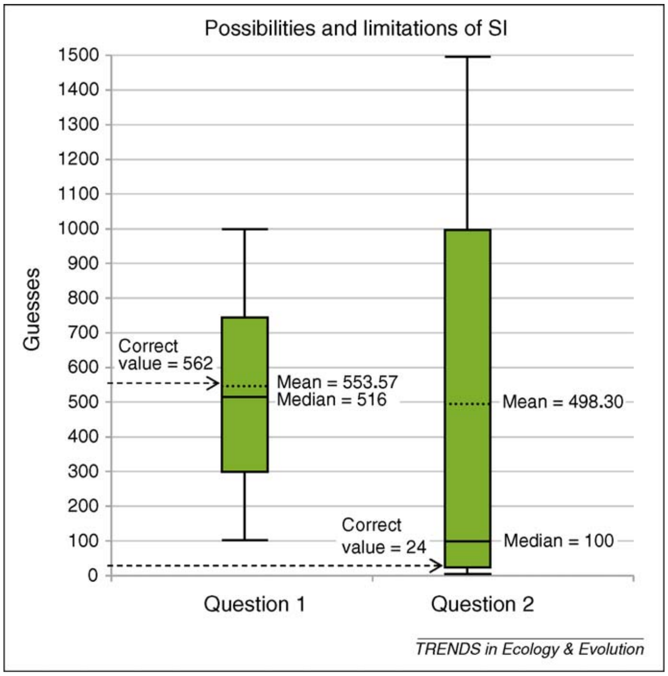

Figure 1. Possibilities and limitations of SI. Members of the public were presented with two questions. The first question was to estimate the number of marbles in a glass jar and the second question was to estimate the number of times a coin needs to be tossed for the probability that the coin shows heads on all occasions to be roughly as small as that of winning the German lotto (which is a probability of 1 in 14 million). Box-and-whisker plots are shown for the questions 1 (number of marbles) and 2 (number of coin tosses). The boxes are bounded by the 0.25 and 0.75 quantiles, and the whiskers end at the 0.1 and 0.9 quantiles. The means are marked by dotted lines and the correct values by dashed arrows. For question 1 ($N = 2057$), the absolute deviations of mean and median from the correct value are small (1.5% for the mean, and 8.2% for the median). For question 2 ($N = 1953$), however, the mean is a poor approximation to the correct value (absolute deviation = 1976%). The median is better than the mean, but is still far away from the correct value (absolute deviation = 317%).

problems, such as navigating accurately over short or long distances [16–20], efficient taxis in a noisy environment [21] or finding a suitable new nest site (Box 1; quorum formation in social insects). Navigational accuracy increases with group size based on the many wrongs principle [16,17]. The assumption underlying this principle is that all individuals have a common target destination that they want to reach but that each individual navigates with some error. If group members average over each other's directional preferences, then the error with which the group moves toward the target decreases as a non-linear function of group size. In this example, the individual errors follow a normal distribution. However, the principle of the many wrongs is not restricted to this type of distribution. As long as the mean of the individual vectors approximates the desired target direction, there are many other types of distribution that could produce a similar outcome (i.e. reducing navigational error with group size). Likewise, there is no particular reason why an averaging principle should necessarily be used and other ways of processing the information held by individuals are possible [16].

Evolutionary perspective

Traditionally, biological texts compile long lists of diverse benefits that group living enables [1,29,30]. Rather than listing effects in this way, individual-based modelling has opened up the possibility of an agent-based approach, in which each additional behaviour or capability that we allow the agents facilitates the emergence of new system properties [31]. This view is different and interesting because the additional capabilities at the individual level could be seen as mutations that then open up a new set of social interactions and subsequent fitness gains to group-living animals. Let us consider several such capabilities to understand the mechanism by which the systems properties of groups could arise:

