CHAPTER 4

Human Swarm Problem Solving

4.1 Background

In CI research, biological research and studies of animals' collective behavior is considered to be one of the most important research areas. Although biologists sometimes use CI as a term, the more biologically orientated term "swarm intelligence" is more common. Usually, the notion of a swarm describes the collective behavior of a decentralized, self-organized system like fish schooling, bird flocking, ant colonies, animal herding and honeybee swarming. When operating in large groups, these swarms are together able to solve far more complex problems than a single of these individuals can do alone (Bonabeau, Dorigo, & Theraulaz, 1999; Corne et al., 2012; Krause et al., 2010). One of the most remarkable features of this type of collective behavior is that it often can be described and predicted with mathematical models. Although individual behavior varies, the predictive value of statistical models suggest the presence of unique mechanisms at a group level (Sumpter, 2010). Inspired by the behavioral rules these animal groups or swarms use to coordinate actions, humans have even invented similar artificial systems that can function effectively by following the same principles. As an academic term, swarm intelligence was introduced by Gerardo Beni and Jing Wang (1993) who created robotic systems where agents were programmed to follow very simple interactional rules without any centralized control structure that dictated local individual behavior. Despite the simplicity of these rules, the collective behavior of the agent would be surprisingly intelligent at a level that was unknown to the individual agents (Bonabeau et al., 1999; Corne et al., 2012; Krause et al., 2010). Such artificial systems will not be the topic of this chapter. Instead, the chapter will address how human swarm problem solving also builds on some of the same behavioral rules and basic mechanisms that other animals use. The term "swarm problem solving" highlights that the sections are organized according to a

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few selected biological mechanisms that also resemble how large human groups sometimes solve some types of problems together.

As such, the chapter will primarily link current biological research on animals' collective behavior to the wisdom-of-the-crowd approach within CI research. In 2005, Surowiecki coined the term the "wisdom of the crowd" in describing how a crowd, a large groups of amateurs, can outperform individual experts in many different areas if four conditions are fulfilled. First, a heterogeneous group with diverse opinions produces better quality solutions than a homogeneous group. Second, individual must make independent contributions without being influenced by others. Third, individuals should work in a decentralized and autonomous manner. Fourth, the contributions need to be aggregated in an effective way. Under these conditions, an increase in the group size will also increase the chances of producing the best solution (Surowiecki, 2005).

These principles became the most important guidelines for a new research area within CI that examined new crowdsourcing methods and "wisdom of crowd" effects. However, Surowiecki and few others have compared human crowd behavior with animal crowds. This chapter will address the issue by examining five different swarm mechanisms that, to some degree, humans and animals have in common when they solve problems. Several crowdsourcing methods will be analyzed and framed with terminology from biology. By choosing this approach, the goal is to illustrate how biological research can provide valuable insights into mechanisms that are often studied in the "wisdom of crowd" literature as being uniquely human.

The biological studies in the chapter primarily describe how animals make consensus decisions. In many situations, animals have to decide between two or more options. Most of these examples concern how groups choose a new shelter or migrate to a new home. In this setting, information transfer is required and collective decisions build on alternatives that remain stable. Cohesion, speed and accuracy are considered important factors that will influence how all or nearly all group members come to agree on the same option. The overall key question is how individuals reach a rapid consensus for the best of a number of available options (Sumpter, 2010).

Building on recent biological research, this chapter discusses five mechanism related to animals' collective problem solving that are also considered to be relevant in explaining human swarm problem solving. These mechanisms are:

- Decision threshold methods
- Averaging
- Large gatherings
- Heterogeneous social interaction
- Environmental sensing

Animals also use both averaging methods and decision threshold methods that build on statistical rules and resemble how humans aggregate information from a large group. In addition, biological studies show that animals coordinate qualitatively different actions in effective ways when they solve different types of problems. Here, three animal mechanisms – large gatherings, heterogeneous social interaction and environmental sensing – will be presented and compared with how large human groups operate in similar ways.

A key issue in human decision-making is whether it should build on aggregation with no information exchange versus letting a group inform each other in different ways (Tindale & Winget, 2019). While the original wisdom of crowd literature stressed the need for individual independent opinions in crowds, there is today a stronger emphasis on the possible positive influence of dependent contributions (Davis-Stober et al., 2014; Tindale & Winget, 2019), such as in prediction polls or decentralized communication networks (Becker, Brackbill, & Centola, 2017). New technological platforms that build on dependent swarm contributions are also being invented (e.g., Willcox et al., 2020). By connecting these studies to biological research, I found human swarm problem solving to be the most appropriate term to cover a large variety of crowdsourcing methods. Here, the notion of a swarm covers the aggregation of both independent and dependent crowd contributions.

4.2 Decision Threshold Methods

Decision threshold methods attempt to reach consensus by following a response threshold rule. This can primarily be done in two different ways. On one hand, quorum decisions ensure that a minimum number of individuals (the actual quorum number) are ready to shift from one behavior to the next. On the other hand, a majority decision let all contributions or votes count, but only a certain percentage of consensus is required to reach a decision, typically a simple majority.

4.2.1 Quorum Decisions as Swarm Problem Solving among Animals

In animals' collective decision-making, quorum decisions will rely on independent assessments in the first phase of the process. When a specific threshold is met, there will be a distinct behavioral shift in mode towards dependent behavior. Everyone will copy the preferred behavior. Most importantly, both the speed and accuracy of decision-making can be improved by copying the choice of a better-informed neighbor (Sumpter, 2010). Quorum decisions ensure that a minimum number of individuals (the actual quorum number) are ready to shift from one behavior to the next. Because decisions taken by several individuals are generally more accurate than individual decisions made alone, quorum thresholds reduce the risk of errors (Bousquet, Sumpter, & Manser, 2011).

This behavior has primarily been studied in honeybees, ants, and fish (Bousquet et al., 2011). However, there are differences, as ants use tandem runs as recruitment signals, while bees use dances (Figure 4.1). Still, there are also strong similarities between the decision processes of Temnothorax ants, honeybees, and even cockroaches since all three species exhibit positive feedback and quorum responses. Because decision-making in animal groups often will be decentralized, positive feedback plays an important role. A plausible explanation is the evolutionary consequence of a need by individuals to reach consensus (Sumpter, 2010).

In one experiment, small groups of fish had to swim through a Y-shaped maze where replica conspecifics were set up down both sides of the maze. Interestingly, smaller groups of one or two fish were more likely to be influenced by the replicas than larger groups of four or eight fish. If the difference between the number of replicas moving to each side was only one (e.g., if left:right was 1:0 or 2:1), the larger groups were not influenced by the majority at all. However, if the difference in replicas was two (e.g., if left:right was 2:0 or 3:1), the larger groups were much more likely to follow the majority. The results show that fish only follow a certain majority size (response threshold), and they are able to compare their own group size with the numbers of fish in their surroundings (Sumpter, 2010).

In another experiment on a potentially dangerous situation, groups of four or eight fish only swam past a predator replica when guided by two or more "leader" replicas, while they usually ignored the behavior of one single "leader" replica. However, a single fish who would never swim past a predator alone would still do it sometimes if led by a single "leader" replica. The results show that uncommitted individuals in larger groups only follow above a threshold number of leaders. This threshold dramatically reduces the probability of errors being amplified because if the probability of one individual making an error is small, the probability that two fish independently make the same error simultaneously is very small.

Interestingly, experiments show that humans also ask for the opinions of two other individuals if they want to be more certain about a particular choice. The quorum rule of following more than one leader allow both fish and humans to make more accurate decisions as group size increases (Sumpter, 2010).

Another example is Temnothorax ants who live in colonies of between 50 and 500 individuals in small rock or wood cavities. If their nest is damaged, they are able to move to a new site within a few hours, and will nearly always choose the best site from as many as five alternatives. They are able to assess new sites from several environmental cues such as cavity area and height, entrance size, and light level. Around 30 percent of the colony participate in the nest siting, and these ant scouts go through different phases of commitment. Each ant first searches for nest sites, and when finding a spot, the length of the evaluation will be inversely proportional to the quality of the site. Once the site has been accepted, the ant moves into a canvassing phase, whereby she leads tandem runs, in which a single scout ant follower is led from the old nest to the new site. However, the newly recruited ants make their own independent evaluation of the nest and then return to recruit new ants. Since ants use more time to accept lower quality nests, the better quality nests will have a more rapid recruitment. Here, the ant decision-makers face a *trade-off between speed and accuracy*. Greater speed in making a final decision increases the risk of not choosing the best available nest site option. Recruitment via tandem runs is rather inefficient because ants only move at one third of their usual walking speed. When the size of support for one site exceeds a certain quorum threshold, a recruiting ant will move into a committed phase, and instead begin to carry passive adults and other items to the new nest site. These transports are done at a normal walking speed, marking a shift from slow to rapid movement into the new nest (Sumpter, 2010).

Until recently, researchers have thought that dominant individuals lead decision-making in vertebrate groups (animals with backbones: mammals, birds, fish, reptiles, amphibians). However, recent studies show that consensus decisions are more common than previously thought, for example when animal groups decide in what direction they want to move. Only a small proportion of individuals in the group may possess the relevant information about the route. Some may also differ in their preferred direction. A consensus decision is then necessary to prevent the group from splitting. Typically, a group begins to move in a particular direction when a certain threshold of individuals make the same signal with their head movements (whooper swans), gaze in a particular direction (African buffalo), or use calling (gorillas) (Dyer et al., 2008).

Figure 4.1 Two worker ants of the species *Temnothorax albipennis* performing a tandem run, image courtesy of Thomas O'Shea-Wheller, 2016

Another example is meerkat groups which stay together during daily foraging (Figure 4.2). Some of their specific moving calls build on quorum decisions, which is used as an efficient temporal coordination tool of group movement. A quorum of at least two and usually three meerkats are necessary to enable the whole group to move to a new foraging patch. The quorum shows that an accumulation of evidence is needed, increasing the likelihood of the foraging patch actually being food-depleted. This decision-making system avoids that one individual makes the wrong conclusion. Neither dominance status, sex, nor age affects the calls and suggests they are made as independent individual assessment of the food patch quality. If none or only one extra individual join in on the moving call, the group will continue to forage in the same area. However, the moving calls are not used as a directional coordination tool. Because meerkats' prey are widely distributed underground, it is more important for them to know when it is best for them to leave instead of where to go next. The system provides a simple mechanism to coordinate group cohesion while at the same time maximizing foraging success for the majority of the group (Bousquet et al., 2011).[1]

It is also interesting that the quorum number is an absolute value, either two to three individuals. Other studies show similar results: it takes more

Figure 4.2 Meerkat (*suricata suricatta*) digging in the Kalahari Desert, photo © Tim Jackson/Getty Images

than two fish to make a decision in groups of up to ten individuals. It appears that two to three individuals acting as signalers is a common requirement in several species, at least for group sizes ranging from six to 22 individuals. It shows that a quorum number does not need to be large to be effective since errors decrease exponentially with quorum size. If the probability that one meerkat wrongly concludes that it is time to leave a foraging patch is 5 percent, then the probability that two and three individuals will independently reach the same conclusion is 0.25 percent or 0.0125 percent, respectively (Bousquet et al., 2011).

However, recent studies suggest that the response threshold in several different animal groups does not depend on the absolute number of other individuals exhibiting a certain behavior, but rather on a fraction of the perceived individuals who exhibits a certain behavior (Couzin, 2018). For example, a study of whirligig beetles, tested at what threshold the beetles initiated a flash expansion when observing a predator. The ratio of sighted beetles was manipulated so one could test whether the threshold was an absolute number or a proportion of the group size. The results supported the proportional hypothesis since the response occurred when more than 10 percent of the beetles saw the predator (Romey & Kemak, 2018).[2]

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Sumpter (2010) emphasizes that quorum responses can substantially reduce errors compared with independent decision-making. Positive feedback combined with quorum responses can aid accuracy in collective decision-making without requiring full consultation of all group members. While the quorum mechanism leads to improvement in accuracy over individual decisions, it does not achieve the same accuracy level as in majority decisions. For example, if 40 individuals each have a 2/3 probability of making the correct choice, the probability of a majority error is just 3.33 percent. In a similar group, a quorum response that is elicited when 5–15 persons make the same choice will produce an approximate error rate of 10 percent. In a quorum response, there is a risk that small initial errors can be amplified and lead nearly all individuals to make the same incorrect choice, which they would not have made by themselves. However, compared with making individual decisions the simple copying rule based on threshold responses substantially reduces the number of errors. The mathematical model suggests that response thresholds not only provide cohesion, but also facilitate accuracy. This is because quorum responses allow effective averaging of information without the need for complex comparison between the options. Evidence shows that in most cases, quorum responses allow for greater accuracy than complete independent behavior or just having weak responses to the behavior of others (Sumpter, 2010).

4.2.2 Human Quorum Response as Swarm Problem Solving

The noun "quorum" is plural of *qui* in Latin, meaning "of whom." The first quorum refers to commission papers that authorizes a group to be the justices of the peace. Today, the meaning of the term typically refers to the minimum number of members who must be present at a meeting in order to make official decisions. A human quorum often refers to the majority or supermajority of quorum (in most cases, the bylaws will state the rules for a quorum), but as in animal groups, a quorum can require a group minority significantly lower than 50 percent. It varies whether a specific percentage (quorum quotient) or a fixed absolute number is required to make decisions.

