Attack of the Zombie

The emerald jewel wasp is a cockroach’s worst nightmare

By Kenneth C. Catania
EMERALD JEWEL WASP targets the American cockroach to supply food for the wasp’s young.
YOU STILL DON’T UNDERSTAND WHAT YOU’RE DEALING WITH, do you? Perfect organism. Its structural perfection is matched only by its hostility.... I admire its purity. A survivor, unclouded by conscience, remorse or delusions of morality.” That is how the android Ash famously describes filmmaker Ridley Scott’s extraterrestrial monster in the 1979 blockbuster Alien. The movie provided nightmare fodder for an entire generation of science-fiction fans with its tale of an alien creature that attaches itself to the face of a crew member of the spaceship Nostromo and implants an embryo that later bursts from his chest. Technically speaking, the alien is a parasitoid, an organism that, unlike most parasites, ultimately kills its host. No one who has seen the film will ever forget how it reproduces, even if they want to.

Recently I have come to share some of Ash’s sentiments about chest-bursting parasitoids. But don’t judge me too harshly. I am not talking about monster parasitoids from outer space. I am referring to what seems to be the closest thing we have here on Earth: the parasitoid emerald jewel wasp, Ampulex compressa, which makes zombies (and worse) out of the American cockroach.

To give you a little background, I am a neurobiologist, and every fall I teach a course about animal brains and behavior at Vanderbilt University. On Halloween I like to showcase an appropriately creepy bit of biology as a memorable way for students to learn some basic neuroscience. When I began teaching about the emerald jewel wasp, I became so intrigued by the species that I just had to bring some of the wasps to my laboratory to see their behavior for myself. I started with a simple plan to take pictures and make some videos for my class, but soon I found myself carrying out research on this striking insect. The jewel wasp was already well known for being a parasitoid, but through my experiments over the past few years, I have learned that it is even more remarkable than researchers previously understood. And the roach, it turns out, has a nifty trick of its own.

TAKING CONTROL

BEFORE I TELL YOU what I discovered that filled me with admiration for this creature, I should explain how it first gained notoriety. Every female jewel wasp is on a mission. To reproduce, the wasp needs to find a host that will supply the necessary food for her young. Like many parasitoid species, the emerald jewel wasp is a specialist with only one option for a host—in this case, the American cockroach, Periplaneta americana. This target is one reason the jewel wasp is so popular even among insectophobes: as the proverb goes, the enemy of your enemy is your friend.

Among biologists, however, the emerald jewel

Kenneth C. Catania is a professor of biological sciences at Vanderbilt University. He studies comparative neurobiology with an emphasis on animal sensory systems. His latest book is Great Adaptations (Princeton University Press, 2020).
wasp elicits respect for its remarkable attack strategy. Frederic Libersat of Ben-Gurion University of the Negev in Israel and his colleagues—including venom specialist Michael Adams of the University of California, Riverside—have conducted a series of elegant studies that tell a story rivaling science fiction. It all starts when a female wasp locates an unfortunate cockroach.

The jewel wasp has an incredibly nuanced attack. It takes a neurosurgical approach to paralyzing its host, first stinging the cockroach directly in a part of the central nervous system called the first thoracic ganglion. This structure houses the motor neurons that control the roach’s front legs. The wasp’s venom contains gamma-aminobutyric acid (GABA), an inhibitory neurotransmitter that shuts down the motor neurons, temporarily paralyzing the legs. This first surgical strike leaves the roach unable to protect its head from the next sting, which the wasp directs through the soft membranes of the roach’s throat and straight into its brain. This second dose of venom has the insidious effect of changing the roach from a violently struggling (and dangerous) opponent into a compliant and pacified host—that is, a zombie.