(i) In their simplest form, group-living agents are attracted by conspecifics and are repulsed at close range [32,33]. In addition, they might respond to the body orientation of near neighbours by alignment [34]. Implicit in the above rules is that each agent can independently gather information and also copy the behaviour of others. These simple rules alone would provide the basis for the encounter-dilution effect, the many eyes effect and the confusion effect [1]. This means that the agents can benefit from others detecting a predator, food and so on, even if they do not know which cue other group members respond to at any moment in time. Simple copying of local neighbours already opens up a range of potential collective properties for the group [35–37]. Interestingly, none of this requires any form of social learning or signalling: simply a follow-response to others in their vicinity. Agents with these properties should be capable of some forms of SI, such as quorum

Box 1. Quorum decision-making in social insects

Many examples of SI come from the social insect literature, where quorum sensing has been identified as an important mechanism for decision making [2,3]. Insect colonies are often faced with having to find a new nest location either because their old nest became too small or was destroyed. The problem that the colony needs to solve often reflects a complex tradeoff between speed and accuracy of decisions.

Mechanism

A proportion of individuals explore the surroundings for suitable nest locations and, if successful, these individuals then try to recruit others to this new potential nest location (e.g. as occurs in honey bees, *Apis mellifera*: [22,23] and ants, *Leptothorax albipennis*: [24,25]). Once the number of individuals in support of a particular nest location reaches a threshold (i.e. a quorum), the entire colony will favour this location. If speed is important, then the quorum threshold can be low, resulting in lower accuracy (i.e. a reduced chance of deciding in favour of the best new location among the available options). If speed is not a constraint then the quorum threshold can be high, which increases accuracy [26]. A similar type of quorum-based decision making has also been described in fish shoals that have to make a decision about which path to take to avoid danger or which leader to follow [27,28].

Costs and benefits

One of the main advantages of using quorum decisions is that it enables comparisons between multiple options based on the information that others have gathered and that copying cascades of maladaptive decisions is unlikely because it takes several individuals to come to the same conclusion independently to reach a quorum threshold. The reduction of quorum thresholds under time pressure indicates one of the potential disadvantages of quorums, namely that they can be time consuming in contrast to hierarchical decisions that are top down and quick.

decision-making [26]. It might also result in improvement in navigational abilities [16,38] and efficient taxis in noisy environments [21].

(ii) If we allow the agents to store and recall information (i.e. to learn), then they could recognise other agents and remember outcomes of social interactions. This ability could lead to cooperative interaction networks [39,40] and potentially enable collective solutions to challenging problems to emerge.

(iii) If we bring signalling into play, then it becomes possible for agents to inform others (e.g. about food locations) without physically guiding them (e.g. the waggle-dance in honey bees [41]). Signalling in combination with learning is an effective way of widely distributing information within a group.

(iv) So far, we have assumed that all individuals carry out identical behaviours and that there are no differences in social roles. Furthermore, we could introduce division of labour, but assume that every individual is still capable of adopting any task or role, and see what additional properties emerge.

For all of the above four categories, we could explore the importance of group size. How does the performance of a group of a given size compare to that of an average single animal? Or how does the performance of a group compare to a high-ability performer in the population (provided that individuals can be ranked in terms of their individual cognitive abilities)? If the collective behaviour can be measured as the time that it takes to solve a problem or the accuracy of a solution, we could, for instance, look for non-linear relationships between group size and problem-solving time. However, this criterion alone is probably not sufficient to indicate SI.

Box 2. User-driven content

Everybody knows Lego™ bricks from their childhood and the company behind this popular toy uses some innovative strategies, known as consumer-driven content, to design new products (see LEGO Mindstorms: http://mindstorms.lego.com/eng/Egypt_dest/Default.aspx). The idea behind this approach is to involve Lego users in the design of new toys.