The main purpose of a quorum is to avoid a few members becoming too powerful when important decisions are made. Many democratic institutions also use quorum rules to ensure the "legitimacy" of decisions if it is likely that not all eligible voters will participate. For example, it may not only be enough with a majority, but the total number of votes will also need to exceed a particular threshold. Quorum rules are common in referendums like for example in Switzerland, which let citizens challenge a law approved by the parliament or propose a modification of the federal constitution. They organize several different types of referendums, including mandatory referendums that propose a modification of the national constitution, optional referendums which require that citizens collected 50,000 signatures against a law accepted by the national Assembly and demand a referendum, and there are also federal popular initiatives with voting on a change of the constitution, which require a minimum of 100,000 ("How to launch a federal popular initiative," 2020). With 1,000 signatures in Kraków, Poland, a proposal can be presented to organize a citizens' assembly, and with 5,000 signatures, the mayor is required to organize an assembly (Gerwin, 2018). Town meetings is another example of a quorum response where those who show up make the decision. However, there are major challenges in this method since studies show that very few eligible voters show up and very few speak up in these settings. In Switzerland, direct democracy continues to play an important role at a local (cantonal) level, but it is increasingly as a referenda and not as the large gatherings where everyone meet together face-to-face. The Landsgemeinde or cantonal assembly only persists in two cantons (Fishkin, 2018: 26, 47) (see Figure 4.3).

With the emergence of new digital technology and an online setting, quorum response mechanisms are now also used in new ways. In certain types of synchronous decisions-making systems, individual votes can be graded and collective decisions are made when a certain threshold level of support is reached (Patel et al., 2019; Willcox et al., 2020) (see example in Section 4.4.2 Large Gatherings as Human Swarm Problem Solving). One interesting example is Kickstarter, which is a crowdfunding platform that gathers money from the public as a new way of financing new ventures and bringing creative projects to life. Here, the quantitative response threshold is not votes, but money. Project creators in need of economic support will describe the project on the website and choose a deadline and a minimum funding goal. The model builds on microfinancing and make it possible for anyone to contribute from anywhere in the world within a short fixed period (Kuppuswamy & Bayus, 2017).

In 2017, Kickstarter reportedly received more than $1.5 billion in pledges from 7.8 million persons to fund approximately 200,000 projects. The projects range from the invention of equipment, art projects, design, technology, film, music, games, comics, and food-related projects. People who support Kickstarter projects are usually offered tangible rewards and

Figure 4.3 People raise their hands to vote during the annual Landsgemeinde meeting at a square in the town of Appenzell, April 29, 2012. Appenzell is one of Switzerland's two remaining Landsgemeinden, a 700-year tradition of an open-air assembly in which citizens can take key political decisions directly by raising their hands, photo Christian Hartmann/ Reuters/NTB ©

the opportunity to buy some of the products for a reduced price (Kuppuswamy & Bayus, 2017). The collective decision of whether to fund the project or not is left open to unknown others or outsiders in a global online setting. In some projects that aim to sell a product, it may be relevant to check whether the product is interesting for potential customers in the future. These online platforms enable people to create products that it would have been very difficult to fund in other ways. In this way, crowdfunding resembles arts patronage, where artists go to the audiences to fund their work. The difference is that the outreach is to potential backers from all over the world.

This fundraising resembles a quorum response because it builds on an "all-or-nothing" model. If the project is not fully funded within the deadline, the project owner gets no money at all. If the funding goal is overambitious, there is a risk that one may raise no funds at all. However, the project can continue to receive contributions until its deadline even after the funding goal has been reached. The crowdfunding process is also transparent in providing information about the total amount of money received at any point of time. Anyone can see how much money is needed to reach the pledge or the decision threshold point. There is also information on the number of backers and days of the crowdfunding period (Kuppuswamy & Bayus, 2017). Micro funders have an updated overview of the aggregated collective contribution at any time. Because contributions are given as money, the size of the contribution is also much more flexible compared with votes.

4.2.3 *Majority Decisions*

Majority decisions is another decision threshold method that is particularly important in human decision-making and democratic political systems. When problems involve discrete alternatives, large groups will often use majority or plurality rule to make a decision. The most important theorem that explains the epistemic advantages is the Condorcet Jury Theorem from 1785. According to the theorem, majorities are virtually certain to be right when some assumptions are fulfilled. The theorem states that if voters (1) face two options, (2) vote independently of one another, (3) vote honestly and not strategically, and (4) have, on average, a greater than 50 percent probability of being right, then, as the number of voters approaches infinity, the probability that the majority vote will yield the right answer approaches certainty (Anderson, 2006). These principles were first applied in the design of a jury system that aimed to determine the optimal number of jurors. Today, it is used in a much broader sense to prove how majority rule decisions can be better than individual decisions. It explains the relative probability of a given group of individuals arriving at a correct decision. The theorem also covers plurality voting with multiple-choice options (Anderson, 2006; Landemore, 2013: 70–72, 75).

Voter Competence

However, in reality, it is often very difficult to meet the Condorcet conditions of voter competence and voter independence. First, voters need to be better than random at choosing the correct solution. Then the probability of being correct increases rapidly even in a relatively small group. For instance, if the probability that each individual is correct is 60 percent ($p = 0.6$), a group of one hundred individuals will hardly ever make a majority error if each individual also makes independent decisions (Sumpter, 2010). Among large electorates voting on yes and no questions, majoritarian outcomes will almost certainly make the best decision if the Condorcet conditions are fulfilled. If ten voters have a 51 percent of being

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correct, a majority of six individuals will have 52 percent chance of being right. However, when the group size increases to 1,000, a majority of 501 persons will have 73 percent change of being correct. Because of the properties in the law of large numbers, the majority opinion moves closer to complete certainty as the group size moves toward infinity (Landemore, 2013: 71–72, 148–153).

While Condorcet originally believed that each voter had to better than 0.5 correctness probability, it is today considered to be enough that the median voter is above 50 percent change of being correct. This permits a larger diversity in voter competence, and one can still end up with a correct result (Landemore, 2013: 72). Unfortunately, the theorem also implies that if the group is sufficiently big and the individuals are slightly worse than 50 percent average, the group as a whole will almost always be wrong. The same mechanism that pulls the results up also pulls the results down (J. F. Mueller, 2018).

In direct democracies, the voter competence may be quite low on issues related to new laws or constitutional amendments. The voters may not have considered the issue before or they may lack knowledge. This opens up special interest groups who can try to confuse or manipulate voter preferences, or simply discourage them from voting. There is a risk that the voting does not end up with the best result (Fishkin, 2018: 49–50). Most of the problems in democracies are also complex, with different effects on individuals depending on geographic location, social class, occupation, education, gender, age, race, and so forth. In addition, knowledge about these effects will be distributed unevenly in the population (Anderson, 2006).

Enhancing citizens' competence can also strengthen the majoritarian outcome. If the percentage size of the majority is higher, it increases the probability of being right (Landemore, 2013: 71). Therefore, one option can be to use supermajority rules (see information about the Delphi method in Section 4.5 Heterogeneous Social Interaction). In democracies, this rule is often used in important political decisions. The long tradition of requiring supermajorities rather than simple majorities implies that opinions should approach unanimity. The disadvantage is that supermajority privileges the status quo over change (Fishkin, 2018: 20).

Voter Independence

The second condition in Condorcet's theorem is that individuals must vote independently of each other and be unbiased. Votes cannot have causal effects on each other. The probability of one person being right on the problem must have nothing to do with whether other persons are right on the same question (Landemore, 2013: 72). In practice, it will often be difficult to determine variation due to error or systematic bias. The assumption that individuals are independent leads to a paradox in the theory of many wrongs. On the one hand, the theory says that the group is collectively wise, but if individuals behave completely independent from each other, there is no sharing of information or benefits from the input of others. On the other hand, if there is too much information transfer between individuals, the decisions will not be independent anymore. Positive feedback can spread particular information quickly through the group, and also encourage all individuals to make the same, possibly incorrect choice (Sumpter, 2010).

Another paradox is that deliberation before voting is likely to increase voter competence, but it may also have a negative influence on voter independence. However, in a free and plural society that values a diversity of perspectives, it is essential to let voters influence each other through political discussions. From this perspective, Condorcet becomes less relevant for modern democracies that rely on critical discourse, a free press, and public discussions prior to voting. If it is not possible to share information and opinions, this can easily create incompetent voters, which according to Condorcet is also a threat against the best solution (Landemore, 2013).

Majority Decisions among Animals

Even animals sometimes follow a majority rule when making decisions between binary discrete options. This typically happens when there is a conflict of interest and large discrepancies in the group, for example, when the angle between two directional options is more than 90 degrees (Strandburg-Peshkin, Farine, Couzin, & Crofoot, 2005). Condorcet's theorem is also relevant in explaining how animal groups are able to make accurate decisions when there are discrete options, like when fish swim through a river network (Berdahl et al., 2018). One experimental study shows that when the size of groups of fish increased, more of the fish managed to follow the more attractive leader fish. Decision accuracy improved with group size (Sumpter, Krause, James, Couzin, & Ward, 2008 & Sumpter, 2010).

When navigating, animal groups operate according to the "many wrongs principle." Each individual makes a noisy estimate of the "correct" navigation direction, but by pooling these individual estimates, the accuracy is improved. The basic mechanism builds on the law of large numbers. If errors in individual estimates are unbiased and not perfectly correlated with each other, then a simple averaging across estimates reduces noise and comes close to the optimal decision. This mechanism covers both group movements and selection of alternative pathways. In this case, majority rule serves the same purpose as simple averaging (Berdahl et al., 2018).

4.3 Averaging

4.3.1 Averaging as Swarm Problem Solving in Animals

The section on decision threshold methods describes situations where one individual has a piece of information, like the location of food, which is then transferred to others through positive feedback. It can then be effective to copy the behavior of the individual that possesses the relevant information. However, animals also make decisions when there are two or more options when none in the group knows more than the others. For example, when a group looks for food in an unfamiliar environment, each individual has some probability of making the "correct" decision, but no individual is more likely to be correct than any other (Sumpter, 2010). Under such circumstances, animal groups will sometimes use an averaging strategy.

As already mentioned, the "many wrongs principle" refers to the general idea that social interactions reduce individual errors, improves navigational accuracy when groups move together. For instance, individuals which move together in herds, flocks or swarms, will continually adjust their route based on real-time perceptions of the movements of other agents. Simulations have demonstrated that averaging can describe local social interactions if individuals balance their own preference with how their neighbors move. These simple mathematical models assume that all individuals in the group are identical, follow the same interaction rules and have the same level of navigational information or error (Berdahl et al., 2018).

At first, one might think that averaging is a distinctly human decision method since it follows a relative complex statistical rule, but surprisingly, animal groups are also able to use this mechanism when navigating. Already in the 1960s, some researchers proposed that birds and fish moved in the average preferred direction of all individuals (Berdahl et al., 2018). Recent empirical studies have also proven the existence of such a mechanism. One example are wild baboons, which prefer a process of shared decision-making instead of following dominant individuals when they

Figure 4.4 Olive Baboons crossing Uaso Nyiro River in Kenya, photo Don Farrall/Getty Images ©

navigate (Figure 4.4). If the disagreement on the angle of the direction of movement is above 90 degrees, the baboons will choose to travel in one of two preferred directions. In this case, majority rule counts, and every one will eventually move in the same direction. However, below a critical angle, if the differences in preferences are lower than approximately 90 degrees, the baboons' compromise. The group will then move towards the average of the preferred directions (Strandburg-Peshkin, Farine, Couzin, & Crofoot, 2015). Honeybee swarms use the same mechanism. Prior to lift-off to a new nest site, the bee dances encode the direction to the chosen nest site with some individual differences. The actual flight direction will then be close to the average direction advertised by the different bees in their dances (Oldroyd, Gloag, Even, Wattanachaiyingcharoen, & Beekman, 2008).

When averaging, both baboons and honeybees improve their navigational accuracy because of the "many wrongs principle" (Simons, 2004). When all individuals want to reach the same target destination, they will navigate according to their unique directional information such as visual landmarks, internal compass, and smell and so on. Each individual will therefore navigate with some error, but when this error is unbiased, the

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average direction of the group is more likely to be correct than a random individual in the group. Assuming there is no cost to aggregating information, navigational error in the average direction decreases in proportion to the group size. This is analogous to the central limit theorem that shows how the standard error shrinks when the sample size increases. Averaging effects reduce "noise" at the individual level of information, and produce more accurate collective actions (Berdahl et al., 2018; Krause et al., 2010; Strandburg-Peshkin et al., 2015; Sumpter, 2010).

However, animal groups do not explicitly average individual estimates in a group because they can only observe their near-neighbors. Instead, the collective behavior relies on individuals having access to different information. According to "the many eyes principle," animal groups can integrate more information about the environment because it is distributed among all the individuals. Therefore, the dominant male in the baboon group does not have a higher chance of getting followers, in decision-making on group movements. These daily decisions are shared equally between the members of the group (Strandburg-Peshkin et al., 2015).

4.3.2 Human Averaging as Swarm Problem Solving

By now, there exists a lot of research that demonstrates averaging effects within the "Wisdom of Crowds" literature (Surowiecki, 2005). A classical example is the jelly-beans-in-the-jar experiment, in which the group's estimate is superior to the vast majority of the individual guesses. In one study with 850 beans in a jar, only one of the fifty-six individuals beat the crowd guess of 871. If ten different jelly-bean-counting experiments are done successively, it is likely that one or two students will beat the group each time. However, it is very unlikely that the same student outperforms the group. Over ten experiments, the group's performance or the crowd will almost always be the winner compared with single individuals (Surowiecki, 2005; Treynor, 1987).

