Kinds of collective behavior and the possibility of group minds[1]

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Many species of bacteria "form complex communities, hunt prey in groups and secrete chemical trails for the directed movement of thousands of individuals" (Shapiro 1988). As they grow, divide and multiply, they reflexively release a species-typical signaling molecule known as an autoinducer. At low levels of concentration, autoinducers rapidly diffuse; but they are reliably detected as their concentration increases. When *Alvibrio fischeri* detect their species-typical autoinducers, they express genes that evoke bioluminescence (Bassler 2010; Camilli & Bassler 2006; Rutherford & Bassler 2012). Bobtail squid have evolved to exploit the bioluminescent properties of these bacteria. They hunt at night, in clear, shallow water. By monitoring the moonlight, and adjusting the shutters on their light organ, they can cancel out their shadows and hunt in stealth mode. But each morning, they expel most of the bacteria in their light organ and bury themselves in the sand. The lights turn off. But the remaining bacteria multiply throughout the day. And as night falls, the lights come on. The squid hunts. And the cycle repeats.

Like all bacteria, *A. fischeri* are tiny adaptive machines, which have been optimized for pursuing nutrients and avoiding toxins.[2] They benefit from their mutualism with bobtail squid (which provide enough sugar and amino acids to minimize competition for nutrients). And this has put selective pressure on their capacity for collective-bioluminesence. Nonetheless, their behavior can be fully explained in terms of individual mechanical capacities: each cell releases an autoinducer, each cell tracks the prevalence of that autoinducer, and each cell responds to that autoinducers as a salient feature of its environment. Nothing needs to be represented by the group, and behavioral alignment arises mechanically through the synchronized production and uptake of chemical signals. These bacteria only track autoinducers, and they only respond to locally available information. So it would be a stretch to call this a social phenomenon, even though it is a collective phenomenon.

Put bluntly, bacteria are like windowless monads. Without representing one another, they adjust their behavior in parallel. Since each organism acts in the same way, at the same time, a robust form of behavioral alignment emerges. But the resulting form of collective behavior can be fully explained by appeal to individual forms of behavioral adjustment. Each organism has been optimized to act as part of a group; but the group itself doesn't possess the capacity to adjust its behavior in light of changes in its environment. We may someday find a bacterial species that can collectively learns to track group-relevant phenomena. But for now, it is unclear what bacterial colonies could gain by moving beyond self-organized forms of Leibnizian harmony.

The main question I want to pursue in this chapter is: What more would it take for organisms to act together; and more intriguingly, what more would it take for a group of organisms to constitute a single mind. I explore these questions by examining the swarming behavior of desert locusts, the schooling behavior of golden shiner fish, and the foraging behavior of colonies of army ants. And I suggest that many organisms find reasons to act together out of contextualized self-interest.

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[1] I would like to thank Mattia Gallotti, Ruth Kramer, Georg Theiner, and an audience at the School of Advanced Study (London) for assistance in thinking through these issues.

[2] As I learn more about bacteria, I find it harder to deny them mentality, but nothing in this chapter will turn on this issue. See Bassler (2012) and Shapiro (1988) for overviews of bacterial capacities; and see Figdor (in prep) for arguments supporting the claim that bacteria literally have minds.

1. Behavioral alignment

Desert locusts typically live as solitary animals. But when protein becomes scarce, their bodies change and they begin to move in coordinated bands. At low levels of population density, these bands display little behavioral alignment, but as density increases, "a rapid transition occurs from disordered movement of individuals within the group to highly aligned collective motion" (Buhl 2006, 1403). When this happens, a million locusts can move together in unison, adjusting their behavior without external cause. This seems to suggest a centralized regulatory mechanism. But these patterns are governed by a more insidious drive.