Mechanism

Traditionally, companies have large design departments that come up with new product ideas. The investment in such design departments can be considerable and it does not guarantee success (in terms of producing many successful new designs that are bought by consumers). Lego realised that many popular new toys of the past were designed by users rather than by professional designers. There are several potential reasons for this: (i) user communities can consist of large numbers of individuals larger than any design department; and (ii) users are more likely to come up with modifications to existing toy designs or new toys because they, and not the designers, are the ones who spend time playing with the toys.

These insights prompted Lego to create an internet platform in which users of Lego can talk about their design ideas, showcase their work and vote on each other's designs. The outcome of these debates often results in highly creative new designs that have the potential to reach the mass-market and contribute to the success of the Lego brick.

Where do we see the SI signature in the strategy of consumer-driven content? It fits our definition in that people independently develop ideas, the ideas are brought together and interactions allow for processing of these ideas that can subsequently result in new creative designs.

Costs and benefits

The strategy of user-driven content is cheap and can provide access to the creativity of large user communities. The full benefit might depend on how this approach is harnessed. Recent developments show that users not only develop new design ideas, but they also market and sell their own designs. This means that Lego benefits from both the design ideas and the entrepreneurship of users.

The role of diversity

In humans, SI is often utilised in the context of government panels, scientific committees and teams in companies. The size and composition of the group is strategically planned with the aim to maximize the benefits of group performance in terms of problem solving. The composition of such groups is often arranged in a way that utilises functional diversity (differences in the approach used for problem solving) and identity diversity (differences in race, gender, religion or ethnic background) to maximise the performance potential and perceived social equality of the group through representation. Studies that investigated the effect of identity diversity on performance (in terms of financial gain) through direct social interactions in teams or organisations, however, obtained mixed results. In some studies, increased diversity was not beneficial to group decision making, whereas in others a clear performance advantage was found [42,43]. These results are at least partly owing to the fact that differences in perspective can create communication barriers and that identity diversity can result in a lack of trust and mutual respect [42]. This means that there is a need to distinguish between the SI potential of a group and what can be realised, both of which are interesting areas of research in their own right. An important point regarding functional diversity is that a range of skills in itself within a group is not SI (in fact, this is a common misconception about SI) but it is the interaction between these functionally specialized individuals that has to produce new solutions.

Internet use for SI purposes

The electronic media have unlocked a hitherto largely untapped potential for SI in humans with relevance for company management, product development, prediction of elections and the media entertainment sector to name but a few (Boxes 2–4). In fact, the strong interest from companies has already resulted in many meetings on this topic organised by industry. Information gathering from individuals has become possible on an unprecedented scale facilitated by the open and wide-spread access to electronic media that enables the process of tapping directly into the collective knowledge or memory and most importantly creativity of huge (potentially global) collections of people. Furthermore, every simple desk-top computer now has enough processing power to deal with such large data sets. But what should be done with the information that has been acquired in this way? Are there solid lines of approach that can be followed? A quick look at the internet gives the impression that SI has become the playground for both innovative research and wild speculations, generalisations and misunderstandings, a situation that partly motivated our decision to write this article.

Box 3. Collective management

A recent attempt to use SI in management decisions is the case of a football club, Ebbsfleet United, which involves its ~30 000 or so members (http://www.myfootballclub.co.uk).

Mechanism

For a small fee, anybody can become a member and participate in the decisions of which players should be bought and which players should be part of the team for particular games. This management system is a dream come true for all those people who regularly disagree with the coach of their favourite football team over team selection and strategy issues.

Costs and benefits

Whether this collective management idea produces the desired outcome of a more successful team, however, remains to be seen. As indicated earlier, SI not only provides opportunities, but also has limitations and there is some way to go before it can be predicted accurately *a priori* whether SI can make a valuable contribution and when it will fail. For example, such a collective decision-making process might well be resistant to error because one individual's crazy idea does little to affect the collective decision; however, the drawback to this might be that innovation, adjustment to new circumstances, flashes of genius and creative thinking might be stifled by just the same process. So, where this approach works well might come down to whether football games tend to be won by flashes of genius or whether they tend to be lost by blunders.

