Unexpected similarity between honey bee and human social life

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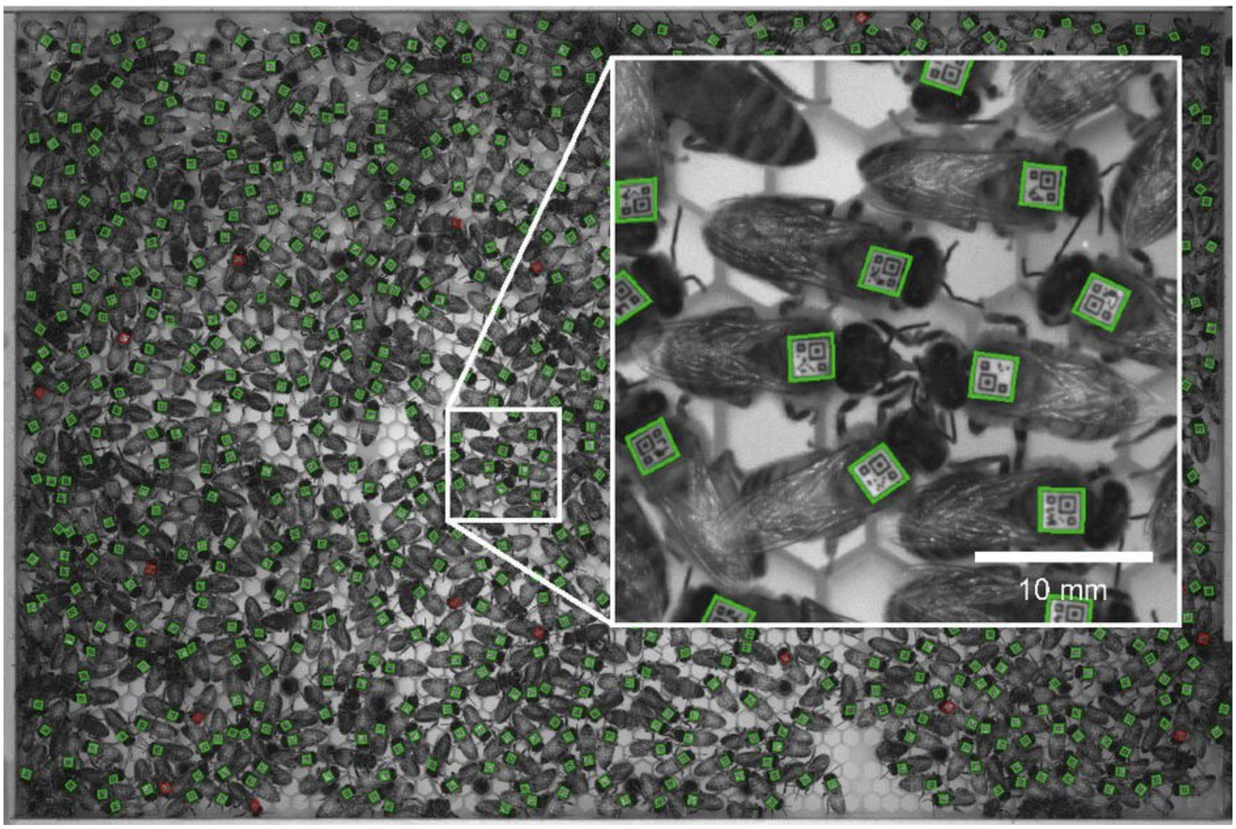

An image obtained from the system showing barcoded bees inside the observation hive. Outlines reflect whether a barcode could be decoded successfully (green), could not be decoded (red), or was not detected (no outline). The hive entrance is in the lower-right corner, and the inset reveals two bees that were automatically detected performing trophallaxis. Credit: Tim Gernat, University of Illinois

Bees and humans are about as different organisms as one can imagine. Yet despite their many differences, surprising similarities in the ways that they interact socially have begun to be recognized in the last few years. Now, a team of researchers at the University of Illinois Urbana-Champaign, building on their earlier studies, have experimentally measured the social networks of honey bees and how they develop over time. They discovered that there are detailed similarities with the social networks of humans and that these similarities are completely explained by new theoretical modeling, which adapts the tools of statistical physics for biology. The theory, confirmed in experiments, implies that there are individual differences between honey bees, just as there are between humans.

The study, which measures the extent of individual differences in honey bee networking for the first time, was carried out by first author physics Ph.D. student Sang Hyun Choi, postdocs Vikyath D. Rao, Adam R. Hamilton and Tim Gernat, Swanlund Chair of Physics Nigel Goldenfeld and Swanlund Chair of Entomology Gene E. Robinson (GNDP). Goldenfeld and Robinson are also faculty at the Carl R. Woese Institute for Genomic Biology at Illinois, of which Robinson is the director. The collaboration comprised experimental measurements of honey bee social behavior performed by Hamilton, Gernat and Robinson, with data analysis by Rao and theoretical modeling and interpretation by Choi and Goldenfeld. Their findings were published in a recent article in the journal *Proceedings of the National Academy of Science*.