After protein depravation, these locusts will begin to cannibalize conspecifics, as a way of obtaining salt and protein. And their cannibalistic motivations generate stable patterns of collective motion, which are driven by chasing and fleeing behavior (Bazazi 2008). Each individual runs from the insects behind them; and tries to cannibalize the insects in front of them; and their motions align because attacks are more common from the side than from the front or back (Bazazi et al. 2010). In these insects, the drive for self-preservation generates forward movement as well as behavioral alignment. While the social interactions between swarming locusts are more robust than the interactions between bacteria, their collective behavior is a by-product of the flow of information between conspecifics. These flows of embodied information do facilitate self-organization. Swarms can avoid obstacles, because the individuals that compose them do so; but each locust pursues its own reproductive fitness, and all forms of responsiveness flow upward through the aggregation of individual movements. These kinds of collective behavior are not cooperative; they are guided by the invisible hand of self-interest.

Of course, collective behavior is rarely governed by such severe forms of self-interest. But milder forms of self-interest often lead to robust patterns of collective behavior. Across the phylogenetic tree, forms of collective behavior arise as self-interested animals respond to the position and motion of nearby animals (Kao et al. 2014: e1003762). Like swarms of insects, schools of fish move in coordinated ways, rapidly changing speed and direction on the basis of information that only some individuals could possibly know.

Golden shiner fish, for example, prefer darker environments. And individuals will swim toward darker spaces, and slow down once inside them. They also prefer to move away from nearby fish, and toward fish that are two to four body lengths away (Katz et al. 2011). Within groups, the location of nearest-neighbors becomes a more accurate predictor of speed and direction than individual preferences (Berdahl et al. 2013). And in environments with light and dark patches, fish on the 'light' side will swim faster than fish on the 'dark' side (because of their individual preference), causing the school to curve toward darker spaces. As group size increases, the strength of attraction and repulsion are enhanced, generating stronger forms of behavioral alignment (Tunstrøm et al. 2013). And as a result larger schools rapidly find preferable schooling locations, simply as a result of the aggregation of individual decisions.

Golden shiners also display reflexive predator avoidance behavior in response to visual, olfactory, and acoustic information (Rosenthall et al. 2015). But they are also jumpy, and they sometimes engage in similar displays though no predators are around. In schools, the effect of such false positives is dampened, as information flows through a school. And the process, here, is intriguing. These fish respond to the avoidance displays of any fish within their visual field. But they do not respond if their view is obstructed. So fish at the boundary of a school produce more avoidance signals, propagate them more frequently, and respond to most signals by others. Fish closer to the center of a school, by contrast, only respond to strong threat signals. Where many fish react in unison, the threat signal cascades through the school: each fish sees an avoidance display, and reacts out of self-interest. The flow of false positives is inhibited, however, as the view of an initial reaction will be blocked for most fish, and the response will only spread as far as it can be seen. Consequently, false positives yield a local response, while predators trigger avoidance behavior rapidly cascades through the entire school.

Since group life has a high pay-off for these fish, golden shiners often face a trade off between relying on their own preferences and favoring group cohesion. This is what makes it clear that their decisions are guided by self-interest. By schooling, these fish can rely on the information possessed by group-mates, in ways that can reduce the cost of seeking new information. Suppose a school of fish contains some fish that prefer to forage in location A, and others that prefer to forage in location B. The fish at the head of a school will typically act on their own preferences; and if their decisions happen to converge, fish further back in the school will adjust their preferences in light of this new information. But if there is noise in the initial signal—for example if some fish at the head of the school prefer A and others prefer B—fish further back in the school will tend to act on their own preferences. As with predator detection, each fish pays attention to the patterns they see. But where the information they receive from shoal-mates is inconsistent, personal preferences dominate decision-making. Intriguingly, if these later decisions weigh heavily in favor of A, this can help to resolve the initial conflicts at the head of the school, as fish that initially preferred B will revise their preference in light of the emerging consensus (Miller et al. 2013). Note, however, that this is not a school-level computation. The individual fish rely on local information to make their own decisions, and this allows them to have a greater sensitivity to conflicting preferences. And importantly the aggregate success of the fish in a school depends on the independence of their decisions, and the preservation of local control and local decision making: "when individuals sense too much of the group, the result is a filtering of the local influences and an averaged (compromised) collective response" (Leonard et al. 2012: 232). And this can yield sub-optimal decisions, which are worse than the decisions that individuals would have made on their own.