Open-access interactive systems

Striking examples of recent SI use are internet-based platforms for discussions of problems that are characterised by open access (i.e. every user can contribute to a given problem) and their interactive format, which enables potentially vast numbers of people from all over the world to voice their opinions and make a contribution. The open and interactive qualities result in partially self-organised and partially decentralised systems. Examples of this form of SI use are the development of the Linux operating system (http://www.linux.org/info), The Apache Software Foundation (http://www.apache.org/), medical discussion forums and user-driven content for design problems (Box 2). On the more experimental front is the collective management of football clubs (Box 3). It is debatable whether Wikipedia (http://www.wikipedia.org/) should be considered as an example of SI because bits of information are mainly accumulated but not necessarily processed to provide a new cognitive solution to a problem. Admittedly, it is possible for people to edit what others have written and to combine ideas in new ways. Nevertheless, the very purpose of Wikipedia is largely incompatible with the SI concept because Wikipedia is meant to represent what is already known about a particular topic, rather than generate new insights.

In Box 3, we identify a potential problem with SI; namely, that the simple averaging of all opinions will not make the best use of creative sparks by gifted individuals. The Lego case study in Box 2, however, shows that this is not necessarily a general weakness of SI because use-driven content can be a highly creative process making use of SI. In conclusion, whether SI stifles or promotes creativity probably depends on how opinions interact with each other.

Centralised information collection

We have already given an introduction to this category in the section on the possibilities and limitations of SI, with the example of the marbles in a glass jar. The aim of this type of SI use, which is known as a prediction market, is usually the assessment and prediction of developments (Box 4). In this case, the interaction between the opinions occurs in form of trading virtual shares (Box 4) but the interpretation of the share value often requires further calculations. In all animal groups and many cases of human groups, social interactions will substitute for these calculations.

Prediction markets are essentially a tool and, therefore, can be used for private gain (they were originally developed to provide companies with a competitive advantage) or public good depending on how the tool is used. However, prediction markets lack the partially self-organised quality of open-access systems.

Conclusions and prospects

Opportunities of SI research

In contrast to individual intelligence or animal cognition, one of the intriguing aspects of SI is that it is possible to understand its mechanisms in great detail. The simulation

Box 4. Prediction markets

The combination of individual forecasts to achieve higher forecast accuracy has a long tradition [44,45]. However, a method that has grown in popularity in recent years with wide-spread application is that of prediction markets. These can be used for predicting election outcomes, economic developments and outcomes of sporting events (to name but a few possibilities) [46,47]. Many companies use these types of prediction markets already (e.g. Hewlett Packard, IBM and Google).

Mechanism

The basic concept of prediction markets is a simple one. People are asked to place bets on the outcome of certain events (e.g. election outcome) or to trade shares. What is often found is that the odds of the bets or the price of the shares reflect the likelihood of the event that one is trying to predict. Prediction markets can be set up using real money or even toy money without any systematic studies comparing the two approaches to date. The essential principles of prediction markets rely on the fact that: (i) people are motivated to provide information; (ii) that people truthfully give their opinion; and (iii) that a suitable mechanism can be found for processing the opinions. Hewlett Packard, for instance, uses a system in which individuals are invited to buy and sell shares whose value is tied to the outcome of future market developments. Over a certain time period, the risk-taking behaviour and predictive power of individuals is measured against real market developments, building up a profile for each participant. The aggregated and weighted prediction of all participants can be used to predict future events and outcomes and has been shown to be successful in several case studies [46].

Costs and benefits

Prediction markets have been shown to perform strongly compared with more conventional methods of market or election predictions [46–47]. However, prediction markets are not without their critics [48]. In addition to the limitations that we mentioned above, prediction markets can also suffer from partisanship (people expressing wishful thinking rather than their best guess) and speculation bubbles. Thus, a careful case-by-case assessment is needed to decide whether their performance is up to expectation.

of the behaviour of individuals and their interactions on a computer can provide insight into how solutions to cognitive problems come about as a result of SI [3,31,38]. In this context, SI provides a great opportunity for collaborations between the mathematical sciences and disciplines such as psychology, sociology, economics and biology.