The basic requirement in human averaging is that estimations, predictions, or judgements can be quantified. The crowd will often be studied as the aggregation of separate individual judgements. Typically, the crowd will solve simple tasks that assume the existence of a correct solution, such as predicting changes in the stock market or betting on a sports event. Each member of a crowd will submit some relevant information (signal) and some random errors (noise). When these errors are truly random and not systematically biased, the average will perform very well because the errors cancel. A good example of the crowd estimate is the temperature in a room, since individuals use uniquely different strategies when they guess the temperature (Davis-Stober et al., 2014; Surowiecki, 2005).

If certain conditions are fulfilled, a group can be remarkably smart when their averaged judgements are compared with the judgements of individuals. The individual heterogeneity in the group makes the aggregate more accurate (Lorenz, Rauhut, Schweitzer, & Helbing, 2011). From one perspective, this effect is primarily a statistical phenomenon that requires some type of averaging technique. A typical definition of "crowd wisdom" refers to the performance of a group average compared with an individual selected randomly. If guesses exhibit a random deviation from the correct answer, these deviations tend to cancel each other out when a large number of them are aggregated. When inaccurate perceptions are diverse, the shortcomings of the ones tend to compensate for the shortcomings of the others. This gives a more accurate, global estimate. Other definitions of crowd wisdom are more mathematically orientated, comparing the mean of the individuals with the mean individual or defining accuracy as the average squared error of prediction (Davis-Stober et al., 2014).

Several of the citizen science projects from Chapter 2 use averaging techniques to aggregate independent volunteer contributions. The same micro task is done by several persons independent of each other a certain number of times. This increases the likelihood of getting correct and valid information. For example, in the Galaxy Zoo project, hundreds of thousands of online volunteers helped astronomers by classifying the shapes of astronomical objects. Even though some single volunteer made mistakes, this became less of a problem when many volunteers looked at that same object. The group results were very accurate and showed that the crowd can perform well on relatively simple tasks.

A comparison of several wisdom of crowd studies found that simple crowd average is robust across different aggregation and sampling rules. In most cases, the simple average of individual judges is wiser than a single individual estimate. If the true score is well bracketed by multiple estimations (near the median or average), the aggregate accuracy will perform much better than the typical judge in the group. This crowd wisdom effect is present even when judges are individually biased and the crowd aggregate is not particularly accurate. Unless it is easy to identify the best individual across tasks that are done repeated times, the best option is instead to choose the unweighted aggregate of the crowd if the size is large. Over time, even the best performers will lose against the crowd average (Davis-Stober et al., 2014). Although the simple average or mean is the most popular aggregation technique, others have argued that median is a viable option. When group size is small, medians are less sensitive to extreme member estimates and may provide a more accurate result (Tindale & Winget, 2019).

There are also other treats against averaging. If individual have very little background knowledge, the crowd aggregate may be very bad. In one study, the crowd made a very poor estimate when asked how many times a coin must 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. Here, the estimate of a single "expert" is better, as a person with competence in mathematics can quickly estimate the correct answer to be 24 coin tosses. Compared with the jelly bean experiment of the temperature task, the coin example shows not only that those individuals are imprecise, but there is also a huge systematic bias. Most real-life problems include both imprecision and bias, and it is not always easy to distinguish these from each other (Krause et al., 2010).

One way of improving the averaging methods is to weight individuals differently, for example by giving more weight to expert members (Tindale & Winget, 2019). However, there is still a risk that the decrease in variance of predictions can offset bias in future aggregations. Another key concern is the role of social influence. It is almost impossible to collect independent opinions in society because people are part of social groups and will be influenced by each other (Davis-Stober et al., 2014). An important condition in the original "wisdom of crowds" approach is that the estimations need to be made independent of each other (Surowiecki, 2005). While animal groups are very effective in producing individually independent information, humans are much more vulnerable to social influence. There is a risk that negative social influence can reduce the diversity of perspectives. For example, one study found that when the crowd received information about the group estimate, the individuals changed their estimates and performed worse as a group.

In the first round of the study, all subjects answered independently. Afterwards, the subjects were allowed to reconsider their response after having received full information of the group response. The new estimates narrowed the diversity of opinions in a negative way even when the individuals were not allowed to discuss the task with each other. One explanation is that when individuals become aware of the crowd estimate, they may move closer to the average because they assume that the crowd is wiser. If all predictions are more narrowly distributed around a value, this "range reduction effect" makes the crowd less reliable. The negative effects of social influence will also be smaller if the individuals are more confident in their own estimates (Lorenz et al., 2011). The Delphi method builds on this assumption (see Section 4.5.2).

4.4 Large Gatherings

4.4.1 Large Gatherings as Swarm Problem Solving among Animals

Are humans the only ones who let a large number of people come together to solve a problem? Not entirely. Arguably the most famous example in the animal world is the "waggle dance meeting" which is an event honeybees arrange to find out where to move their nest. The house hunting will usually begin when colonies become overcrowded in their nesting activities. About a third of the worker bees stay at home and rear a new queen, while the rest, a group of ten thousand bees, leave together with the old queen to create a daughter colony. The migrants travel about 30 meters before they stop and form a beardlike cluster, where they stay for a few days. From this place, several hundred house hunter bees will travel out and explore 70 square kilometers (30 square miles) of the surrounding landscape for potential home sites. They will usually identify around a dozen potential home sites, which are evaluated by several bees to check if they are sufficiently spacious or provide good protection. What is remarkable is that the bees almost always select the single best site from the options they have first identified (Seeley, 2010: 6). In this process, they utilize a range of strategies that are also relevant for human swarm problem solving.

The scout bees follow three steps in their collective decision-making process. First, they search widely for prospective nesting sites and identify all the available options in the surrounding area. They look for small, dark openings that can provide a roomy and protective nest cavity. None of the bees checks the same area; they are able to maximize the diversity of their searching behavior, and thus optimize the chances of finding an excellent home. The differences in flight routes may be due to where they have previously worked as foragers or differences in their "personalities." Since the search group is so large, with several hundreds of bees participating, they are usually able to identify the best sites very quickly, usually within hours or a few days (Seeley, 2010: 224, 234–235).

The second step is that the bees meet at the cluster and freely share information about all the available options. The scout bee that has located a good potential nesting site announce the discovery through a waggle dance which aims to recruit other scouts to the fly-out and evaluate the sites. These recruited bees will then fly out, assess the site independently, and then return to dance for that site. Dances are more frequent for better sites, leading to a faster recruitment of scouts. This is how the positive feedback loop of recruitment to the different sites begins (Sumpter, 2010).

What is extraordinary with the honeybee waggle dance is that it gives specific information about the distance, direction, and desirability of the site (Figure 4.5). The duration of each waggle run is the distance coding and gives information about the length of the outbound flight. Second, the waggle run is positioned as a direction coding by running at the same angle as the proposed outbound flight relative to the sun's direction. The dance is a specific flight instruction: "Should we consider this site which is located X degrees to the right (or left) of the sun and Y meters away." In addition, the number of dance circuits inform the relative desirability of the site. The better the site is, the stronger the advertising dances will be, resulting in a stronger positive feedback for this site. The dance attracts the other uncommitted scout bees to a specific site, and the scouts who made the original discovery tend to be especially persistent in sharing their information (Seeley, 2010: 11, 224, 226–227 235–236).[3]

One can look at the waggle dances as a large gathering with competing "dance" advertisements for different candidate nest sites. At any given point of time, some scout bees will be committed to a candidate, while others are still uncommitted. A committed scout will advertise "her" site to uncommitted scouts and recruit them to visit the advertised site. When the recruited bees return, they advertise the same site and begin to recruit even more scouts to the particular site. Supporters of one site can also become apathetic and rejoin the neutral voters. Since the bees that have found the best site will dance most intensively, they will gain supporters more rapidly and these supporters will move back to a neutral status more slowly. The interest in some sites will shoot up, while others fade away.

All bees are free to advocate any site, and all views are voiced and respected. What is important is that the scout bees do a personal, independent evaluation of the different sites. Each individual decides whether she want to fly out to the site and whether she want to advertise it when returning. No scout bee will follow another dancer without inspecting the site. This is important because if scout bees blindly copy other bees, they would make biased decisions by overemphasizing the reports from the first scouts. The aggregated information builds on an open debate with contributions from dozens, if not hundreds of scout bees with independent opinions (Seeley, 2010: 224, 226–228, 235–236).

Figure 4.5 The honeybee waggle dance. The direction the bee moves informs others about where the site is. The duration of each dance informs about the distance to the site, photo Paul Starosta/Getty Images ©

The positive feedback mechanisms aim to recruit a sufficient number of scouts to one site to pick a winner. Even when the best site is discovered several hours after the other candidates, it will still quickly dominate the competition. The decision-making process is essentially a competition between alternatives to accumulate support, and the winning alternative is the one that first surpasses a critical threshold of support from the bees. When the scouts visiting one of the potential home sites exceed a specific threshold number, a quorum response is initiated which suddenly makes them return to the swarm. There is enough evidence to make the best decision. Back in the swarm, the scout bees who are convinced begin using piping signals to inform thousands of nonscout bees to begin warming their flight muscles. These preparations even start before all scouts have reached consensus since it is vital to speed up the process. Quorum responses ensure that the consensus decisions are both very accurate and time efficient since not all have to agree before a decision is made (Seeley, 2010: 8, 230). At the same time, the honeybees show that their solutions are surprisingly accurate (Seeley, 2010: 8, 226–230).

The bees' survival depends on the decision about their new home. This is why they expend a lot of effort in searching for possible home sites and debate it for several days. The large gatherings of honeybees are interesting also in relation to human swarm problem solving, both in how all relevant options are identified, how this information is effectively shared, and how accurate decisions can be made more quickly through a quorum response (Seeley, 2010: 226–230). If we look at the basic idea of deliberative democracy, there are several similarities. People should listen to each other, include all relevant arguments, and criticize them in a fair way. Without these qualities, democracy can easily end in manipulation and misled opinions (Fishkin, 2018).

4.4.2 *Large Gatherings as Human Swarm Problem Solving*

Deliberative Polling

If we look at large gatherings as a specific mechanism in human swarm problem solving, Deliberative Polling is one example that resemble how honeybees quickly solve problem together. It is a participatory governance method developed by James Fishkin (2018). It includes the "whole territory" by inviting a representative sample from the whole population. Random sampling is a strategy that ensures inclusion by gathering the whole population in a smaller group to make it easier to deliberate. The problem with self-selected participation is that the samples are unrepresentative, and participants who show up will often have special interests and not really be engaged in finding out what is best for the whole community. In Deliberative Polling, criteria for demographic and attitudinal representativeness are therefore included to optimize representation. Demographics representativeness cover standard categories such as class, gender, education, income, and ethnicity. Attitudinal representativeness is equally important and seeks a representative microcosm of the political viewpoints in the population. It is also important that the group is large enough, so the sample size is representative and includes all relevant diversity in the whole population. A large group makes it possible to produce meaningful statistically representative results. Usually, several hundred persons will participate in a poll. One of the advantages with this sampling, is that it is an effective way to get access to the opinions of an entire nation. If all members have an equal chance to participate, this is another variant of equal opportunity. Demographic and attitudinal representativeness ensure that all relevant viewpoints and interests are included in an appropriate proportion in relation to the population (Fishkin, 2018).

The poll participants are the "scout humans" that do the work for the entire population. Similar to bee nest siting, the poll participants will typically meet to deliberate a couple of days. While the bees are genetically designed to share and listen to all information in an open way, humans will often need somebody to help them organize a similar process. Small group discussions can easily become polarized. Cass Sunstein has found that if an issue has a midpoint, the group will often move further away from the midpoint and become more extreme. One reason is an imbalance of arguments. If most people are positioned on one side of the midpoint, they are more aware of arguments supporting only one of the positions. Another reason is the "social comparison effect" which occurs when people compare their views and feel a social pressure to fit in (Fishkin, 2018: 76, 142).

Deliberative Polling addresses this challenge by using balanced info materials and moderators that ensure that everyone is allowed to speak. Discussions can easily become too dominated by men or those who are educated. It is important that the ground rules for the discussions protect individual opinions from the social pressures of consensus. Therefore, the facilitators are trained to bring out minority opinion and to set a tone for respecting all opinions equally. The briefing materials are typically made beforehand by an advisory group which seek to include competing accounts. The participants also pose answers to experts with different opinions in the plenary sessions. In order to ensure independent opinions, and avoid conformity pressure, the participants' final considered judgements are collected in confidential questionnaires at the end of the process (Fishkin, 2018).

An interesting example of Deliberative Polling is the participatory budgeting project in the capitol of Ulaan Baator, Mongolia. Over two days, 317 persons participated in the Government Palace. These respondents were drawn from a larger stratified random sample of 1,502 residents. The randomly selected individuals comprised a balanced representation of households, from both apartment areas and the traditional tent communities. When the participating residents arrived, they were randomly assigned to small groups of about 15 persons who would be together during the weekend. The participants received briefing materials and the moderators supported the group processes. The groups also identified key questions that panels of competing experts addressed in the plenary sessions (Fishkin, 2018: 94–95).

It was expected that the final results would give the proposed Metro system top priority, but instead the best-ranked proposal was "improved heating for schools and kindergartens," mainly because Ulaanbaatar is one of the coldest major cities in the world. The groups also opted for a cleaner environment, even if it would make energy prices higher. In addition, the participants reported greater respect for others' opinions by being part of the process. The results from the Poll were afterwards included in the Action Plan for the City Master Plan in the exact order determined by the citizens. Other elected representatives in the city experienced the process as a legitimate democratic process (Fishkin, 2018).

