How moths integrate sensory and control information

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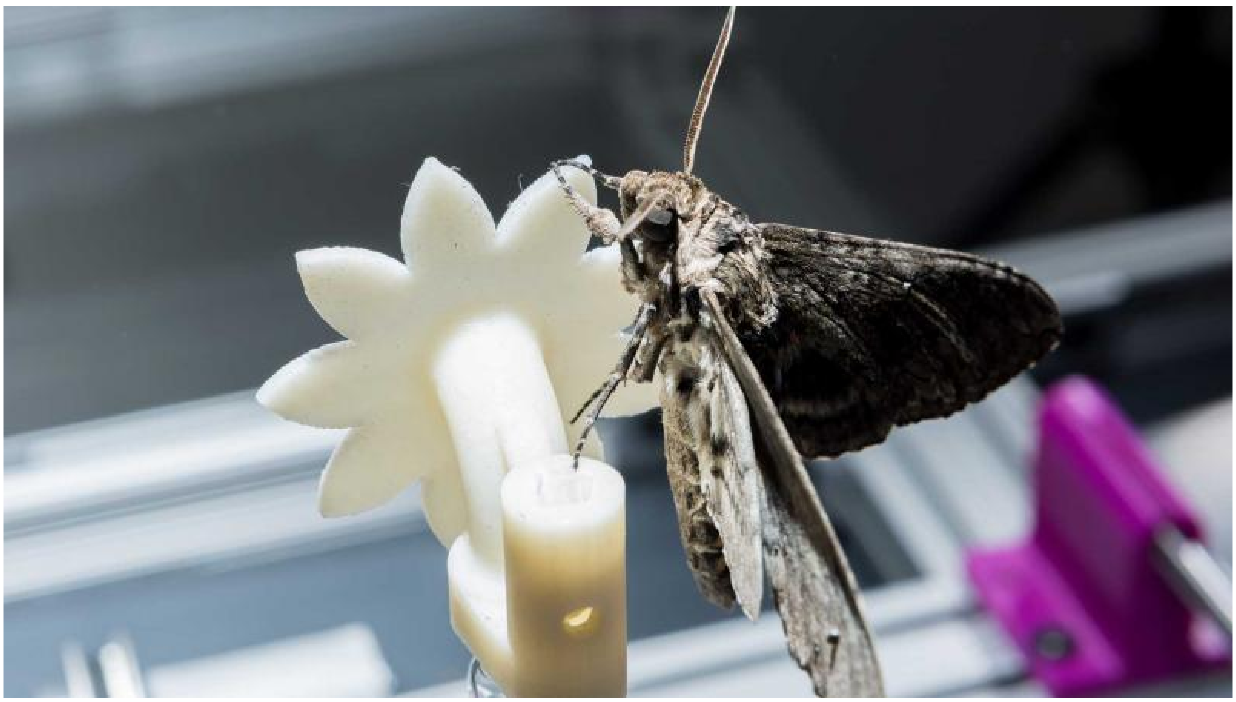


The hawkmoth (Manduca sexta) rests on a plastic flower that was produced with a 3-D printer. The robotic flower can be moved in different directions and at varying speeds to challenge the moth’s ability to follow it while in flight.

It's difficult enough to see things in the dark, but what if you also had to hover in midair while tracking a flower moving in the wind? That's the challenge the hummingbird-sized hawkmoth (Manduca sexta) must overcome while feeding on the nectar of its favorite flowers.

Using high-speed infrared cameras and 3-D-printed robotic flowers, scientists have now learned how this insect juggles these complex sensing and control challenges—all while adjusting to changing light conditions. The work shows that the creatures can slow their brains to improve vision under low-light conditions—while continuing to perform demanding tasks.

What the researchers have discovered could help the next generation of small flying robots operate efficiently under a broad range of lighting conditions. The research, supported by the National Science Foundation and Air Force Office of Scientific Research, has been reported in the journal *Science*.

"There has been a lot of interest in understanding how animals deal with challenging sensing environments, especially when they are also doing difficult tasks like hovering in midair," said Simon Sponberg, an assistant professor in the Georgia Tech School of Physics and School of Applied Physiology. "This is also a very significant challenge for micro air vehicles."

Scientists already knew that the moths, which feed on flower nectar during the evening and at dusk and dawn, use specialized eye structures to maximize the amount of light they can capture. They also surmised that the insects might be slowing their nervous systems to make the best use of this limited light. But if they were slowing their brains to see better, wouldn't that hurt their ability to hover and track the motion of flowers?

Sponberg and colleagues at the University of Washington studied this question using high-speed infrared cameras and nectar-dispensing robotic flowers that could be moved from side to side at different rates. While varying both the light conditions and the frequency at which the flowers moved, the researchers studied how well free-flying moths kept their tongues—known as proboscises—in the flowers.

They also measured real flowers blowing in the wind to determine the range of motion the insects had to contend with in the wild.

"We expected to see a tradeoff with the moths doing significantly worse at tracking flowers in low-light conditions," Sponberg said. "What we saw was that while the moths did slow down, that only made a difference if the flower was moving rapidly—faster than they actually move in nature."

