Information processing constrains how E. coli bacteria navigate chemical gradients

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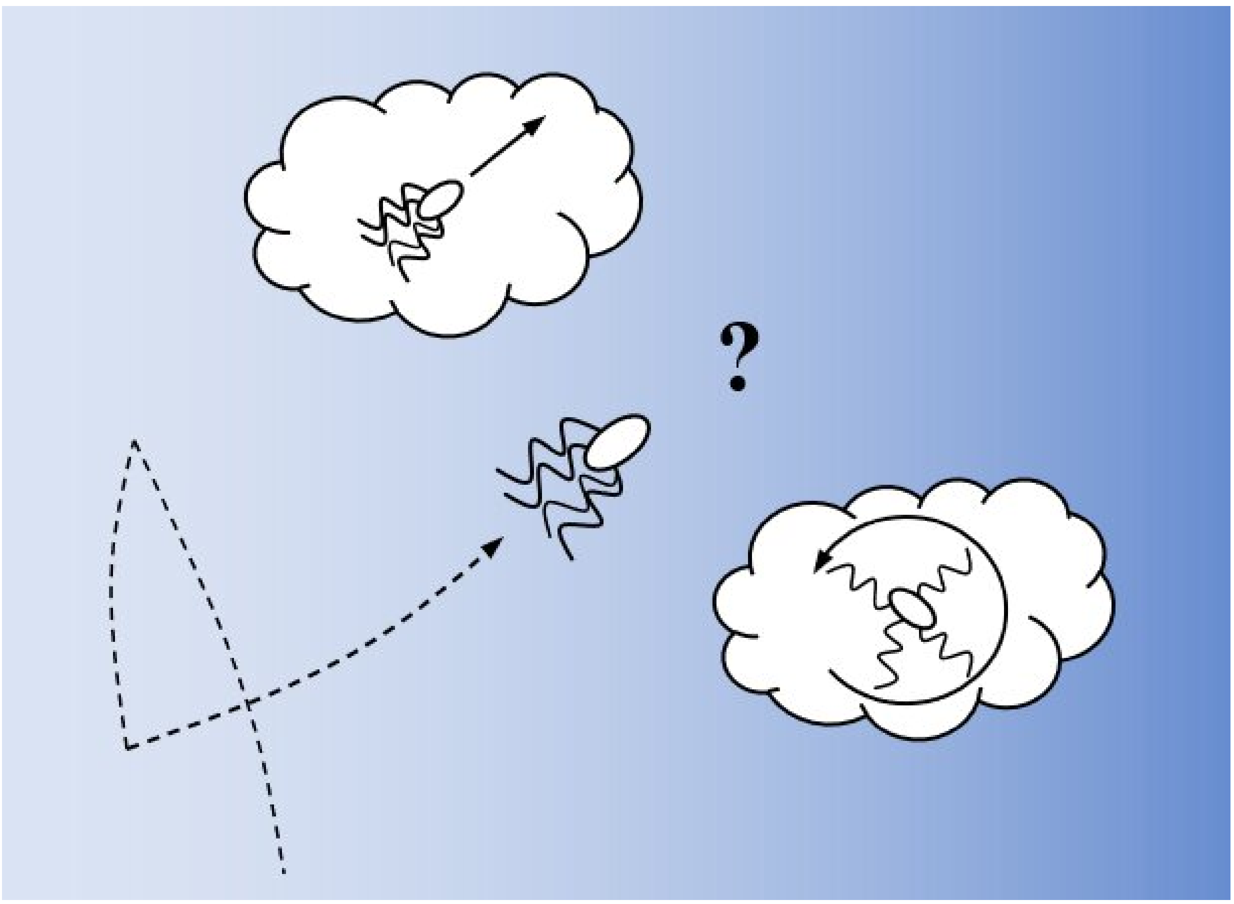

To climb chemical gradients of nutrients, E. coli bacteria need to continuously decide whether to keep swimming straight or change swimming direction. Researchers at Yale have recently shown that although E. coli make this decision with high uncertainty, they climb gradients nearly as fast as theoretically possible, given that uncertainty. Credit: Yale University.

Living organisms adapt their behavior and movements based on information they acquire from their surrounding environment. But oftentimes this information is imperfect, and the organism needs to act under uncertainty. So, does imperfect information limit an organism's performance at specific tasks?

Researchers at Yale University have recently investigated this possibility, specifically examining the behavior of the coliform bacterium Escherichia coli (E. coli). Their findings, published in *Nature Physics*, show that the information that E. coli bacteria gather from their environment limits their performance at chemotaxis, the process by which they guide their movements in response to chemical signals.

"It has long been appreciated that cells function in the face of noise and uncertainty," Henry Mattingly, Keita Kamino, Benjamin Machta and Thierry Emonet, the researchers who carried out the study, told Phys.org via email. "Since information theory was first invented around 1950, researchers have recognized that it could be a powerful tool for understanding how organisms deal with noise."

Most past research focused on the quantity of information that cells can acquire from their environment. Measurements gathered so far suggest that evolution selects biological systems to effectively transmit information, reaching up to the fundamental constraints imposed by physics.