Furthermore, in 2017, the parliament of Mongolia passed a law that requires Deliberative Polling as a form of public consultation before the parliament can consider amendments to the constitution. In the first poll that built on this law, a national random sample of 785 was invited over the weekend to deliberate in the Government Palace. It was an extraordinarily high rate of participation for those invited. Also on this occasion, the results gave important advice to the national parliament. Two of the most ambitious proposals for change, the indirect election of the president and introduction of a second chamber, were rejected. The main reason was the negative results from the Deliberative Polling (Fishkin, 2018).

Deliberative Polling appears to be a successful example of human swarm problem solving. According to Seeley (2010: 224), the honeybee researcher, swarm problem solving depends on four things. First, the group needs to be large enough for the challenge. Likewise, it is important that the sample size in the Poll is large enough to be representative for the whole population. Second, the swarm must consist of people with diverse backgrounds and perspectives. The Poll ensures this through not only demographic representativeness but also attitudinal representativeness. Third, individuals should, like the bees, be encouraged to do independent exploratory work. In the Poll, this happens by letting many smaller groups deliberate independent of each other. In the end of the process, the participants also make an individual, independent assessment through anonymous voting. While the bees end up selecting only one winner site, the Poll ends up with a ranked list of prioritized solutions. However, a major difference is that the bees identify all available options and collect information by themselves during the process. In the Poll, most of the background information is collected in advance by experts and summarized in briefing material. It is essential that this information is balanced and unbiased.

Fourth, it is important to create a social environment where everyone feels comfortable about proposing solutions and sharing information with full honesty. The waggle dance of the bees shares information regarding the options in a precise way, and the goal with the deliberation is also to let everyone be free to put forward arguments and criticize them in an open way. In the Poll, a moderator supports the group to ensure that the group dynamics are as good as possible. The bee competition for the best site is friendly because the bee swarm has a common interest. Likewise, the Deliberative Poll often addresses issues that are relevant for all citizens, like constitutional change.

Hackathons

Obviously, there is a huge variation in how humans use large gatherings to solve problems together, also in nonpolitical areas. In the offline setting, the hackathon is one such example of a gathering with up to 1,000 participants (Figure 4.6). It is an event where people who not usually meet, gather for a few days to solve a problem together. Most hackathons center on software development. For instance, Google, Facebook, and open-source software projects like Linux host hackathons to rapidly advance work on specific development issues. In addition, universities and national and local government agencies increasingly arrange hackathons to build technology that addresses different societal issues, such as helping the elderly cope with dementia. Some events may have as many as 1,000 participants (Trainer, Kalyanasundaram, Chaihirunkarn, & Herbsleb, 2016). A hackathon is also called a "hackfest," which is an

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Figure 4.6 Hackathon in Berkeley, California in 2018. Students work at Cal Hacks 5.0, the largest collegiate hackathon, in Berkeley, CA, November 3, 2018, photo Max Whittaker/The New York Times/NTB

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abbreviation of hacking festival. Codesprints or codefest is another term that avoids some of the negative connotations associated with the term "hack." These sprints are usually organized as an intensive computer-programming event with specific goals and a short timeframe. However, most hackathons are quite open-ended and exploratory, with various activities going on at the same time. At the end of hackathons, individuals or groups will usually present or demonstrate their results (Briscoe & Mulligan, 2014).

Like with the honeybees, the participations will work hard within the short time period of the event. Typically, a hackathon will last between a day and a week in length. Eating and sleeping is often informal, and sometimes people will even sleep on the site. Participants will usually need computer programming skills; the exception is some hackathons organized for educational or social purposes. Participants must also be able to work comfortably with new people in small informal teams. This includes intense work conditions with time pressure. At the end of the hackathon, they must be able to present the work to others in a compelling way in a short time (i.e., pitching to potential investors) (Briscoe & Mulligan, 2014).

Hackathons will usually begin with a plenary presentation about the event and the contest format, including the challenge prizes if available. Sometimes, the prizes will be a substantial amount of money. A panel of judges will then select the winning teams, and prizes are given. The judges can be organizers, sponsors, or peers. It varies to what degree information is shared online before the conference starts. The number of participants and the organization of teams will depend on the concrete tasks. Usually, the participants suggest ideas and form teams, based on individual interests and skills. Sometimes they will pitch their ideas to recruit more team members (Briscoe & Mulligan, 2014). This is somewhat similar to how the honeybees also attempt to recruit other scouts to join them in investigating one specific site.

Although the hackathons are brief, one of the expected benefits is to build a community (e.g., often only a few days). When the participants observe and interact with another, they share the feeling of being at the same place. This proximity can contribute to the development of durable social ties. During the hackathon, it is important that the interpersonal relationship is of such a quality that people feel free to ask and offer help, and work openly so others can observe their work. By getting in contact with others, participants have the opportunity to identify common interests. If they share the same interests, it is more likely that they will trust each other and want to work together (Trainer et al., 2016). Like with the honeybees, the hackathon let all participants move freely around, interacting with whomever they want.

Because of time pressure in completing work within the deadline, participants learn a lot about each other. However, one study still found that some participants were not comfortable asking for help, showing the importance of participants becoming acquainted. Some participants also maintain contact after the hackathon (Trainer et al., 2016). Hackathons illustrate that an offline setting can be used to let a large gathering of people solve problems in effective ways within a short period.

Swarm Platforms

In the online setting, new swarm platforms are being invented that attempt to involve large gatherings of people in collective problem solving. One interesting example is the UNU platform, which attempts to enable large groups to solve a challenge within an extremely short period. This is done in an online environment that enables a group to synchronize all their contributions in real time. Modeled after biological swarms and how many species reach group decisions by deliberating in real-time systems, the platform lets online groups work together as a dynamic moving group or "swarm" that can quickly answer questions and make decisions by exploring a decision-space and converging on a preferred solution. By giving people a very short decision-making time, the intention is to reduce social biasing effects like snowballing, which is considered to be a problem in majority voting systems, which arise from sequential voting where persons can observe how other votes have been given (Rosenberg, 2015).

The design of the UNU platform is inspired by honeybee nest siting – how they integrate diverse information, competing alternatives, and converge on a unified decision when a sufficient quorum is reached. The primary goal is to design a system that allows networked users to make intelligent decisions by reaching decisions in real-time systems, modeled after natural swarm behavior (Patel et al., 2019; Rosenberg, 2015; Willcox et al., 2020). This process is labeled as Artificial Swarm Intelligence (ASI) because the system architecture runs algorithms modeled on the decision-making process of honeybee swarms. All participants receive instant feedback on the movements of the human swarm group. This allows each user to adjust their own preferences in relation to the changing swarm behavior. Inspired by the complex body vibrations in the "waggle dance," the technology intends to model something similar in human groups (Patel et al., 2019; Willcox et al., 2020).

Individuals in the swarm respond to a question by pulling a "graphical magnet" with their mouse cursor towards one of the proposed answers. The group will in real-time collectively pull on the puck toward one of the preferred answer options. Every individual can also at any moment change behavior, making it possible to negotiate among alternatives. The answer period varies, but is usually within 60 seconds, often much quicker. The group output is the result of a "tug of war" between all participants. Individuals who do not adjust their magnet will lose influence over the swarm's outcome, just like bees vibrating their bodies to express favor for a new home site in a biological swarm. The pull from each user's magnet is visible to other users, and the aggregated force from all of the magnets controls the movement of the puck (Patel et al., 2019; Willcox et al., 2020).

Like with the bees, the collective decisions build on reaching a threshold level of support, weighing the input from the group of swarm members, and their mutual excitation and inhibition. When a certain number of individuals prefers one specific option, and exceeds a certain threshold, the answer is eventually selected (Patel et al., 2019; Willcox et al., 2020). A study of the system found that the group's final answers when swarming were significantly different from the swarm initial mean and the survey answers. The results show that individuals respond to the swarming experience and do not only change their answer to conform to most of the individuals in the group. The changes in responses are both influenced by the dynamic expression of individual answers and the confidence in those answers. Individuals must intuitively negotiate many factors in a short period, including their own conviction in their answer and the real-time, changing distribution of answers in the group at large. When individuals choose to pull for other alternatives, they choose a nearby option that is also still close to their original preference (Willcox et al., 2020).

Human online swarming can be regarded as a new wisdom of crowd approach. However, the collective performance of such systems is still uncertain. A few scientific studies have shown positive results compared with other wisdom of crowd approaches. It illustrates that it is possible to utilize real-time dependent contributions and not only aggregate separate independent contributions (Patel et al., 2019; Rosenberg & Willcox, 2018; Willcox et al., 2019, 2020). For example, when assessing whether patients were positive for pneumonia based on their chest X-rays, a group of radiologists reduced the percentage of errors by 33 percent compared to the averaging the individual estimates (Rosenberg et al., 2018). In another study, the human swarm also performed better than one of two machine-learning models (Patel et al., 2019). In general, these online swarm platforms are interesting because they allow for a very large group of individuals to gather for a very short time and make effective, relatively accurate, decisions.

4.5 Heterogeneous Social Interaction

4.5.1 Heterogeneous Social Interaction in Animal Swarm Problem Solving

Do individuals in animal groups usually behave the same way when they solve problems together? While averaging methods and decision threshold methods assume that individuals are identical units, there is today increased interest in how individual differences influence group behavior. For instance, genetically diverse honeybee colonies maintain a more stable nest temperature than genetically uniform bees. The reason is that diverse bees respond at different temperatures, thereby avoiding "all or nothing responses" that could easily overshoot the target temperature (Sumpter, 2010).

In other animal groups, group heterogeneity includes the presence of both leadership and other specific social structures (Jolles, King, & Killen, 2020). Individuals will fulfill different roles in a group when they solve a problem together. When chimpanzees hunt monkeys in groups, they take complementary roles. The driver chases the prey in a certain direction, while the blockers prevent the prey from changing directions. Although this type of group hunting looks like genuine collaboration, the most likely explanation is that they follow simple interactional rules. Each animal fills whatever spatial position is still available at any given time. Encircling is, in this way, accomplished in a stepwise fashion. The group hunting does not require a prior plan or agreement; each individual chases the prey from its own position (Moll & Tomasello, 2007).

Complementary roles in a group hunt can be explained as simple associative learning. One simple rule is that each individual follows their preferred stalking pattern and goes straight towards or circle around the prey. The timing of actions between the animals needs to be synchronized to make the hunt effective. For example, when wolves fan out and encircle prey, they follow two simple rules; get to the closest safe distance from the prey, and get the best possible view of the prey (Figure 4.7). By following these two rules, each individual will at the same time move both towards the prey and away from other individuals, so those in front do not obstruct their view (Bailey, Myatt, & Wilson, 2013).

Body posture may be important as communication, particularly in instances where the prey is only visible to the first animal. It provides

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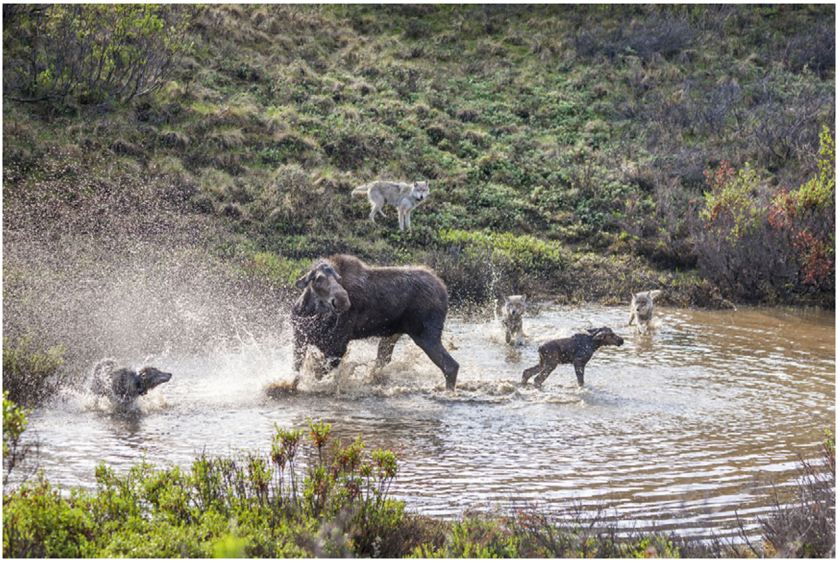

Figure 4.7 Cow moose defends her newly born calf from the Grant Creek wolf pack while surrounded in a tundra pond in Denali National Park, Alaska, photo Patrick J. Endres/Getty Images ©

information about prey position and direction of travel to the other pack members. For example, when lions see prey, they adopt a ridged, alert posture which give the other lions information about the prey's presence and location. In addition, individuals often choose to adopt a similar posture or speed of travel to that of conspecifics during hunts resulting in greater synchronization. This copying of behavior between individuals is effective because individuals base their decision both on information from the environment and from each other. In most circumstances, these strategies, which require a low level of cooperation with simple interactional rules, may be very effective (Bailey et al., 2013). Studies of schooling fish have also shown that they organize themselves in an attempt to obtain independent individual information. Their network of social influence is structured to reduce the probability that individuals obtain correlated (redundant) information from others (Couzin, 2018).