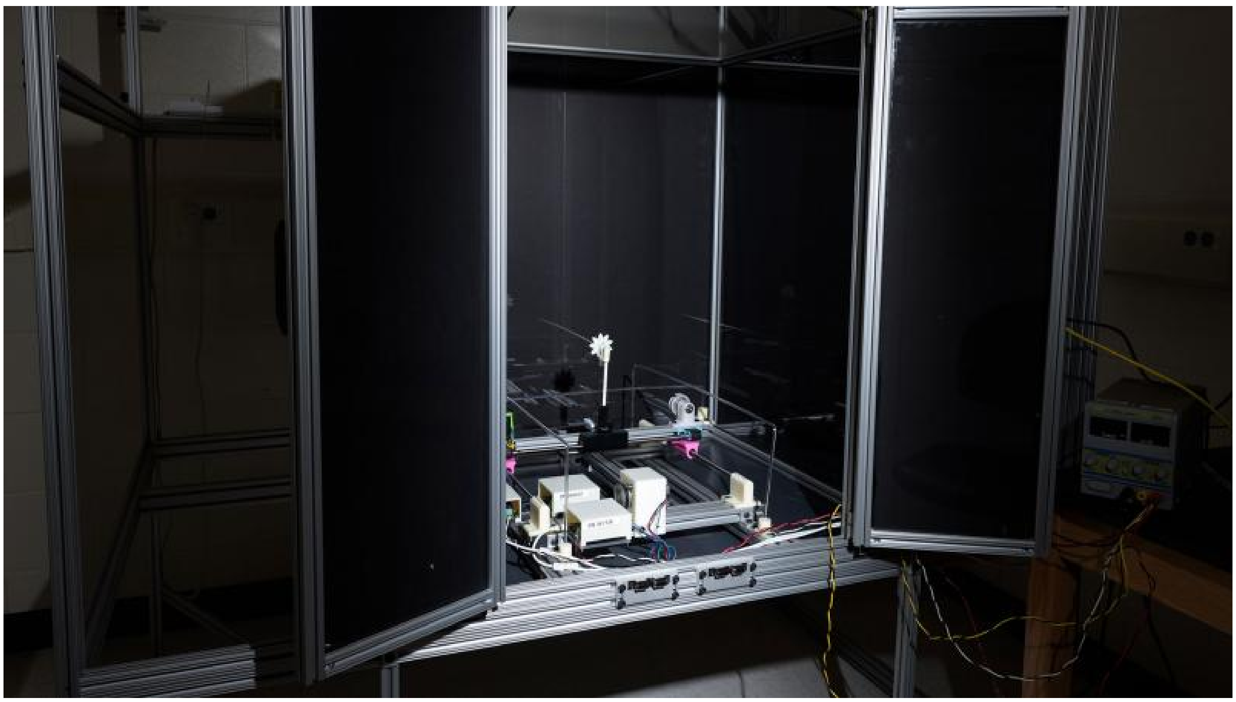
In the experiments, the moths tracked robotic flowers that were oscillating at rates of up to 20 hertz—20 oscillations per second. That was considerably faster than the 2-hertz maximum rate observed in real flowers. Because the moths' wings beat at a rate of about 25 strokes per second, they had to adjust their direction of movement with nearly every wing stroke—a major sensing, computational, and control accomplishment.

"This is really an extreme behavior, though the moth makes it look simple and elegant," Sponberg said. "To maneuver like this is really quite challenging. It's an extreme behavior from both a sensory and motor control perspective."

In the natural world, light intensity varies 10 billion-fold from noon on a sunny day to midnight on a cloudy evening. Operating in that range of luminosity is a challenge for both moths and the sensors on human-engineered systems. Understanding how natural systems adjust to this range of conditions could, therefore, have broader benefits.

"If we want to have robots or machine vision systems that are working under this broad range of conditions, understanding how these moths function under these varying light conditions would be very useful," Sponberg said.

To gather the data reported in this paper, the researchers used a robotic flower able to move in one dimension. Recently, they used the actuator devices from a 3-D printer to build a robotic flower that moves in two or three dimensions, providing an additional challenge for the moths. In future research, Sponberg and his colleagues hope to incorporate their robotic flower into a low-speed wind tunnel to study the moth's aerodynamic functions—including the role of wing vortices and the flow-effect interaction of the insect's wings with the flowers.



The test chamber used to study hawkmoths includes a robotic flower that can be moved with positioning equipment taken from a 3-D printer. Infrared video cameras track the movement of the insects, which normally fly only during low-light conditions. Information from the research could help future generations of small flying robots deal with challenging computational and vision requirements.

The hawkmoth has been studied extensively to investigate the fundamental principles governing the development and function of its neural system, noted Tom Daniel, a professor in the Department of Biology and co-director of the Institute for Neuroengineering at the University of Washington. Daniel's research group has experimentally characterized the response of flying hawkmoths using a sensory input comprising the linear sum of sine waves.

Sponberg's paper, based largely on data he collected at the University of Washington as a postdoctoral researcher, extends application of the "sum of sines" approach, Daniel said.

"Simon's work took the formal methods of control theory to dissect out how neural circuits adapt to vast ranges of luminance levels," he explained. "By looking at the time delays in the movement dynamics of a freely flying moth—interacting with the input of a robotically moved flower—Simon was able to extract the luminance-dependent processing of the moth's central nervous system."

Human-engineered devices must often operate at various speeds and in different environments. Seeing how well an animal with a tiny brain is able to track complicated movements and adjust its performance to different light levels was a surprising result of the work, Sponberg said.

"This was an interesting example of how an organism can tune its brain to maintain its ability to gather food," he added. "The moths do suffer a tradeoff by slowing their brains, but that tradeoff doesn't end up mattering because it only affects their ability to track movements that don't exist in the natural way that flowers blow in the wind."

Provided by Georgia Institute of Technology

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