Does Size Matter? Lessons from studying signaling in honey bee colonies

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Does the size of the community in which you live affect what kind of information you are exposed to, and how you behave? And do these differences, in turn, affect how successful your community is? Our recent studies in the Nieh lab at the University of California San Diego suggest that they do—at least if you are a honey bee! But this finding could have implications beyond the lives of bees. Our work is part of an effort to understand how groups of organisms at different levels of biological organization—from single cells to societies of humans—make decisions.

For years, scientists have observed that some group-living insects, such as colonies of honey bees, behave like single organisms. These *superorganisms* make group decisions about what and where to forage, who to fight, and where to live. Remarkably, such decisions appear to emerge from the collective interactions of the colony members without top-down direction from a "leader."

On the flip side, what we usually think of as a single organism—a human, for example—can also be considered a tightly-knit colony of individuals. All animals, including humans, are made up of collections of single cells, each with its own unique set of properties. Like bees in colonies, the cells within our bodies manage to work together to allow us to make intelligent decisions. Such living groups of individuals (cells, bees, humans, etc) that act together are known as "biological collectives."

Biological collectives share many interesting properties. One key property is the ability to make smart choices, even when the world changes—what scientists call "robustness". This feat might seem trivial—after all, each of us makes thousands of such robust decisions every day—but in fact, scientists still do not know exactly how we do it.

On the Path to Understanding Robust Decision-Making

So far, we think that some of the answer comes from how individuals within collectives share information. We know that bees in colonies and neurons in animal brains communicate with one another using a balance of "excitatory" and "inhibitory" signals. An excitatory signal causes the recipient to *do something*, and possibly to pass on the message. For instance, a positive restaurant review causes readers of the review to be more likely to visit the restaurant. If the experience of the visitors is also positive, they may write their own reviews, which will draw even more visitors. In contrast, inhibitory signals prevent action. A negative review causes more people to avoid the restaurant. If people do not visit the restaurant, they have no reason to write a review.

One way that scientists test their understanding is called "analysis by synthesis." The idea is that if we have truly understood how something works, we should be able to build it. But when people build artificial neural networks with inhibitory and excitatory parts, this usually is not enough for the network to make reliable decisions, especially under different conditions. So, what other features are shared by biological collectives, and could some other property also be playing a role?

Biological Systems Adapt To Changes

A universal property of all living things is the capacity for change. We call this “plasticity.” Several types of plasticity have been studied. The two most well-known are synaptic plasticity—the ability for the connections between brain cells to change—and behavioral plasticity—the capacity for the behavior of organisms to change. Behavioral plasticity is also called learning, which is defined as a behavioral change in response to an environmental factor.

Learning has been the subject of serious investigation for well over 100 years. In that time, multiple forms of learning have been identified. One consistent finding, widely observed throughout biology, is that when an organism is repeatedly exposed to a stimulus that has neither positive nor negative implications for its life (e.g., the sound of a clock ticking on a wall), the organism will stop responding to it. We call this “habituation.” Interestingly, habituation is seen at many different levels of biological organization, including in single neurons—although in neurons, it is called "desensitization." Regardless of what it is called, the phenomenon looks the same: when a message is repeated too often without consequences, the receiver of the message begins to ignore it.

So, what does plasticity have to do with group decisions?

Habituation and Honey Bees

Honey bees have been studied by many people for many reasons, but one of the main ones is their sophisticated system of communication. Two interesting signals in this system are the waggle dance and the stop signal. The excitatory waggle dance is used by foragers to tell other members of the colony how to get to a profitable food source. The inhibitory stop signal makes it less likely that waggle dancers will continue advertising a food source that has become less than ideal due to overcrowding or dangerous predators. Stop signals consist of a vibration that we hear as a 350 Hz tone, and a head butt that is delivered to a waggle dancer.

In honey bee colonies, it has been shown that the overall rate of vibrational signaling (what can be recorded using microphones) is higher in small colonies than large colonies. Since stop signals have a vibrational component, we wondered if this pattern was true for stop signals specifically. And if it were true, we wondered if it meant that bees from small colonies might be more habituated to stop signals than those from large colonies.

To answer the first part of our question, we tracked signaling over a number of years in several colonies. As we had predicted, we found that the number of stop signals per bee increased as the colonies got smaller. That means that each bee in a small colony experiences more stop signals than each bee in a large colony.

Answering the second part of our question about whether bees in smaller colonies are therefore more habituated to stop signals required designing a method of generating artificial stop signals. After quite a bit of trial and error, we created an artificial stop signal that, like natural stop signals, caused waggle dancers to briefly pause. We then used the artificial signal on waggle dancers from colonies of different sizes. By measuring how long waggle dances lasted, we found that bees from small colonies were indeed less likely to listen to the message from our artificial signal than those from large colonies.

But Why?

Is there a good reason for small colonies to respond less to the stop signal than large colonies? We think it comes down to the natural life cycle of a honey bee colony. In the absence of intervention from a beekeeper, a colony normally begins its life when a queen and a group of workers from a large colony leave to establish a new home. This new colony begins with a relatively small population and no food stores. They need pollen and nectar from the environment to grow their population. The lifespan of a typical worker is only about 40 days, but it takes 21 days to produce a replacement. All this translates into the new colony having a relatively small window in which to become established, or die out—and *that* means the colony cannot afford to be choosy about food sources.

On the other hand, a large, established colony with food stores has the luxury of being able to optimize where it gathers food. If a site becomes less than ideal, it can redirect its workforce elsewhere because it has a larger workforce and because, if the foragers fail to find anything better, the colony is in relatively little danger of immediate starvation. After it has grown past the point of danger, a large colony can further enhance its productivity by targeting only the best foraging sites.

One outstanding question that will be the focus of future work is exactly *why* bees from smaller colonies produce more vibrational signals than those from larger colonies.

Regardless of the specific mechanism, the message is clear: ***a strategy that works to keep a small colony going is not necessarily the optimal strategy for a large colony.***

More Than Bees

Although the idea needs to be thoroughly tested, we think it is possible that this size principle holds for other types of biological collectives. For example, scientists have evidence for similar phenomena in networks of brain cells. In a completely different vein, there are at least superficial similarities between how large and small bee colonies, and large and small human organizations (e.g., companies) choose to direct their energy. It has been reported that small companies, like small bee colonies, are also less likely to listen to new information that would cause them to change course.

Finally, we think that incorporating size-dependent plasticity mechanisms into the design of artificial networks might help to create smarter artificial intelligence. After all, the best robust decision-making systems we know of are the biological ones designed by evolution.

References

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