From there things go predictably downhill for the roach. The venom injected during the brain sting includes the neurotransmitter dopamine, which causes the roach to incessantly groom its legs and antennae when it should instead be trying to escape. In the meantime, the wasp goes in search of a crypt in which it can entomb the roach with an egg. Once it finds a suitable location, the wasp returns to the roach and does something that might seem gratuitous in a horror movie. It grasps one of the roach’s sensitive antennae and bites off most of its length, leaving only a bleeding stump. It then does the same to the other antenna, and it uses the stumps like straws to drink the cockroach’s blood. You can think of roach blood as the wasp’s favorite supplement, providing energy and nutrients after the intense struggle (I do not see the fad catching on). Next, the wasp grasps one of the antenna stumps and, walking backward, pulls the cockroach forward. The cockroach follows like a dog on a leash. Once they are inside the tomb, the wasp glues a single small egg on one of the roach’s two middle legs. Then it exits the tomb and uses nearby debris to securely block the entrance before departing.

Take a moment to consider this astounding product of evolution. For any predator, it is plenty hard to stalk, catch and kill elusive prey. The emerald jewel wasp has an even greater challenge—taking its prey prisoner so it can serve as a living larder for the larva when it eventually hatches. To do so, the jewel wasp must deliver venom to two small neural targets inside the armored body of an insect that specializes in escaping from threats. No other animal that scientists know of has such a sophisticated means of manipulating another animal’s nervous system. And yet there is more to the story.

**A MOTHER’S TOUCH**

It is safe to say that no one ever walked away from watching *Alien* wondering about the trials and tribulations of the poor little chest-bursting parasitoid that scurried off the lunch table in the *Nostromo*. Much the same could be said for the typical view of the jewel wasp’s larva. Even scientists studying the wasp usually cut to the credits once the wasp seals the cockroach in the tomb. It is assumed that the larva will hatch from the tiny egg, find a soft spot from which to feed and break through the cuticle to eat the living cockroach from the inside, later emerging from the roach triumphant in a familiar, *Alien*-parasitoid fashion.

But life is not so easy for a hopeful chest burster, as I had occasion to learn when I was distracted by other projects and my wasp colony almost died out. It was only then that I tracked each larva, hoping I

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A female jewel wasp is on a mission to reproduce. To do so, it needs a host, specifically an American cockroach. First observed decades ago, the encounter between wasp and roach was thought to be well understood.

Sting a roach with debilitating venom.

Lead the zombified roach into a tomb.

Lay an egg on the compliant host and block its escape.

When hatched, the larva burrows into the living roach.

Once inside, the larva feeds on the roach and spins its cocoon.

Some 40 to 60 days later an adult wasp emerges from the roach, victorious.

The emerald jewel wasp is well known to biologists for its sophisticated manipulation of the American cockroach’s nervous system that turns the roach into a living food source for the wasp’s developing offspring. Recent investigations have revealed that the wasp’s tactics are even more ingenious than previously thought.
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Placing the egg in the proper spot is vital for the survival of the larva. Once it hatches, the helpless larva must be able to locate a weak point in the roach’s armor: a soft membrane in the joint of the midleg where it can chew through and crawl inside the host.

Previous studies found that the wasp stings the roach twice in its attack: First it stings the roach in a part of the central nervous system called the first thoracic ganglion to immobilize the front legs, then it delivers a second sting directly to the brain “zombifying” the roach.

New research has revealed additional stings.

Just before the wasp deposits its egg on the roach, it stings the roach in in another part of the central nervous system called the second thoracic ganglion. This sting activates motor neurons that extend the roach’s middle legs, exposing the prime location for the wasp’s egg.

Small hairs on the mother wasp’s abdomen function as sensors to find just the right site on the roach’s leg for the egg.

The roach’s counter-strategy is simple: do not let the wasp get close. It keeps careful track of the wasp with sensitive antennae. And it uses its size and strength to its advantage.

Stand tall on long legs to maintain distance. At just the right moment, deliver a stunning kick to the wasp’s head.