2. Social minds?

The types of collective behavior I have addressed so far are the tip of a much larger iceberg, but they help to make it clear why self-interest plays such an important role in the production and guidance of collective behavior. In most cases, thinking together would be costly, and it would offer no additional advantage beyond what can be gained by acting on self-interest. Consequently, most species of insects, fish, birds, and mammals that act together appear to act on "locally acquired cues such as the positions, motion, or change in motion, of others" (Couzin 2002: 36). As the case of the golden shiner fish suggests, locally acquired cues can be amplified or dampened in ways impact the flow of survival-relevant information through a group: positive feedback can increase the likelihood of detecting threats, and negative feedback can diminish the effects of false positives on uninformed individuals. As a result, informed individuals can bias group behavior in ways that can guide naïve individuals toward resources and away from threats (Couzin 2002: 39). There is a great deal of variation in these effects, but in general information appears to flow in two directions: from individual decisions to patterns of collective behavior; and from patterns of collective behavior to individual decisions. This allows the individuals in schools to better track evolutionarily salient risks and rewards by treating one another as informational resources. But it is individuals who do this tracking, not the groups themselves—and this fact is important.

Even in hierarchically organized species, such as olive baboons, decisions about where to forage are typically guided by consensus, not dominance: "baboons are most likely to follow when there are many initiators with high agreement. However, when agreement is low, having more concurrent initiators decreases the likelihood that a baboon will follow anyone" (Strandburg-Peshkin et al. 2015: 1361). And in some cases, forms of human decision-making can rely on a similarly aggregative process to yield results that are more accurate than expert opinion. The reason for this is simple: "If you ask a large enough group of diverse, independent people to make a prediction or estimate of probability, and then average those estimates, the errors each of them makes in coming up with an answer will cancel themselves out" (Surowiecki, 2004: 10).[3] But perhaps more importantly, humans often need to capitalize on transient diversity within a group to arrive at scientific knowledge (Zollman 2010). In this respect, collective decision-making in humans may share a great deal in common with the patterns of decision-making we find in other species.

3. Adaptive decisions

That said, there are cases where animals act together in ways that yield more robust forms of informational integration. Some ants (*S. invicta*) form rafts to escape flooding. They adjust the structure of their rafts to maintain buoyancy; and they keep the the queen and larvae at the center to prevent predation. As individuals move from the periphery to the center, they are rapidly replaced to preserve the raft's average thickness (Mlot et al 2011). Strong selective pressures have favored this form of collective behavior. The native environment of these ants floods frequently, and raft-building colonies have been more likely to survive floods than those that do not. Since ants are highly related (each pair sharing as much genetic material as a brother or a sister), selection occurs in response to these colony-level pressures.[4] But this type of raft-building also relies on individual computations and local heuristics. Individuals track the number of ants walking on top of them, and they adjust their behavior against this locally computed value (Anderson et al. 2002; Mlot et al. 2011). As a result of these computations, colonies respond well to flooding.

This is a form of local updating, much as we saw above. But in ants, these patterns of local updating can sometimes allow colonies to function as "parallel information-processing systems capable of intricate collective decision-making during essential tasks such as foraging, moving home or constructing a nest" (Couzin 2002: 39). Where this occurs, individual behavioral adjustments resemble Hebbian processing (i.e., neurons that fire together wire together). To see what this means, consider species of army ants that link their bodies to form ladders, chains, and bridges to cross otherwise impassable landscapes.