"Originally, we wanted to use honey bees as a convenient social insect to help us find ways to measure and think about complex societies," said Goldenfeld. "A few years ago, Gene, Tim, Vikyath and I collaborated on a large project that put "bar codes" on bees so that we could automatically monitor everywhere they went in the hive, every direction in which they pointed, and every interaction partner. In this way, we could build a social network in time, something known as a temporal network."

That study, done a few years ago, involved high-resolution imaging of barcode-fitted honey bees, with algorithms detecting interaction events by mapping the position and orientation of the bees in the images. In those studies, researchers focused on trophallaxis—the act of mouth-to-mouth liquid food transfer—when measuring the social interactions between honey bees. Trophallaxis is used not only for feeding but for communication, making it a model system for studying social interactions.

"We chose to look at trophallaxis because it is the type of honey bee social interaction that we can accurately track," said Choi. "Since honey bees are physically connected to each other by proboscis contact during trophallaxis, we can tell whether they are actually engaging in an interaction or not. In addition, each honey bee is tagged so we can identify each individual engaged in each interaction event."

"In our earlier work, we asked how long bees spend between events where they meet other bees, and we showed that they interact in a non-uniform way," said Goldenfeld. "Sang Hyun and I took the same data set, but now asked a different question: What about the duration of interaction events, not the time between interactions?"

In looking at the individual interactions, the time spent varied from short interactions to long interactions. Based on these observations, Choi developed a theory where bees exhibited an individual trait of attractiveness that could be likened to human interaction. For example, humans might prefer to interact with friends or family members rather than strangers.

"We developed a theory for this based on a very simple idea: if a bee is interacting with another bee, you can think of that as a sort of "virtual spring" between them," said Goldenfeld. "The strength of the spring is a measure of how attracted they are to each other so if the spring is weak, then the bees will quickly break the spring and go away, perhaps to find another bee with whom to interact. If the spring is strong, they may stay interacting longer. We call this theoretical description a minimal model, because it can quantitatively capture the phenomenon of interest without requiring excessive and unnecessary microscopic realism. Non-physicists are often surprised to learn that detailed understanding and predictions can be made with a minimum amount of descriptive input."

Goldenfeld explained that the mathematical framework for their theory originated from a branch of physics called statistical mechanics, originally developed to describe gas atoms in a container, and since extended to encompass all states of matter, including living systems. Choi and Goldenfeld's theory made correct predictions about the experimental honey bee dataset that was previously collected.

Out of curiosity, the theory was then applied to human datasets, revealing similar patterns as with the honey bee dataset. Choi and Goldenfeld then applied an economic measure for wealth and income disparities in humans—termed the Gini coefficient—to show that bees displayed disparities in attractiveness in their social interactions, although not as different as humans. These results indicate a surprising universality of the patterns of social interactions in both honey bees and humans.

"It is obvious that human individuals are different, but it is not so obvious for honey bees," said Choi. "Therefore, we examined the inequality in the activity level of the honey bees in a way that is independent of our theory to verify that honey bee workers are indeed different. Previous work done in our group has used the Gini coefficient to quantify the inequality in honey bee foraging activity so we thought that this method would also work to examine the inequality in trophallaxis activity."

"Finding such striking similarities between bees and humans spark interest in discovering universal principles of biology, and the mechanisms that underlie them," said Robinson.

The researchers' findings suggest that complex societies may have surprisingly simple and universal regularities, which can potentially shed light on the way that resilient and robust communities emerge from very different social roles and interactions. The researchers predict that their minimal theory could be applied to other eusocial insects since the theory does not involve honey bee-specific features.

In future studies, the same techniques from statistical mechanics can be applied to understand the cohesiveness of communities through well-characterized pair interactions, said Choi and Goldenfeld.

"This was my first project after I joined Nigel's group, and it took a long time for me to figure out the right way to approach the problem," said Choi. "It was fun and challenging to work on such an interdisciplinary project. As a physics student studying biological systems, I had never expected myself to use concepts from economics."

"It was very exciting to see how simple physical ideas could explain such a seemingly complex and widespread social phenomenon, and also give some organismal insights," said Goldenfeld. "I was very proud of Sang Hyun for having the persistence and insights to figure this out. Like all transdisciplinary science, this was a really tough problem to solve, but incredibly fascinating when it all came together. This is the sort of advance that arises from the co-location of different scientists within the same laboratory—in this case the Carl R. Woese Institute for Genomic Biology."

More information: Sang Hyun Choi el al., "Individual variations lead to universal and cross-species patterns of social behavior," *PNAS* (2020). www.pnas.org/cgi/doi/10.1073/pnas.2002013117

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