A famously adaptable survivor, the cockroach can, with a few simple maneuvers, fend off one of nature’s most sophisticated predators.
would end up with enough wasps to resurrect the colony. The colony survived, but from this experience I learned that the tiny, soft-bodied wasp larva is not very competent. Unlike the frighteningly dexterous face huggers in *Alien*, a wasp grub moves slowly, if at all, and it can feed successfully only at one soft membrane on the cockroach. If it misses the target by a fraction of a millimeter, it dies (and the lucky roach recovers from the brain sting after about a week).

The grub’s fragility puts a lot of pressure on the mother wasp, who must glue its egg in just the right location for its young to survive. How does the wasp do it? To explore this question, I flipped a microscope upside down and bolted it to a table, and then I arranged a clear-bottomed chamber as a tomb for the wasp to find. This rig allowed me to get a close-up recording of the entire egg-laying process. The video showed the wasp making a very thorough investigation of the cockroach leg with the tip of its abdomen before laying the egg right next to a weak spot in the roach’s armor. (Like all insects, cockroaches have a tough exoskeleton, but just like medieval armor, the exoskeleton has weak points at the joints.) When I looked at the tip of the wasp’s abdomen under a scanning electron microscope, I noticed an array of minuscule hairs, almost like a set of miniature whiskers. Could these be the sensors the wasp uses to find the right location for the egg?

To test this possibility, I anesthetized wasps and trimmed off the hairs. That might sound simple enough to do, but it is a comically delicate operation that I could carry out only by holding the groggy (soon to be very angry) wasp with two bare fingers while gently shaving the equivalent of its private parts with an ultrasharp obsidian scalpel. It is a good setup for the ultimate fail. But it worked, and the results confirmed my suspicion: hairless wasps had trouble finding the right spot to place the egg. This observation not only revealed a key sensor used in the egg-laying process but also confirmed the critical importance of proper egg placement—a larva that hatched in the wrong place usually died without finding the roach’s weak spot.

**CHANCE DISCOVERY**

While I was studying the wasp’s sensory hairs and larval survival, I discovered something else that was entirely unexpected. Before each female wasp found the sweet spot for its egg, it extended the tip of its abdomen and repeatedly probed the center of the cockroach in front of the middle legs. In response, the cockroach often extended the middle leg on the side where the wasp was, as if annoyed by having its underside poked.

At first I did not know what to make of this behavior. It seemed like a distraction from the wasp’s egg-laying mission, as well as from my own mission of trying to understand the role of the wasp’s sensory hairs. But eventually I decided to look more closely at the wasp’s probing behavior by increasing the magnification of my microscope. I was astounded to see that the wasp was not just feeling around under the roach. Rather I could see the wasp’s stinger as it extended below the roach’s partially transparent cuticle. How could this be? Everyone who studies the jewel wasp knows it stings the roach twice—once in the first thoracic ganglion to paralyze the front legs and once in the brain to zombify the roach. Perhaps I was seeing a confused wasp, an outlier that was behaving abnormally.

I decided to change my focus, both literally and figuratively, and follow up on this observation. I soon learned that before laying an egg, every female jewel wasp delivers three stings to the central portion of the roach’s body under a very specific part of its armor called the basisternum. This structure is situated directly over the second thoracic ganglion, another part of the cockroach’s central nervous system. Recall that the wasp’s first sting goes into the first thoracic ganglion, paralyzing the front legs during the initial attack. The second thoracic ganglion, as you might guess, houses the motor neurons that control the second pair of legs, one of which the wasp will choose as the site for its egg. I realized that the odd leg-extension behavior I had noticed occurred within a few seconds of the newly documented stings. It seemed that the wasp’s sting was...
somehow forcing the roach to move its leg. Could this be one more stage in the wasp's process of establishing mind control over the cockroach?