Furthermore, in most cooperative hunting species, there is some degree of information transfer amongst individuals in group hunting, achieved via visual, tactile, vocal or olfactory cues/signals or a combination of these. Depending on the hunting strategy, this can take the form of both

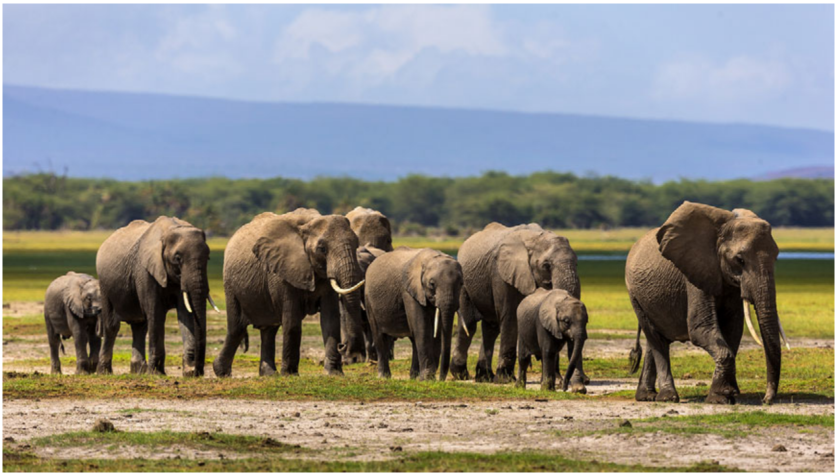

Figure 4.8 African Elephant herd walking on marshy area of Amboseli National park, Kenya. The oldest female is the leader of the herd, photo Manoj Shah/Getty Images ©

inadvertent behavioral cues or intentional signals. For example, vocal communication is ineffective for predators that typically rely on ambush, because the sound would alert prey. Dogs, however, rely less on surprise and thus can use vocal communication. In high levels of vegetation with poor visibility, calls may help coordinate pack movements, but they do not communicate specific hunting behaviors (Bailey et al., 2013).

These studies are interesting because they illustrate that higher-level cognition is not necessary to perform highly organized cooperative hunts. Effective coordination is achieved by following simple interactional rules in combination with some degree of associative learning (Bailey et al., 2013). Although chimpanzees are "mutually responsive" and adjust their individual actions according to the actions of other individuals in the group, there is no indication of joint planning. Nor is there any indication of a chimpanzee leader which directs the group activity (Moll & Tomasello, 2007). The collective behavior of these animal groups illustrates how simple interactions at the local level create complex patterns of coordinated activity at the system level.

Although these examples illustrate collective problem solving without leadership, many animal groups will still rely on a small minority acting as leaders. Leadership emerges when informed individuals successfully guide naive individuals towards favorable environments. Like elephants, smaller groups may recognize some individuals to be leaders, but this leadership is usually anonymous in large groups (Figure 4.8). For instance, if information sharing about who has the relevant knowledge cannot be directly signaled, leadership can instead be achieved when the informed subclass moves more quickly than the naive majority. When speed variations are used to transfer information, surprisingly few informed individuals are required to effectively lead a group (Berdahl et al., 2018). When moving together, individuals with faster speeds or slower turning behavior will tend to end up at positions towards the front and edge of groups. The leader in the front of groups will have a larger influence over group movements and decision-making because of how the information flows in the group. For example, fish leaders will elicit following from naive conspecifics by showing more directed movement paths or greater likelihood of initiating motion. In many cases, those individuals with relevant information or experience are more likely to get followers. For example, in groups of elephants and killer whales, knowledgeable and older individuals lead foraging decisions, especially when the environment is changing. Individuals which are central in social networks are also more likely to get followers (Jolles et al., 2020).

However, there will be a conflict of interest between maintaining group cohesion and moving towards the individually preferred target. If the group becomes too large or too diverse, it may become fragmented. One mechanism that helps avoid this is that members of the group rotate at being leaders. Because it is costly to devote a lot of attention to gathering information, it may also be more effective to have some leaders who primarily focus on environmental cues and followers who predominantly rely on social cues. This group heterogeneity may be an outcome of evolution, rather than simply a consequence of age structure or mixing (Berdahl et al., 2018; Jolles et al., 2020).

Studies show that only a very small group of goal-oriented individuals is required to lead a large numbers of uninformed individuals to novel resources. Naive individuals can even improve collective navigation, because they, in line with the many wrongs principle, contribute with errors that can actually stabilize consensus decision-making and increase the speed and sensitivity of consensus (Berdahl et al., 2018; Jolles et al., 2020). Likewise, studies of human groups show that a small, informed minority (5 percent) could guide a group of naive individuals to a target without verbal communication or obvious signaling. When conflicting directional information was given to the informed individuals in the group, the time taken to reach the target did not increase significantly. It suggests that this mechanism can also be effective even when the informed subgroup disagrees on the preferred options. When there was a disagreement, the majority dictated the group direction (Dyer et al., 2008).

Another aspect of group heterogeneity is the possibility of *social learning*. Social learning allows knowledge possessed by informed individuals to spread through the group and across generations through unidirectional copying behavior. If naive individuals follow more knowledgeable group individuals along a path or a migration route when they travel, they may learn the route by being exposed to the cues associated with that route. This learning is unidirectional in the way that individuals gain personal information by following others who already have that information. Over time, they will become an informed subset. For example, cranes have no genetically encoded preferred direction in navigational tasks but will instead rely on social learning over generations. Because there are different levels of knowledge in the group, naive individuals can learn migratory routes that may be helpful in future journeys. In such groups, there will both be informed and naive individuals. Intergenerational leadership will be one way that social learning can emerge. For example, neither genetic, nor environmental factors, explain Atlantic herring annually returning to specific sites to feed and breed. The most likely explanation is that young individuals school with and learn from older and more experienced individuals. Light-bellied brent geese also choose staging and wintering sites in adulthood that are identical or very near to those of their parents, indicating social learning of migratory routes. In such cases, successful navigation will be more effective with leadership by the informed subgroup. The other alternative, navigating by the "many wrongs" principle and averaging estimates across the entire group, would be worse when a large group of naive individuals lack experience of the route (Berdahl et al., 2018).

4.5.2 Human Heterogeneous Social Interaction as Human Swarm Problem Solving

There is also CI research that examines heterogeneous interaction through collective problem solving in different social network structures. These social structures will follow specific interactional rules. For instance, an important part of the original wisdom of crowd approach is decentralization (Surowiecki, 2005). Centralized networks are organized around a core or a leader, while decentralized networks open up for more direct social interaction. Here, the emphasis is on utilizing local and specialized individualized knowledge and avoiding a too strong centralization of the collective work.

In contrast, centralized networks have a structure where communication flows disproportionately through one or more members instead of being equally distributed among all members. In highly centralized structures, the core, or a coordinator, will broker all interactions amongst the peripheral group members. This guarantees that the core has access to all critical information and sole responsibility for coordinating activities for the whole group. The potential disadvantage is that the periphery will then become completely dependent on what the cores decides to share of information. Individuals in the periphery cannot share knowledge or learn from each other directly, and this is assumed to inhibit the problem-solving process. The core may end up being a bottleneck if a large quantity of information must flow through it or it can lead the whole network astray with bad ideas (Shore, Bernstein, & Jang, 2020).

Decentralized Networks

Because of limitations in centralized networks, decentralized structures have become more popular in recent years. It is assumed that a peripheral individual, who is closer to the problem, is more likely to provide a good solution. In addition, knowledge sharing can be done more effectively throughout the system. One study finds that in decentralized communication networks where everyone is equally connected, group estimates become more accurate because of information exchange instead of just aggregating the independent individual contributions. The social learning results in both individual and collective judgements becoming more similar and more accurate. In decentralized networks, social learning aims to utilize the heterogeneity of contributions in a more effective way (Becker et al., 2017). The results point to the importance of learning between near-neighbors and having a transparent access to information in these closer surroundings. Less confident or informed individuals can adopt better solutions from their peers. This communication may also lead to learning and important sharing of knowledge that increase the collective performance. It can be particularly valuable to rely on peers' knowledge when newcomers lack sufficient relevant experience (Lave & Wenger, 1991). Both IdeaRallys and hackathons, mentioned in the previous section as an example of a large gathering, also build on a decentralized network structure. This structure allows for flexible social interaction that enables participants to easily engage with each other without needing to communicate through a central core. The Foldit gaming community also resembles a decentralized network with different teams competing against each other, but at the same time, they share information and learn from each from other. Individuals take on different roles in teams, being both "solvers" and "evolvers" (see Section 2.3).

However, some wisdom of crowd studies also point to negative effects of social influence and knowledge sharing because individuals align their judgements and produce more bias. If a few individuals dominate, group estimates will more likely increase the error (Lorenz et al., 2011). Social influence does not automatically lead to learning but can result in "herding," with individuals just following the group instead of making their own individual independent judgement. Subgroups within a decentralized network may become too attached to an existing set of ideas. In uncertain environments, individuals will also have a tendency to copy their peers, which can lead to collective bubbles and clustering that increase conformity pressure (Shore et al., 2020).

Centralized Networks

There is lack of research in the field and it is far from obvious that decentralized networks are always superior to centralized networks. Human groups use many different network structures depending on the problem they want to solve. For example, wisdom of the crowd problems typically focus on a limited range of problem types, which involve static information. In rapidly changing environments, one recent study finds that centralized networks are more effective. This experimental study tested the effect of seven network structures on problem solving in a shifting environment. A murder mystery task was given, and early information encouraged individuals to first draw the wrong conclusion. When they later received new information, they would have to change the proposed solution (Shore et al., 2020).

The results show that the best performers were the centralized networks with peripheral nodes not being connected with each other. The core nodes in the centralized network identified more unique solutions than other networks structures such as a complete clique or local cluster. The two-way communication between the core and the periphery ensured the flow of communication and spread of good ideas. The positive effects arose because herding and conformity pressure were minimized and learning maximized. The inability of peripheral nodes to interact with each other did not limit problem solving, but preserved a degree of independence of judgement. This resulted in more openness and adaptation to new information. The periphery was more adaptable to new information and less likely to retain a wrong answer that had been established in the group too early. The centralized network also generated solutions that were more diverse. Although these were not recombined, good ideas still spread effectively even when they contradicted the majority opinion (Shore et al., 2020).

Furthermore, the core node appears to be essential in this network structure. The core gets access to many different opinions and uses its special position to learn from the peripheral independent nodes. It also acts as a filter, selecting promising ideas and sharing them with the periphery. Nor will the central node feel the same group pressure as a smaller cluster that is internally cohesive. This reduces the likelihood of being stuck with a premature consensus solution. The core can also make everyone voice their opinion to maximize the production of diverse ideas. The success lies in limiting conformity pressure, but still retaining efficient connectivity, promoting social influence as learning without herding.

However, there is a risk that the core becomes a bottleneck by giving too much weight to a few ideas or their own idea. If a central node has a bad idea, it can have a negative influence throughout the network. This is in line with the original assumption by Surowiecki (2005) that crowd wisdom occurs only if no single individual is too influential. Another issue is that in the experiment, random individuals were in the key central positions, which is not usually the case in authentic problem solving (Shore et al., 2020). Still, the findings suggests that both centralized and decentralized networks can utilize heterogeneous social interaction in effective swarm problem solving.

The Delphi Method

Moreover, there are specific crowdsourcing methods that seek to solve complex problems by using a centralized network structure. One of the most well-known methods is the Delphi technique or the Delphi method, a method often used in idea-generation and forecasting, but has since been widely applied in other areas (Tindale & Winget, 2019). It has been applied in various fields such as program planning, needs assessment, policy determination, and resource utilization (Hsu & Sandford, 2007). The method can be used to determine expert consensus when it is difficult to use other research methods or there is a lack of research on the topic. Panel members will typically be invited to solve the problem by using their professional or personal experience, i.e., practice-based evidence (Jorm, 2015). It is a widely used and accepted method for gathering data from respondents within a specific domain of expertise. The communication is organized to stimulate a convergence of individual opinions around a specific problem. The consensus evolves gradually through a collection of data from the panel members in multiple iterations (Hsu & Sandford, 2007).

The method is used to explore possible strategic alternatives within an area, explore underlying assumptions around a problem, and seek out a broad range of information, like connecting informed judgements on a multidisciplinary topic. Evidence may be available, but it can be incomplete or cannot be adapted to practice in a simple way. For example, in mental health research, the method has been used to define foundational concepts or determine collective values within an area (Hsu & Sandford, 2007; Jorm, 2015). The panel members who often are experts will use a range of different evidence to make their judgements, such as systematic reviews, individual experiments, qualitative studies, and personal experience. The panel may also include a wide range of stakeholders such as clinicians, researchers, consumers, and caregivers (Jorm, 2015).

The process has many variants, but the first step is usually to formulate a clear question that is answerable by the methodology. The group is challenged to make an estimation or a prediction, such as for example what mental health research topics should be prioritized by funders (Jorm, 2015). A facilitator will organize the Delphi study and recruit a group of individuals (panel members) with some expertise on the topic. Ideally, there should be a specific sampling strategy to recruit these experts. Although the group size can vary a lot, it will typically be from ten to 50 participants. Since the process depends on a statistical analysis, it is normal to recruit a relatively large number of participants to produce stable results (Jorm, 2015).

Typically, questionnaires will be used to collect data. The facilitator will compile a questionnaire with a list of relevant statements that the experts are to rate for agreement. The items can build on literature search or through qualitative feedback from the expert panel or other stakeholders. These items will usually attempt to give a complete coverage of an area (Jorm, 2015).

The facilitator will then send out and collect independent individual responses from the questionnaire. The invited group members make a series of independent estimates, rankings, or idea lists on a specific topic. The facilitator then compiles or aggregates the member responses and sends it back again to each participant as a meaningful summary (mean rank or probability estimate, list of ideas with generation frequencies, etc.) (Tindale & Winget, 2019). The feedback is sent anonymously to each individual in the group, but they can still compare the individual responses with the rest of the group. The results will typically be given as percentage endorsement or mean score for each item on a Likert rating scale. The emphasis is on describing the participant's own position in relation to the whole group. Qualitative feedback is used less often. It will be distributed as a summary of the group comments and make each participant aware of the range of opinions and the reasons that are given (Hsu & Sandford, 2007; Jorm, 2015).