"Yet acquiring information is not necessarily the end of the story for biology: information must be acted on appropriately," the researchers explained. "We wanted to test a broad biological hypothesis: that organisms make the best use of the information they acquire to perform behaviors and other functions. To investigate this, we needed a behavior simple enough that we could quantify how much information it needed and chemotaxis by the bacterium E. coli is a perfect example of such a behavior."

E. coli bacteria continuously acquire information about the chemical signals in their environment using biological sensors. They then use this information to adapt their behavior and navigate chemical gradients. If E. coli bacteria did not gather information from their surroundings, they would be unable to identify whether they are heading towards nutrients or away from toxic substances.

"Experimental tools are now available for measuring this behavior and for probing the dynamics of the chemical pathway linking the cell's sensors to the motors it uses to navigate," the team said. "Combining these measurements with simple models for their behavior, we realized we could measure the amount of information a bacterium was able to gather (in bits per second), while also understanding how much information they would need to navigate at the speeds observed."

The authors' primary objective was to gain a better understanding of whether the limits of their biological sensors affected chemotaxis behavior in E. coli. To achieve this, they first set out to calculate the theoretical performance limit, which is the maximum speed at which a bacterium could navigate up a chemical gradient, based on a fixed rate at which it acquires information about chemical signals.

"To do this, Henry modeled how the bacterium's swimming behavior responds to signals it experiences," the researchers explained. "Different response strategies have different 'information costs' to implement, but a strategy that requires a high information cost does not necessarily cause the cell to climb gradients quickly. Finding the response strategy that maximized gradient-climbing speed with a fixed information cost resulted in the performance limit."

To determine the rate at which E. coli cells acquire information during chemotaxis, the team had to understand how they translated signals they perceived, in the form of changing nutrient concentrations, into the activity of their internal signaling network. They achieved this using a microfluidic approach developed by Kamino. This approach works by delivering calibrated pulses of nutrients to bacteria, while simultaneously measuring activity in their chemical response network.

"Using the same experimental system, Keita also measured the magnitude of spontaneous noise in the response network in the absence of signals," the researchers said. "With these measurements, as well as measurements of the typical signals a swimming cell experiences in a gradient, we estimated how much information E. coli would extract from its chemical environment while navigating a natural gradient, for the first time."

As a final experimental step, the team had to determine how fast E. coli climb chemical gradients using the information they gathered. To do this, Mattingly established shallow chemical gradients between two reservoirs and tracked the swimming trajectories of bacteria as they navigated the gradients. After observing hours of these trajectories in different gradients, the researchers could determine the speeds at which they climbed the gradients.

"Combining our measurements of information acquisition and gradient-climbing speed allowed us to determine how well E. coli use information to navigate relative to the theoretical limit," the researchers said. "We found that while climbing shallow gradients E. coli get very little information from their environment, about 0.01 bits/s. With an internet connection of this rate, it would take several thousand years to download a typical feature film in 4K resolution."

Mattingly and colleagues found that the bacteria use the little information they get to climb gradients at speeds that are almost as fast as theoretically possible, considering the limitations of their sensory system. This suggests that to survive, organisms should efficiently use the information they acquire to perform specific tasks.

"The 0.01 bits/s that E. coli need, and get, is orders of magnitude less than the ~1 bit per second a cell would need to determine whether it is swimming up the gradient or not before choosing a new direction at random," the researchers said. "Our study is the first to use information theory to place bounds on the performance of an organism on a behavioral task, connecting the fidelity of the signal transduction pathway to its ability to carry out functions critical for its survival."

This work provides interesting new insights about the effects of information acquisition on E. coli chemotaxis. In the future, it could inform new studies aimed at understanding the link between an organism's ability to process signals in its environment and perform survival tasks.

In their next studies, Mattingly, Kamino, Machta and Emonet plan to measure E. coli's sensing fidelity and compare it with theoretical predictions. This will allow them to further test the hypothesis that the information processing of biological systems is close to limits imposed by physics.

"So far, we measured how much information E. coli cells get during chemotaxis and how efficiently they use that information, but we didn't address how much information they could potentially attain with an optimal sensor," the team said. "E. coli sense chemicals in their environments by counting molecules that randomly collide with its surface, and this poses limits on its sensing fidelity. This is something that others have thought a lot about, but so far without comparing it to E. coli's actual sensing fidelity."

E. coli bacteria reproduce extremely quickly, doubling in quantity in as little as 30 minutes. Their reproduction speed makes them ideal candidates for studying evolution in laboratory settings. In their future work, the researchers would also like to leverage this advantageous quality to test hypotheses about how evolutionary selection acts on information processing.

"Finally, models and measurements of both behaviors and signal processing in more complex organisms might be at the point now where we can apply the same ideas to study their behaviors as well," the researchers added. "The simplicity of E. coli chemotaxis made it an ideal system to start with, but similar ideas might apply to the behaviors of animals."

More information: H. H. Mattingly et al, Escherichia coli chemotaxis is information limited, *Nature Physics* (2021). DOI: 10.1038/s41567-021-01380-3