It seemed possible, but how could I ever tell whether the sting was actually directed into the second thoracic ganglion, which is inside the roach's body? The same question had been asked about the wasp's first sting into the first thoracic ganglion, and it was a matter of long-standing debate until Libersat finally solved the mystery once and for all with an ingenious approach. He made the wasp, and thus its venom, radioactive. After the wasp stung the cockroach, he was able to show that the first thoracic ganglion contained the radioactivity.

I confess that I am not so brave as Libersat when it comes to making wasps radioactive—or to undertaking all the paperwork involved in getting the necessary permission to do such a thing. Fortunately, there was a more direct way to find out where the wasp was stinging. I anesthetized a cockroach and cut a small window into its cuticle so that the ganglion was visible. Then I increased my microscope's magnification and watched as the wasp stung. Sure enough, the sting was directed into the ganglion. (This approach would not work for tracing the first sting, which occurs during a pitched battle with the wasp.) Better yet, the sting was aimed at the side of the ganglion controlling the leg on the same side as the wasp—the side where it would later glue its egg. It is pretty clear that the wasp's venom during these later stings contains a component that activates the motor neurons in the second thoracic ganglion, thus causing the leg to extend.

But why would such a remarkably specialized behavior evolve? In other words, how does extending the roach's leg help the wasp reproduce? This time the answer was obvious. When the cockroach folds up its middle leg, the wasp cannot explore the surface with its sensory hairs to find the sweet spot for its egg where the larva can later feed and break through. For its egg to hatch, the wasp must grab hold of the roach. The two contestants circle each other, advancing and retreating in turn. Often the wasp will make a lunge at the cockroach, which bobs away from the wasp, making it a more distant and difficult target. At the same time, the roach's legs present a phalanx of sharp spines to the wasp as it tries to reach the roach's vulnerable body. The wasp cannot deliver the first sting until it has grabbed hold of the roach. The two contestants circle each other, advancing and retreating in turn. Often the wasp will make a lunge at the cockroach, which bobs and weaves to avoid the clamping jaws before reestablishing its defensive stance.

But the real surprise for me (and seemingly for the wasp) during my observations of such encounters came in the form of powerful kicks delivered by the cockroach with its spiny hind legs. These kicks often landed squarely on the wasp's head and shoved the wasp through the air until it crashed into the nearest object. The wasp inevitably dusted itself off with a quick bout of grooming and resumed the attack, at least after the first kick. But if the cockroach managed to land multiple kicks, the wasp usually broke off its attack. Apparently, to avoid becoming zombies and then having an alien burst from their bodies, roaches have to use the same strategy as many a science-fiction character: stay vigilant, don't run and aim for the attacker's head.

**MAKING A STAND**

**SO FAR I HAVE TOLD YOU HOW A WASP DEFEATS A COCKROACH WITH MULTIPLE STINGS TO ITS CENTRAL NERVOUS SYSTEM.**

The outcome seems inevitable if the roach is surprised by the wasp or if it runs. In those cases, the wasp easily gets the upper hand either by grabbing the roach immediately or by chasing it down—a roach cannot outrun a flying wasp. Once the wasp's jaws have closed on the cockroach, it can usually deliver the first sting within about a second, paralyzing the front legs, and—well, you know the grim story from there.

But some roaches have an attitude. They are vigilant, watching and feeling with their long antennae for an approaching threat. When a wasp closes in, these roaches do not run. Instead they get ready for a fight, raising themselves to full height by extending their long, spiny legs. In this so-called stilt-stance posture, the roach appears very much like a fencer in the en garde position, and in fact the stance seems to serve a similar purpose: it raises the roach's body away from the wasp, making it a more distant and difficult target. At the same time, the roach's legs present a phalanx of sharp spines to the wasp as it tries to reach the roach's vulnerable body. The wasp cannot deliver the first sting until it has grabbed hold of the roach. The two contestants circle each other, advancing and retreating in turn. Often the wasp will make a lunge at the cockroach, which bobs and weaves to avoid the clamping jaws before reestablishing its defensive stance.

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