In the second round, the participants can choose to revise or re-rate their initial estimations or judgements based on reading the group results. The results are presented in a well-organized summary of the prior iteration, which allows each participant to learn, gain new insights, and clarify or adjust their own choices. Individuals who deviate from the majority opinion can be asked to explain why, and this new information may also be sent to everyone and can potentially change the majority opinion in the group (Hsu & Sandford, 2007; Jorm, 2015).

Responses will usually converge after some rounds, and a statistical criterion is used to define when consensus has been reached. There is no single answer to what the percentage should be, but the cutoff may be lower for a multidisciplinary group than a single disciplinary group. Since the aim is to reach consensus, a supermajority rule will typically estimate when the group agrees, with items needing up to 90 percent endorsement to be included in the final iteration. Items in the initial questionnaire that deviate a lot from the consensus criterion might be eliminated immediately (Hsu & Sandford, 2007; Jorm, 2015; Tindale & Winget, 2019).

The Delphi method can go over several rounds, but two rounds is most common. The presentation of group opinions as statistical results allows for a more impartial summarization of the collected data. It also ensures that opinions generated by each individual is well represented in the final iteration. The final outcome can range from a frequency distribution of ideas to a choice for the preferred outcome or the central tendency (mean or median) estimate (Hsu & Sandford, 2007; Jorm, 2015; Tindale & Winget, 2019).

The Delphi method deviates from the wisdom of crowds approach proposed by Surowiecki (2005) in some ways. The original claim of making independent individual contributions is only important in the first round of the data collection. This strategy intends to avoid groupthink. In groups where members have similar backgrounds and interests, there is a risk of creating conformity pressure. However, the process is entirely different in the second round. Then, the participants are challenged to modify and seek consensus with the rest of the group based on aggregated group results. The anonymity of the responses intends to reduce conformity pressure and bias by ensuring that individuals do not have to agree with the rest of the group. Since the outcome will be an aggregated quantified result, it is reliant on equal participation and avoids influence from dominant individuals. In addition, the facilitator can remove irrelevant content that focuses on individual interests or statements rather than focusing on the collective problem solving process (Hsu & Sandford, 2007).

The social structure is very similar to a centralized network and dependent on the competence of the facilitator. The process emphasizes knowledge sharing between members, but without any direct contact between group members. The iterations show that individuals are allowed to be influenced by other decisions, but the primary emphasis is on learning and on providing more relevant information to every individual, and at the same time minimizing herding or group pressure. This procedure allows for knowledge sharing between the group members but avoids conformity pressure or undue influence by high-status members (Hsu & Sandford, 2007; Jorm, 2015; Tindale & Winget, 2019). Overall, the purpose of these procedures is to allow for some information exchange while holding control over potential distortions due to social influence. Research on the Delphi method has tended to show positive outcomes and do at least as well as, if not better than, face-to-face groups. (Tindale & Winget, 2019).

Although diversity of expertise is not a requirement, it is often recommended when selecting panel members. Because panel members do not have to meet offline, it is possible invite experts from all over the globe and make it easier to invite a diversity of expertise. Since the process is anonymous and builds on aggregated contributions, there are fewer disadvantages with using the online setting. Part of this diversity is also about ensuring that a diverse range of relevant topics are included in the questionnaire (Hsu & Sandford, 2007; Jorm, 2015).

As these examples show, both centralized and decentralized networks can be regarded as important examples of heterogeneous social interaction.

4.6 Environmental Sensing

4.6.1 Environmental Sensing in Animal Swarm Problem Solving

As mentioned in the previous section on large gatherings, the honeybees display a fascinating ability to maximize environmental information when they search for the best nest site in their surroundings. It is a matter of life or death for the bees, and they are usually able to identify all relevant

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Figure 4.9 Starlings move as one giant organism to synchronize their defence against predators, Kent, United Kingdom, photo Sandra Standbridge/Getty Images ©

options in the surrounding area. This is possible because the individual searching areas do not overlap with each other. Most other mobile animal groups will also aim to utilize individual sensing capabilities by collecting information about the surrounding environment in an effective way (Berdahl, Torney, Ioannou, Faria, & Couzin, 2013). Previous sections showed how groups are able to pool imperfect individual estimates according to the many wrongs principle and use this information to navigate noisy and complex environments.

Often, animals will combine environmental information and social information between members in the group. For example, birds will utilize the "many eyes principle" when they synchronize their decisions on when, and where, to move to find food or avoid threats. A bird spotting a danger will start to fly, and by this example set off the whole flock to fly away. Starlings synchronize their individual actions very rapidly (Figure 4.9). When a predator attacks, a few peripheral group members will make the first encounter. This elicits a sudden change in direction, which then spreads through the rest of the group. Because the birds have different spatial positions in the group, they acquire different information about the surroundings and utilize the "many eyes principle" when spotting danger (Couzin, 2018; Dyer et al., 2008).

Likewise, giant honeybees synchronize their activity to avoid threats. Because they nest on a single, open comb, they are a target for predatory wasps. When attacked, the bees respond by create "shimmering" waves collectively. Initially, a subset of individuals starts a wave by rapidly raising and lowering their abdomens, making the other neighboring bees do the same. As with neurons and other "excitable" cells, individual bees will need to "recover" for a short period after one round of activity. This creates very visible waves of rapidly expanding rings or spirals across the colony surface (Couzin, 2018).

Individuals respond to the body orientation of near-neighbors by alignment. It requires that each agent both independently gathers information about the environment, but also imitates the behavior of others. These simple rules or behavioral algorithms provide the basis for the "many eyes effect" by letting individuals benefit from others, such as when detecting a predator or finding food. This collective navigation is possible even when individuals do not know which cue other group members respond to at any moment in time. It is enough to copy or imitate the response of others in the vicinity (Krause et al., 2010). The group's capacity for surveillance also increases with the number of alert animals. Fragmented individual information will be integrated at a group level and provide a better overall "picture" (Feinerman & Korman, 2017).

Emergent sensing is a label used to describe how animal groups in different ways combine environmental information and social interactional rules, which can be different types of repulsion, alignment, and attraction (Berdahl et al., 2018; Puckett, Pokhrel, & Giannini, 2018). According to Berdahl et al. (2018), emergent sensing occurs when a group is able to navigate even when no individual is aware of the correct direction. In a school of fish, each individual fish directs its behavior based on the perception of the position and speed of its immediate neighbors. For example, if an individual fish has no memory and is only able to make a scalar, one-dimensional, measurement of the environment, it will not be able to assess the gradient of an environmental cue. However, when information from multiple individuals is compared with each other, the group can collectively measure and follow a gradient in the environment. This is possible because a part of the group behavior is orientated towards the environment, like when a school of fish navigate through a changing "noisy" light field. Although these fish are not able to detect environmental gradients individually, the school still manages to swim toward darker waters because of a simple context-dependent rule: when observing the light field, golden shiners swim faster in bright regions and slower in dark regions (Berdahl et al., 2013; Puckett et al., 2018). The movement is not directed by the behavior of one or a few "leader fish," but a self-organizing intelligent swarm system (Figure 4.10).

A study shows that when the fish make movement decisions, they respond more strongly to social influences like the location of near-neighbors compared with the environmental influence of light gradients.

Figure 4.10 Bronze whaler shark swimming through a giant ball of sardines, waiting to feed on them. Off the East coast of South Africa, photo wildestanimal/Getty Images ©

Fish located in bright regions will travel more quickly, but because the fish also attract each other, this creates a rotation in the school, turning the whole group toward the darker region. The swim speed differences within the group causes a turning toward those who move more slowly. The collective sensing of the group level is both a result of individuals adjusting their speed in response to local, scalar, measurements of light (environmental gradient) and the social attraction to others in the group. The group operates as a distributed sensor network (Berdahl et al., 2013, 2018). Another type of fish, the tetras, outperform many other types of fish because they can sense the environmental gradient individually. They rely more on environmental information and less on social information, and can therefore have more distance between the individuals in the group. Most groups will not only navigate on the basis of sharing of information within the group, but they will respond to local environmental cues like light, odor, temperature, or finding the winds or currents that provide a better migration route (Berdahl et al., 2018; Puckett et al., 2018).

Another interesting finding is that simulations of schooling fish show that the group-level responsiveness to the environment improves spontaneously as group size increases. Although increased group numbers reduce measurement error, the key determinant of improved performance is the spatial extent of the group in relation to the length scale of the environment. Groups that are able to span a larger area are more likely to capture variations in environmental cues that are necessary to elicit speed differences between individuals in the group. Each individual exhibits a rudimentary, nondirectional response to the environment. This emergent sensing creates a collective response to the environment not present at the individual level. The results suggest that the ability to respond to environmental information may decline if the group fragments or is reduced in size (Berdahl et al., 2013). Studies of salmon in the wild have shown that in years with more fish, navigation to natal streams is more accurate. The journey home may benefit from the many wrongs principle when crossing the ocean, consensus decision-making when choosing between two freshwater streams and emergent sensing when locating the odor of a river or entrance of a fish ladder (Berdahl et al., 2018).

Social learning within groups is also important. If the size and composition of the groups varies and animals move throughout the environment, there will be present a large local heterogeneity of knowledge about the environment. In such cases, animal groups can make the best decisions by harnessing information from every one and follow the most informed group members. Naive individuals can even contribute with random noise and errors that may lead to the discovery of improved routes over time. This interaction between multiple individuals can sometimes lead to the production of new knowledge. For example, a group can jointly discover an improved route, through "the many wrongs principle," and individuals in the group will then learn this new route (Berdahl et al., 2018). By collecting both social and environmental information, a group of individuals can improve their collective decisions if they are able to balance this information in an efficient way (Puckett et al., 2018).

4.6.2 Human Environmental Sensing

In environmental sensing, the basic assumption is that large groups can perform better because they can access more environmental information. One way of maximizing relevant information from the environment is by having a broad outreach. Many CI projects build on open calls for participation where anyone can join and all who join have equal status. The communication is not targeted towards one specific person or group. Like with a warning cry, the call for participation is just "released" into the surrounding environment, which in this case is the Internet as a global environment. The aim is often to recruit the right problem solvers with relevant competence. The goal is to either find the unknown intelligent outsider or recruit a large enough group of people that can provide a collective estimation or solution to a problem.

Crowdsourcing in Disaster Management

One example of environmental sensing is crowdsourcing in disaster management. In these scenarios, it is important that everyone who is affected contribute with data. Crowdsourcing was first used in the management of the Haiti Earthquake in 2010. Nearly 40,000 independent reports were analyzed in a volunteer-driven effort to produce a crisis map after the earthquake. Volunteers, recruited through social media, did the translation and geocoding of these messages. The countries had limited infrastructure and few roadmaps that could be used to distribute disaster aid. In only two weeks, 640 volunteers helped create road maps of Haiti and mapped displaced persons camps of Haiti. People in the worst disaster areas could send requests for shelter, food, and medicines to the government through an online system. This crowd effort made it easier for the government to organize help (Kankanamge, Yigitcanlar, Goonetilleke, & Kamruzzaman, 2019).

Today, mobile technologies provide new opportunities when citizens can act as moving sensors, reporters, and micro-taskers. An enormous amount of real-time georeferenced information can be collected with speed and diversity (Kankanamge et al., 2019). For instance, citizens produced massive amounts of digital, real time, local information on critical events such as Hurricane Sandy in 2012, or the Nepal earthquake in 2015 (Poblet, García-Cuesta, & Casanovas, 2018), wildland fire incidents (Manavi, Gould, Smith, Thorp, & Guerin, 2020), or floods (Bhuvana & Aram, 2019).

In disasters, traditional communication modes such as wired telephones, television, mobile applications, and radios frequently crash, but social media will often remain intact. Especially, the propagation speed and the reaction time of social media has challenged the use of traditional communication modes during disasters. The communication flow between people through social media has enabled more personalized warnings in disaster areas and is today challenging the conventional disaster warning methods. Today, emergencies are often first reported through the "eyes" of personal mobile cameras and then shared on social media, rather than reported to officials. The first warning alerts happen through communication in personal and informal social networks in the local language. These provide assurance that family and friends are safe. At an aggregated level, this information will typically provide the best updated information about the status of a situation. Ordinary citizens are becoming increasingly important in solving these type of emergent problems (Kankanamge et al., 2019).

If we look more specifically at geomobile technologies, they can maximize environmental information in at least three different ways (Poblet et al., 2018). First, the "crowd as sensors" is a type of crowdsourcing that enables the collection of data from multiple devices, including mobile handsets, and each of these devices provides some local information that can be either automatically generated by sensors running in the background or it can be generated by humans. A large number of users can generate raw data by merely carrying their mobile devices. Sensor-enabled mobile devices (processes run in the backend by GIS receivers, accelerometers, gyroscopes, magnetometers, etc.) automatically collect data in the background. These types of data are especially important in the mitigation and preparedness phases of disaster management. They can inform about stampedes or traffic jams, seismic sensing, and how the population is distributed. Participants do not actively have to contribute with information. However, GPS location services require users' explicit permission of access, while other location sensors such as accelerometers and gyroscopes do not (Poblet et al., 2018).