Bridge construction typically begins at a natural diversion, and longer bridges are built to create shortcuts in the foraging trail as traffic increases (Reid et al. 2015: 15114). But continuous adjustments are made to the size and location of the bridge as ants respond to the flow of traffic across their bodies. When traffic decreases, ants abandon their position in a bridge; when traffic increases, ants are recruited to make the bridge longer. This parallels the kind of behavior that we have seen already. But bridge expansion often stops before the maximum foraging shortcut has been achieved; while no individual represents the costs and benefits to the colony, the variations in recruitment underwrite a form of parallel information processing that is sensitive to "the diminishing returns of shortening the

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[3] This form of judgment aggregation only works if four conditions are satisfied: (1) each decision is made by an individual, (2) on the basis of local values and local sources of information, (3) independently of the decisions made by others, before (4) the decisions are aggregating into a collective decision. As Kristin Andrews (p.c.) notes, it would take a great deal of empirical effort to demonstrate that such conditions are satisfied in informal decision-making contexts; and it remains an open empirical question which forms of collective behavior in humans have this character (cf., Winsberg, Kukla, and Huebner 2014). This is one of the reasons why I remain skeptical of most discussions of collective mentality in humans (Huebner 2013).

[4] In this situation, the distinction between inclusive fitness and group selection may collapse (see Marshall 2011).

trail to avoid the cost of locking up an increasing number of workers in the structure" (Reid et al. 2015: 15116).

These colonies function as computational networks, which analyze the costs and benefits of bridge construction, given the foraging needs of the colony. Each ant carries out a local computation, based on information that is available to it; and as the information embodied in the flow of traffic is integrated with information embodied in bridge-building, the colony adjusts *its* behavior in light of *its current situation*. Experiments reveal that this process reliably generates cost-benefit analyses by following an effective mechanical procedure. The movements of individuals facilitate ongoing coping with biologically relevant patterns in the environment; these patterns designate significant features of the environment (colony level costs and benefits); and this allows colonies to represent a variety of different situations in a systematic way. Finally, there are proper and improper ways of producing and manipulating these representations—and colonies that routinely failed to process the costs and benefits of bridge-construction would be less successful in foraging than their rivals. This gives us good reason to think that these colonies are carrying out distributed computations over collective representations (cf., Haugeland 1998; Huebner 2013).

Something similar happens in nest site selection. Individual ants are able to choose where to live, but doing so requires multiple visits to each location and repeated comparisons of their features. Unsurprisingly, ants rarely have the time for this, but in experimental contexts *Temnothorax rugatulusm* can effectively compare two sites that differ in one respect (e.g., cavity volume, interior dimness, entrance size). As the number of potential nest sites increases, however, and as multiple attributes must be evaluated in parallel, individuals start to make suboptimal decisions (Sasaki & Pratt 2012). Fortunately nests tend to be selected by consensus. Individual scouts visit one site, which they compare "to an internal scale and then decide whether to recruit nest-mates there" (Sasaki & Pratt 2013). Some succeed in recruiting nest-mates, then guide a nest-mate to the site (Shaffer, Sasaki, & Pratt 2013); a comparative evaluation thus arises through 'friendly' competition over recruits. Over time, recruitment "generates positive feedback on the number of ants at each site, with the better site slightly favored by its higher acceptance rate" (Sasaki et al, 2013). As consensus on a high-grade option begins to emerge, scouts start to carry nest-mates to the preferred site, increasing the rate of recruitment by approximately three times (Pratt et al. 2002). Strikingly, where numerous potential nest-sites are compared, across multiple dimensions, this form of consensus decision-making is highly accurate (Sasaki et al. 2013): colonies can chose the best nest site from eight options with approximately 90% accuracy (Sasaki & Pratt 2012).

As with bridge building, these individuals never compare the available options. Some ants recruit nest-mates; others visit advertised sites. But no ant has the information that would be required to compare these sites against one another. The collective decision arises through a winner-take-all algorithm, which is distributed across scouts and recruits.[5] As a result of the high degree of relatedness within a colony, however, individual interests converge with the interests of other ants and with the interest of the colony (Seelely 2010). So competitions for recruits remains 'friendly'. But unfortunately, this friendly competition can go awry. The converging interests of these ants are sensitive to previous experience. And after inhabiting an environment where one factor (e.g., entrance size) has been highly salient to nest site selection, colonies increase their sensitivity to this factor (Sasaki & Pratt 2013). Sub-optimal decisions can then emerge where colonies adjust their shared preferences against their collective experience. Because they process information as a group, these ants become more sensitive to group-relevant, and local sources of distortion.