Interestingly, most of the work on SI in animals has been done on invertebrates, such as social insects and slime moulds [3], with a few recent studies emerging on vertebrates [18–20,27,28]. By contrast, there is a rich literature on this topic in humans [6]. It seems surprising that other vertebrate taxa, particularly non-human primates and cetaceans, have contributed relatively little to the SI debate to date. It might be that the quest for finding the cognitive limits of the individual still dominates debates on cognition in these taxonomic groups. This is an area in which many of the SI approaches developed by psychologists should also be applicable to animals, thus providing much-needed insights into the cognitive benefits of group living. On a related issue, the diversity debate (i.e. exploring the influence of diversity on SI), which is widespread in the social sciences [42], is only in its infancy in the animal literature, with evidence for traditions and culture [49] in many animal populations and experimental support for the existence of animal personalities [50]. These factors in combination could create the basis for a debate of interindividual diversity in some animal species, similar to that in humans.

Both experimental and theoretical evidence indicates that SI performs well if there is: (i) diversity of opinion; (ii) independence of opinion; (iii) an incentive for truthful reporting; and (iv) if estimates of individuals are only hampered by imprecision and not by a systematic bias [6,46,51]. However, despite the fact that there are some criteria for the effective use of SI, the search for well-defined conditions under which SI provides the greatest benefits compared to other approaches remains an important challenge. For instance, models have been developed that explore the precise conditions under which groups can outperform experts and groups of diverse problem solvers can outperform groups of high-ability performers [52]. Future explorations should also include an assessment of the impact that violations of the above criteria have for the use of SI. For instance, incentives (financial or otherwise) for truthful reporting might reduce the frequency of non-serious answers, but it is unlikely that an affordable incentive scheme will reduce this frequency to zero, particularly if thousands or millions of individuals participate. Comparisons of data sets with different degrees of such biases are needed to assess their influence critically.

Potential consequences of SI research

The finding that the judgment of a diverse group can outperform an expert or even a small group of experts under certain circumstances [51,52] has led to speculation that SI developments could make experts obsolete to the extent that even company CEOs might be in less demand in the future [10]. However, this seems unlikely. We predict that a shift might be seen in the type of experts that are needed, towards experts who know the mechanisms to harness and implement SI. Company leaders might need to learn the means to utilize SI principles, but SI is unlikely to replace leadership by a collective that steers itself. SI is more probably a mechanism that provides additional guidance in making decisions.

Why is this so? In social insects, for instance, the individuals might collectively be able to solve cognitive problems. However, even when they have arrived at a solution, a single ant or bee is never going to be in possession of the overall information (or solution). By contrast, humans can purposefully set out to use SI principles to their benefit to gain, for instance, a competitive advantage in business (by better predicting market developments). The point is that the whole SI mechanism (data collection, processing and solution) can be used by single experts (or expert teams). Therefore, the user potential of SI in animals and in humans is fundamentally different in this respect. In animals, SI acts as an enabler for a group of often highly interdependent individuals; in humans, it can be an enabler as well as a tool that can be used to aid decision making.

In conclusion, the evidence from animal and human societies does not necessarily indicate that SI automatically replaces leadership [31,38]. Nevertheless, the continued investigation of SI is beginning to lead to a re-examination of the relationship between the collective and its leadership, be it the voting citizenship of a democratic country and its government, the shareholders of a company and their board of directors or the fan base of a football club and its management. Therefore, it seems only fitting to close with a quote from the groundbreaking article by Galton [8] who said: 'This result [the excellent collective estimate] is, I think, more creditable to the trustworthiness of a democratic judgment than might have been expected.'

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