A second type of crowdsourcing is the crowd as reporters. Social media users (Twitter, Facebook, Instagram, etc.) will also produce first-hand, real-time information on events as they are unfolding (e.g., tweeting about a hurricane and the damages in a specific location). This user-generated content is important in information sharing and also contains valuable metadata added by the users themselves (e.g., hashtags) (Poblet et al., 2018). These data can be used to extract semantically structured information that can give important situational knowledge during an emergency.

One example is data mining of all messages people have posted about the disaster in social media channels like Twitter or Facebook. However, it is not easy to analyze data effectively within a very short period. For example, in the case of 2012 Hurricane Sandy, 26 million tweets were produced over a two-week post period. This is a huge amount of data, which poses challenges for filtering and synthesizing the relevant information (Kankanamge et al., 2019; Poblet et al., 2018). The quality of the data will depend on the credibility of the reporters and a lack of control in this step can mislead decisions. There needs to be some quality control mechanisms based on experience, reputation of sources, and verification with other sources of information (Poblet et al., 2018).

Therefore, the response time of this type of tasks will increase compared with other types of geodata that can be used immediately. Some of the critical issues concerning trustworthiness and privacy are easier to handle as the crowd actively take the role of a "reporter." When people are already identified, assessing the trustworthiness of the source and verifying the incoming information may be less problematic (Poblet et al., 2018).

Finally, "crowds as micro-taskers" includes people executing specific processing tasks, which typically involve a modularization of a complex task into many smaller and independent tasks. One example is the categorization of raw data (labeling images, adding coordinates, tagging reports with categories, etc.). Volunteers can be part of a global response that allow them to participate in a number of tasks such as social media monitoring, data collection, data filtering, tagging, geolocation of events, etc. Because essential information needs to be analyzed rapidly, it requires active contributions from many volunteers. Sometimes, these processing tasks may require a training phase. Automatics tools and machine learning algorithms can also do some of this work and reduce response time further in a disaster management scenario. Still, rescue forces are the key volunteers during disasters, but online volunteerism can potentially support this ground work through information sharing on missing people or damaged property (Kankanamge et al., 2019; Poblet et al., 2018).

New forms of participation for individuals and communities often blurs the skill-based distinctions between amateurs and professionals. This can make it difficult to establish a shared understanding of how different sources of data should be used. Shared standards have also become crucial to facilitate interoperability and reduce misunderstandings (Poblet et al., 2018). The crowdsourcing methods in disaster management are still immature, but the potential in this type of human environmental sensing is significant.

Collecting Environmental Information in Smart Cities

A new trend in human environmental sensing is the development of smart cities that aim to employ information and communication technologies to improve the quality of life for its citizens. Many researchers claim citizens' use of technological infrastructure based on the Internet of Things and mobile technologies could potentially help societies in solving a range of different problems, such as environmental pollution, local economy health problems, or traffic management (Ismagilova, Hughes, Dwivedi, &

Raman, 2019; Staletić, Labus, Bogdanović, Despotović-Zrakić, & Radenković, 2020). These technologies are used to collect digitized information about the city environment.

One area is "smart mobility" that often addresses traffic management. This involves how to avoid road congestion by gathering data from sensors networks, which also involves tracking of moving vehicles. "Smart living" comprises areas such as public safety, healthcare, education, tourism, and smart buildings. For example, in developing countries, public safety is a big area of concern because of growing urbanization. One example is a crowdsourcing project in South Africa that tested the usability of an Interactive Voice Response (IVR) system to let people voluntarily report on any safety issues (Breetzke & Flowerday, 2016; Ismagilova et al., 2019). "Smart environment" is another area that emphasizes quality of air, water, green spaces, emission monitoring, waste collection management, energy efficiency, and monitoring of city trees. In some projects, citizens collect environmental data with their mobile phones. In one study, a crowdsourced weather app combined automated sensor readings from mobile phones and manual input by citizens to estimate current and future weather conditions. The results showed a high level of accuracy in estimating actual weather conditions, indicating that hybrid participation that combine machine intelligence and human intelligence can improve weather condition estimation and prediction (Ismagilova et al., 2019; Niforatos, Vourvopoulos, & Langheinrich, 2017).

Sensor-rich mobile phones allow for the collection of a range of new types of data about the environment. Mobile crowdsensing let ordinary citizens contribute data from their mobile devices, which are aggregated at a collective level. Users are typically supposed to act together, in order to generate knowledge beyond an individual level. The different modalities of sensing include numeric values (such as air quality and GPS coordinates), audios, and pictures or videos. Visual crowdsensing that uses built-in cameras of smart devices has become increasingly popular. In specific projects, people can be asked to capture objects, for example in the form of pictures or videos. Many crowdsensing projects have been developed in the context of smart cities. One example is how phones perform passive tasks and monitor noise and sound in the smartphone's microphones as sound sensing devices for creating large-scale noise maps and for suggesting city managers suitable noise reduction interventions (Staletić et al., 2020).

The notion of smart cities also includes citizen engagement and new types of interaction with the government. In some cases, this is primarily to ensure full adoption of new changes and services, but other models utilize user-generated content and underline the codesign and coproduction of government functions. This includes the collection of user generated content and use of analytics that can be used to generate predictive models, enabling local government to be more strategic and proactive in its responses to citizen requirements (Ismagilova et al., 2019). Decisions are made by aggregating active user contributions (students' favorite jogging and cycling routes, places with major social activities, etc. (Bellavista, Corradi, Foschini, Noor, & Zanni, 2018). One simple example is crowdsourcing of cycling routes in the city, where city planners have gathered data from cyclists to analyses traffic and improve urban infrastructure by adding racks or widening lanes (Ismagilova et al., 2019). Other active tasks may involve taking pictures, using tags, committing actions, answering a survey, etc. Collection of data from passive tasks can be performed automatically by users' smartphones, e.g., triggered by geo-localization of the user position. This can be self-monitoring activities like how much time has been spent walking (Bellavista et al., 2018).

Data are assumed to provide a better understanding of the community conditions and facilitate better evidence-based decision-making (Alizadeh, 2018). Many of these projects are reliant on people being willing to collaborate toward continuous data harvesting processes. It allows people to participate in any aspect of urban planning, by collecting and sharing data, reporting issues to public administrations, proposing solutions to urban planners, and delivering information of potential social interest to their community. Although these projects can be helpful for citizens, mobile users are reluctant to use their devices for these purposes, mainly due to privacy issues (Bellavista et al., 2020).

Furthermore, there is a growing number of planning departments at different levels (e.g., local and state) that use crowdsourcing to seek public opinions, ideas, and feedback on their, mostly strategic, planning. In some cases, especially designed digital platforms have been used to facilitate active crowdsourcing of ideas. However, they are often expensive to maintain and compete with other social media platforms (e.g., Facebook). For instance, the City of Vancouver used an online platform to seek feedback as part of the participatory process involved in the development of its first urban digital strategy document (Alizadeh, 2018). Another example is Citizen Design Science, which challenges citizen to become urban designers by drawing their own habitat. They will build their design on residential rather than economic interests. Neighborhood interests may also diverge from how the municipality thinks (J. Mueller, Lu, Chirkin, Klein, & Schmitt, 2018).

Moreover, in participatory planning, *passive crowdsourcing* has been introduced as an alternative channel to gather people's voices in urban decision-making processes. This type of crowdsourcing passively collects information, knowledge, opinions, and ideas concerning hot topics of the day created by citizens without any initiation, stimulation, or moderation from government postings. It can exploit the extensive political content continuously created in numerous social media platforms by citizens and inform public policy. It differs from the original "task-oriented" crowdsourcing approach in its emphasis on "crowdsourcing of opinions" (Alizadeh, 2018; Alizadeh, Sarkar, & Burgoyne, 2019).

One study illustrates how this type of crowdsourcing can be performed as a sentiment analysis in relation to traffic issues. On Twitter, the query "Parramatta road" is particularly active during traffic congestion or accidents. Tweets can be analyzed automatically according to their sentiment, including both positive and negative opinions. In this particular study, words like "happy," "good," and "sun" were given a positive score and words such as "angry," "traffic," or "lost" were given negative scores. The aggregated results would then inform on when there was a potential breakdown in the road system. Timing is an important factor since certain events create a burstiness of tweets, followed by spans of silence (Alizadeh et al., 2019).

Here, crowdsourcing is no longer about getting a certain task done with intentional help from the crowd. Instead, opinions, ideas, or perceptions from the public are aggregated through polling, sentiment analysis, and opinion mining. Sentiment analysis uses language processing and machine learning to identify which topics different groups talk and care about the most. Social media like Twitter are rich sources of opinions; and can be used for this type of analysis. Social media monitoring is used to continuously crawl and analyze data already available and mostly untapped, sometimes in real time, such as Twitter. These methods are already used by private companies today when they map potential markets, but have rarely been used for public purposes to strengthen the citizen voice (Alizadeh, 2018; Alizadeh et al., 2019). Still, passive crowdsourcing can be regarded as a type of environmental sensing that utilizes a more open government structure that can perhaps complement traditional urban planning approaches in the future.

4.7 What Is Human Swarm Problem Solving?

If we summarize the chapter, we have shown that sections show that animal groups and humans share some of the same mechanisms when they solve problem together. What is both amazing and perhaps quite surprising to the reader, is that animals are able to benefit of wisdom of crowd effects. There are commonalities concerning both decisions threshold methods and averaging methods. These two sections show how information from many individuals can be aggregated in effective ways when solving problems. The three other sections describe social practices that support collective problem solving. The section on large gatherings shows how large groups can solve problems effectively together in various ways; the section on heterogeneous social interaction describes the importance of individual diversity and learning in groups. The final section provides examples of how one can collect environmental information in different ways to maximize informational diversity. Together, these mechanisms provide a picture of a distinct type of collective problem solving, which here is labeled as human swarm problem solving. Compared with the wisdom of crowds literature, this account of human swarm problem solving provides a broader framework that includes both independent and dependent contributions and both quantitative and qualitative contributions. What, then, are the commonalities of the swarm problems described in this chapter? In comparing the analysis in the different sections, a tentative typology of human swarm problem solving will here be described, covering the following four areas:

1. Predefined problems
2. Prespecified problem-solving procedures
3. Rapid time-limited problem solving
4. Individual learning

4.7.1 Predefined Problems

If we look closer at all the examples in this chapter, we see that the problems are predefined in different ways. A project will describe an initial problem or challenge and formulate an "open call for help." In the online setting, the outreach can be to a very large group of potential problem solvers. Some projects look for individuals with special expertise (e.g., IdeaConnection), but in several projects, such as within citizen science (e.g., Galaxy Zoo), anyone can participate. This also includes most of the crowdsourcing projects in Chapter 2. Because the outreach is broad, it is important to formulate the problem in a precise way, so it is easy for potential participants to assess whether the task is relevant to do. Some problems are well-defined because the tasks are relatively simple tasks and do not require much background skills (e.g., Galaxy Zoo project). Regarding complex problems in innovation contests, intermediaries will often support the solution-seeker in formulating the problem in an accessible way. Deliberative Polling and the Delphi method are other examples of complex problem solving that involve a high degree of uncertainty about the best options. Still, both these approaches are reliant on a precise formulation of the problem. In Deliberative Polling, participants receive briefing material that aim to give a balanced and comprehensive introduction to the problem in a short time. In the Delphi method, the problem is described in the questionnaire sent out to the participants. In both these processes, the solutions will also be presented as a statistical result. Disaster management is another example of a predefined problem that centers on an emergency. Although part of the challenge may be to get an overview of the situation and what actually is happening on the ground, there is still no doubt about the general problem whether it is an earthquake or wildland fire.

4.7.2 Prespecified Problem-Solving Procedures

In human swarm problem solving, there is usually no need to metacommunicate about the collective work because the problem, the interactional rules, and the aggregation rules are defined in advance. By minimizing the need for explicit coordination, problems can be solved more rapidly. Nor is direct coordination possible when the group size is large. Two examples are Deliberative Polling and the Delphi method, where both the interactional rules and aggregation rules have been formulated in advance in a quite detailed way. In a hackathon, there are fewer interactional rules and more participant autonomy. Still, the core of the collective work, like the sessions and the contest format, will have been planned.

As animal groups follow a few simple rules in swarm problem solving, so will human swarms do the same in this approach. However, the human swarm contributions are obviously much more heterogeneous, being anything from a vote, an argument, or an informational report. Problem-solving procedures, like interactional rules and aggregation rules, will also vary a lot. Still, both honeybees and humans will in this type of problem solving be similar in the sharing of a common interest and agreement on the objective (Seeley, 2010: 233–234).

Participant Selection

Concerning participant selection, some projects allow for self-selection (e.g., citizen science and innovation contests), while other projects invite specific persons to participate, for example by random sampling (e.g., Deliberative poll) or expert sampling (e.g., Delphi method). Participant selection is important in both the Delphi method and Deliberative Polling when the goal is to maximize comprehensive information about an issue. In the political domain, random sampling of any citizen can give information about the entire population. In contrast, the Delphi method typically invites formal experts to provide a broad coverage of one specific area. In different ways, both approaches seek informational diversity through the careful selection of participants.

Near-Neighbor Alignment

Human swarm problem solving is also characterized by interactional rules, like near-neighbor alignment. The human swarm in the UNU platform has real-time access to the group opinion and will typically align to each other in the rapid "tug of war" problem-solving process. In the Delphi method, near-neighbor alignment is possible through the sharing of statistical results. Participants are asked if they want to adjust or align their individual opinion based on the results from the group opinion. A certain aggregated percentage threshold needs to be reached for each item to be included in the final report, which represents the group opinion. In addition, small group discussions in Deliberative Polling can be regarded as a type alignment to near-neighbors that emerges through discussions. A large group of hundreds of persons is split into many small groups with 15 persons. These groups deliberate in a decentralized network and each group will be "near-neighbors" to each other, being mostly separated from the other small groups.