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[5] For parallel cases in honeybees, see Seeley (2010), who argues at length that honeybee colonies are minded. For further discussion of the kinds of minds that honeybee colonies possess, see Huebner (2011).

4. Group minds?

Natural selection tends to increase the frequency of genes associated with individual fitness, as individuals with such genes typically reproduce more frequently than those with rival alleles. When average relatedness is high, animals often find ways to cooperate; but across the phylogenetic tree, as average relatedness falls, cooperation becomes more closely tied to the immediate fitness benefits of acting together (Clutton-Brock 2009; West et al. 2011). In this chapter, I have examined some ways that contextualized self-interest can generate stable forms of collective behavior in light of these facts. And in the previous section, I suggested that under limited conditions, the pursuit of self-interest can yield a minimal form of collective mentality.

Like most other animals, individual ants act on locally available information. But because of their evolutionary history, they also play roles in the distributed computations that are carried out by the colony. This allows colonies to develop better strategies for navigating the world, and it allows them to carry out complex comparative evaluations as information is propagated between ants; but no individual carries out these evaluations, and no individual develops strategies for furthering the interests of the colony. From an evolutionary perspective, this should be no more surprising than the existence of neurons that think and act together; and the behavior of these ants does bear a striking resemblance to the computational structures we find in individual brains. Each neuron updates its state in light of the behavior of the neurons to which it is connected (e.g., modulating neurotransmitter production, extending and pruning dendritic branches, and adjusting firing-patterns). And since groups of neurons constitute highly integrated, hierarchically organized, and massively parallel computational systems, these interactions often yield computational outputs that generate adaptive behavior, as well as complex comparative evaluations. But decisions are not made by particular neurons, they are made by the system as a whole.

There is good reason to treat colonies of ants (and honeybees) as unified cognitive systems, at least in some cases. But are there forms of collective mentality likely to emerge in other species? Whether it arises in groups our in individuals, mentality requires the ability to adjust behavior in ways that yield skillful coping with unpredictable environmental variation. Individuals do not need to be biologically bounded. And many individuals, including humans, are constituted by numerous smaller entities. But few animals have solved basic coordination problems in ways that would allow groups to function as unified cognitive system. Social organisms face constant trade-offs between the benefits of independence and the benefits of group life, and while they will often rely on one another as sources of information, they rarely form integrated information processing systems. When collective hunting and collective defense arise among hyenas, lions, wolves, and chimpanzees, "each individual simply assesses the state of the chase at each moment and decides what is best for it to do" (Tomasello et al., 2005, 11). They do not need to develop shared plans, and they do not need to process information as a group; and they never subvert their own interests to the needs of the group. Of course, complex coordination dynamics do arise in such groups, and this yields local forms of cooperative behavior that have a high pay-off for group members (much as we saw in the case of golden shiners and olive baboons). But the stable forms of aggregation that would allow a group to think and act *as a group* require solving coordination problems in ways that can prevent local forms of self-interest from intruding into collective decision-making. The unification of multiple entities into multicellular organisms is one way to solve this problem; and eusocial insects have solved it by having one caste whose reproductive futures depend on the success of their colony (cf., Seeley 2010) But most animals settle for more local forms of collective decision making. This is why I believe that collective mentality is incredibly rare outside of the eusocial insects.

I cannot address this issue here, but humans may have found a novel solution to this problem of social aggregation. We take up social roles, and we can build new ones; and we can even build computational unities by using linguistic representations to build high-bandwidth interfaces between individuals. Where this works, we can create transactive forms of cognition. We often see this in long term partnerships, where people remember things and plan together, and highly structured groups can sometimes achieve something similar. But in general these human forms of collective mentality will also be transient. If we wanted to create stable and persistent forms of collective mentality, this would require ongoing control and guidance by individuals, but it may be possible (see Huebner 2013).

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