Coordinators Enforce the Interactional Rules

In animal swarm problem solving, individuals follow interaction rules as a part of their innate behavior. There is no need for someone to control their behavior (Seeley, 2010: 233–234). This is very different in human swarm problem solving because individuals will not automatically follow rules or guidelines. In many of the examples in this chapter, coordinators also need to support the collective problem solving by ensuring procedures are followed. Facilitators in Deliberative Polling ensure equal participation. In the Delphi method, a moderator helps summarizing the work. In a hackathon, coordinators are important as event organizers.

Competition between Different Proposed Solutions

Human swarm problem solving often centers on some type of competition. In Foldit, this requires competition rules and active use of leaderboards. In a hackathon, the individuals compete for prizes within a short time period. Even the Deliberative Polling can be regarded as a contest between different proposed solutions, which in the end will be ranked against each other. The UNU platform can be looked on as a "tug of war" contest between different predefined alternatives. Likewise, the waggle dance meeting among the honeybees also functions as an open competition among the proposed alternatives. Groups compete to gain additional members from a pool of scout bees who are not yet committed to a site. Whichever group first attracts a quorum of supporters win the competition. The winning group then goes on to build consensus among the scouts (Seeley, 2010: 73–75, 226). The difference between bees and humans is that humans use a variety of competition rules, like different voting procedures.

According to Malone et al. (2009), competition is especially useful when only a few good solutions are needed. For example, solution-seekers in innovation contests do not want a large number of alternative solutions to their problems, but only one or a few solutions of optimal quality.

Prespecified Aggregation Rule

Many of the CI projects in this chapter build on the aggregation of all group contributions. Together these contributions can produce one single or a set of optimal solutions, but it can be achieved in various ways. Four aggregation rules are mentioned in this chapter. First, both humans and other animals use averaging strategies. In line with the original wisdom of crowd approach, this statistical rule assumes that the crowd is intelligent when individuals contribute with diverse perspectives in combination with, independent and unbiased opinions.

Second, all contributions can be ranked. In the Delphi method, all items in a questionnaire that receive a certain level of support are included in the final report. Another example is Deliberative Polling, which ranks all results by letting participants vote on proposed solutions.

Third, quorum response ensures that a minimum number of individuals agree before the group shifts to a new behavior. The most well-known quorum response is the majority rule, which selects the most preferred of one of two alternatives. Everyone will then follow this decision. This is an essential decision-making method in all types of democratic decision-making, and even animal groups sometimes use this aggregation method. Today, digital technologies and the online setting make it easier for large groups to use voting methods. Simple majority is most common, but supermajority rule is also sometimes used in political systems and in other types of swarm problem solving such as the Delphi method.

Animal groups even show that the decision threshold can be much lower than a majority. However, there are few such examples of human quorum responses. One example is the presence of a certain number of people to be present to make the vote valid. When not everyone has to be present, this makes the decision-making system more efficient. The UNU platform also uses a decision threshold, but it is uncertain how much support is required. Crowdfunding is another example that illustrates how the total amount of money can function as an alternative quorum response, offering a more flexible individual contribution than equally weighted votes.

A fourth aggregation rule concerns the qualitative contributions. In disaster management, this can be the collective production of a digital map of the disaster area. In these situations, it is essential to get precise information because difficult decisions need to be made within a short time frame. Passive crowdsourcing is another example that illustrates how one can automatically collect social media data. These data can be used to quickly aggregate crisis information. Fluctuations in the use of key words, for instance hashtags, can provide information about what is happening on the ground. This type of aggregation resembles environmental sensing; in letting the "many eyes" of different individuals provide an updated continuous overview of a complex problem. All the individuals operate as one unit, like a synchronized sensor network that maximizes the collection of environmental information through a broad outreach. Smart cities build on the same approach, but here the privacy concerns are much more apparent (Zuboff, 2019).

If we compare the different aggregation rules, we see that optimal swarm problem solving involve both quantitative and qualitative contributions that can be both independent and dependent on each other. However, the aggregation seldom recombines or synthesizes contributions. The aggregation rules are typically prespecified, whether it is an averaging strategy or majority rule.

4.7.3 Rapid Time-Limited Problem Solving

This chapter shows the importance of rapid problem solving. Animal groups operate according to a speed vs. accuracy tradeoff. Among ants, the evaluation time of different nests regulate decision-making because they use longer time to accept lower quality nests. To speed up decision-making, a relatively low quorum number is required. When a certain number of ants move in the same direction, all ants will suddenly switch from slow to rapid movements and begin moving to one of the new nests. Honeybees also act under time pressure when looking for a new nest site. A decision must be made within a few days. The bees elicit a quorum response long before a majority of bees has checked the site and the accuracy of the decision is still very high.

If we look at the examples of human swarm problem solving, they also highlight "decision speed." Both hackathons and Deliberative Polling require a weekend. Decisions in the UNU platform happens within seconds, and in disaster management, even lives depend on rapid decision-making.

The challenge is to enable a large number of individuals to produce new levels of insight under significant time compression. Swarm problem solving is in a hurry or it has a tight schedule to follow. This includes both tasks that allow direct interaction and other projects where contributions must be made separately from each other. The rapid problem solving is typically made possible because everyone adheres to prespecified problem-solving procedures. Here, two types of rapidity are highlighted, solving a problem as fast as possible or within a prespecified deadline.

Making a Decision as Fast as Possible

In some cases, a human swarm will want to make decisions as "fast as possible." When there is an emergency, there will be an immediate need for crowd data that can provide information about the problem. There is no final deadline, just a general sense of urgency. The crowd can be involved as both sensors, reporters, and micro-taskers. Social media is also a channel that continuously produces relevant information that can be utilized. In smart cities, mobile crowdsensing aim to solve problems by collecting sensor data from mobile phones and other geo-technological tools. Citizens can also actively report information through different types of online communication. Today, companies already use these data commercially, and there has been few legal regulations, but this will likely change in the future.

Short Deadlines

In other cases, the human swarm will operate within a prescheduled deadline, typically a short period. There is still a wide range of timescales, covering anything from seconds to months. In swarm platforms, the period can be as shorter than a minute. Hackathons or Deliberative Polling demands intense done during a weekend. However, it varies how tightly organized the work is. A hackathon is more loosely organized, while the Deliberative Polling follows a tightly organized procedure. The Delphi method may last much longer, like several months, since the problem solving covers several iterations. The limitations of a short problem-solving period is compensated by increasing the number of participants joining the project.

Moreover, innovation contests often cover only a few weeks or months. The deadlines can have a positive influence on the creative problem-solving process, as this statement from a top solver illustrates:

> *For me the solutions tend to come quicker nearer the deadline, like a lot of students writing a thesis who tend to get most of it done at the end. I have to confess some of that's true with me. When the deadline comes, it tends to spur creativity a lot. You now, you might think about it for a while and do a little research, but it seems like the biggest breakthroughs tend to come closest to the deadline.*

The solver shows how being in a hurry can boost creativity when closing in on the deadline. This urgency is at the center of what characterizes swarm problem solving.

4.7.4 Individual Learning

It is not apparent that human swarm problem solving always promotes individual learning. In the original wisdom of crowd approach (2005), the ideal is to reduce negative social influence such as herding effects. The risk of individual learning is that it can reduce diversity of opinion and promote herding instead of informed opinions. According to "the many wrongs principle" incorrect guesses at an individual level can make the crowd wiser. This suggests a possible conflict between collective performance and individual learning.

This dilemma is present in several citizen science projects (e.g., the Galaxy Zoo project). When using averaging, it is usually important to gather independent contributions, which ensure the quality of the work. The single individual will then have no information about other contributions. Social interaction is avoided because it can introduce herding effects, groupthink, or systematic bias.

Another example is decision-making process in the UNU platform. It is performed so rapidly to reduce potential negative effects of long-term social influence. As biologists have noted, even naive individuals can improve collective navigation, just by contributing error. Although some individuals are not particularly accurate, they introduce valuable "noise" that makes the crowd wise relative to the individual. Another advantage with minimizing individual learning is that the task can be done faster and make the problem-solving process more time efficient.

Nevertheless, there is much more attention today around the possible positive effects of individual learning in human swarm problem solving. While wisdom of crowd literature originally highlighted the importance of making independent separate contributions, dependent contributions are today considered to be equally important. Even animal groups appear to be able to both share information and simultaneously make individually independent assessments.

In human swarm problem solving, individual learning within a group can also improve crowd performance if one avoids herding or conformity pressure (Shore et al., 2020). However, there is a tension between the need for independent opinions and the need for some degree of information transfer. Learning and herding are two different types of social influence that can be present at the same time (Shore et al., 2020). Collusion, alignment, and peer group pressure are constant threats when social interaction is possible. Groupthink ("Social proof") is our tendency to assume that if lots of people believe something, there must be a good reason why. One important factor is to get people to pay much less attention to what everyone else is saying.

Still, there is a need for learning and deliberation between individuals. The challenge is to find the balance between independent thinkers who create their own opinions and do not simply follow the views of others and those who are able to build on other ideas. This can be described as an *independence vs. learning tradeoff*, which open for different participatory designs. Both Deliberative Polling and the Delphi method expect individual learning to happen during the collective problem-solving process. However, the processes differ because Deliberative Polling promotes direct interaction, while the Delphi method builds on indirect interaction. Participants only get access to aggregated group information. The emphasis is on knowledge sharing and ensuring informational diversity, but without the opportunity of having any discussions. This is very different in Deliberative Polling because participants are encouraged to discuss ideas, but still primarily in separate subgroups.

Individual learning can happen in several different ways in the human swarm, both through observational learning and conversational learning. In *observational learning*, individuals learn by observing what others are doing and what they are discussing. One relevant example is hackathons in an offline setting and the traces of discussions in an IdeaRally in the online setting (Chapter 2). Here, the transparency of the environment is key, as is how it supports knowledge sharing. In centralized networks, the core node will spread information to everyone in the crowd without creating the same conformity pressure (Shore et al., 2020). The Delphi method is one example of how aggregated group results are shared with everyone. This is done anonymously through a facilitator. By not allowing direct interaction between participants, the degree of independent assessment is larger and the role of social influence is minimized. The goal is to maximize learning and minimize herding, like conformity pressure or uncritical copying of others' behavior.

Another example of observational learning is how disaster management platforms give everyone an updated overview of what is happening on the ground. By effectively aggregate all information on one site, individuals will more quickly learn about the situation and act more appropriately. In areas where such incidents occur often, like frequent occurrences of wildfires or flooding, it is essential that individuals learn how to take such systems in use in effective ways.

Furthermore, *conversational learning* is another important part of many human swarms. Both a hackathon and Deliberative Polling center on conversational learning between participants. The discussions can last for two days, and because participants are together most of the time, this allows for intense discussions. There is also experimentation, with discussion in similar large groups in an online setting, such as the previously mentioned IdeaRally (see Chapter 2).

Deliberative Polling can be regarded as a decentralized network, which divides several hundred participants into separate discussion groups comprising 15 persons. Individuals will engage in conversational learning with "near-neighbors" in these subgroups, most of the time separated from others. This may reduce potential negative herding effects.

Compared with the Delphi method, the learning potential is likely to be larger in Deliberative Polling because it is easier for participants to elaborate on each other's arguments. However, this also increases the risk of negative conformity effects. A facilitator is included to avoid such effects and ensure equal participation. Another aspect of this learning process is the briefing materials participants receive. They offer individual learning, but they may also unintentionally create negative herding effects. However, both Deliberative Polling and the Delphi method collect the final results anonymously to strengthen the independent voices in the process.

4.7.5 Summary of the Basic Characteristics in Human Swarm Problem Solving

In conclusion, the quality of human swarm problem solving depends on whether one is able to utilize sufficient diversity of perspectives. Most of the swarm designs aim to produce informational diversity by bringing in people with different backgrounds from different environments. As mentioned in the sections on averaging and decision thresholds methods, individuals may benefit from pooling information to overcome inaccurate estimates according to "the many wrongs principle." These contributions will be aggregated and not recombined or synthesized. The sections on heterogeneous social interaction and large gatherings show how cognitive diversity can be utilized in accordance with the diversity prediction theorem (Hong & Page, 2004). Likewise, the section on human environmental sensing shows how environmental information can be maximized according to "the many eyes principle." Large gatherings also stand out as one of the most interesting swarm mechanisms in an online setting (e.g., IdeaRally).

Honeybee nest siting is in many ways a prominent example that can provide inspiration for human swarm problem solving. When searching the surroundings for the ideal home, they utilize "the many eyes principle" by identifying all relevant options with an extraordinary precision. They then compare all contributions through the waggle dance and are almost always able to identify the best solution through a quorum response mechanism. They have perfected both the informational search process and knowledge sharing process afterwards so the whole process is completed within just a few days. (Seeley, 2010: 73–75, 224). We are still far from designing human swarm problem solving to be as successful as the honeybees, but by better understanding its basic mechanisms, one can hope that new technological inventions can make us better able to utilize this type of problem solving in both an offline and online setting.

Notes

1 Meerkats forage for insects. https://www.youtube.com/watch?v=cFC8irxuvcQ
2 Flash Expansion of Whirligig Beetles. https://www.youtube.com/watch?v=Civ1zL3nIzU
3 The Waggle Dance of the Honeybee. https://www.youtube.com/watch?v=bFDGPgXtK-U

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