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CONVERSATION

Extraordinary creatures: bogong moths

Bogong moths (*Agrotis infusa*) are native to Australia. Each year, the nocturnal insects migrate ∼1000 km from locations including southern Queensland, northern and western New South Wales, eastern South Australia and Victoria to the alpine areas of southeastern Australia at elevations above 1850 m, where they aestivate – the summer equivalent of hibernation – in isolated caves. They then return to their native territory the following year to reproduce and die. During their long-distance migrations, which can take up to a month, the insects are guided by the Earth's magnetic field and the night sky to the caves. Eric Warrant has studied these remarkable insects over the last 15 years, investigating the senses that allow them to follow the navigational cues that guide their exceptional journey. He tells *Journal of Experimental Biology* about these extraordinary creatures, how they are exquisitely adapted to their migration and their cultural significance to the First Nations people of Australia.

A bogong moth (*Agrotis infusa*). Photo credit: Ajay Narendra.

Please tell us about the life cycle of the bogong moth

It starts at the end of the return migration. The moths arrive back at the breeding areas, which are in semi-arid regions across southeast Australia, around April, May, which is the end of the Australian autumn. When they get there, they mate, lay their eggs on vegetation and die. When the eggs hatch, the caterpillars eat the vegetation and develop through the various instars as they grow. They mostly live under the soil during the day and emerge at night to climb up plants and chew on them. They rely very much on winter rainfall that promotes plant growth to provide them with food. During the late winter, the caterpillar pupates in the ground and then a couple of weeks later, in the early spring, a new adult emerges from the ground and that's when the moths begin the 1000 km journey to the alpine areas of Australia, travelling in different directions depending on where they started. When they get to the mountains, they find specific caves – we know of about 25 in New South Wales – and line the walls in their millions. About 4.2 billion moths make this journey, and they tile the walls of the cave – there are about 17,000 moths on every square metre of cave wall – and go into this state of dormancy, aestivation, for about 3 to 4 months. Then, at the at the end of the summer, triggered possibly by decreasing day length and decreasing temperature, they leave the cave and return to the breeding areas where the cycle starts afresh.

About 4.2 billion moths make this journey

Why do the moths migrate to these high-altitude caves?

We know that they've got a very low tolerance to hot temperatures. The maximum temperature they can tolerate over the summer in the caves is likely 16°C, and it has to be continuous; you can't have temperatures over 16°C for any extended period and expect them to remain aestivating, because they won't. The cave temperatures are typically in the vicinity of 10–12°C in the middle of summer at the present time. There are no other places in Australia that have consistent summer temperatures that are below 16°C and that's why we believe there are no other places they can go to aestivate. While they are in the caves, a fraction of the moths bring themselves out of aestivation every night and go out. We have a cave that we've been studying on the side of Mount Kosciuszko – the highest mountain in Australia at about 2200 m – which is about 100 m down from the summit. We've placed cameras in grids around the entire summit of the mountain and we've discovered that some of the moths leave the caves for about one hour, starting exactly at sunset, and then fly in circles around the peak. There are hundreds of thousands, if not millions, of moths flying around. It's amazing to see. We don't know what they're doing but I think they're probably calibrating all of their compasses together. They have a stellar compass and a magnetic compass and at sunset exactly there are lots of directional cues available that are potentially useful for calibration of these compasses. For example, there's a distinct glow of light in the west at sunset and the sun is at the horizon, which means the pattern of polarised light formed around the sun is the simplest that it is all day – the direction of polarised light across the entire sky is north/south, which is a very strong cue. The magnetic field of the Earth is another cue that is omnipresent. The stars are also becoming visible slowly during this flight, so all of these directional cues are being sensed simultaneously by the moths and can be used potentially to calibrate against each other. Circular flight is a classic thing that animals do to calibrate compasses. We know this from birds, and our own cell phones when we calibrate them for GPS. We don't know why the moths make this flight every day and we don't even know if it's the same moths flying every night, but we plan to find out.

What do bogong moths feed on during their migration?

During their migration they feed on spring flowering eucalyptus trees in large numbers. They can be so prolific in some places that beekeepers hate them. And they often forage for nectar during the day, even though they're nocturnal for the most part. If you put a bogong moth in a jar with a lid during the spring migration and leave it there for 20 minutes before taking the lid off, they smell like

Eric Warrant is a Professor at the Lund Vision Group, Department of Biology, Lund University, Sölvegatan 35, Lund, Sweden.
E-mail: eric.warrant@biol.lu.se

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Bogong moths aestivating on the walls of a cave in the Main Range, Kosciuszko National Park, New South Wales, Australia. Photo credit: Eric Warrant.

perfume – it's beautiful. They probably feed on a wide variety of native flowers. Their migration is so long that they go through the natural ranges of a large number of species of plants, many of which are flowering. I think that they tend to be generalists as caterpillars as well and eat quite a wide variety of plants.

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Can you describe one of the migration routes followed by bogong moths?

Some moths we know start their journey in western New South Wales. The country is semi-arid, it's grassy, sparsely treed and fairly flat, so they cross a flat landscape for quite a long time. Then, in the middle of New South Wales the landscape starts to undulate, and you get the odd larger mountain, but nothing more than 600 or 800 m until they reach the Great Dividing Range, which is a large range of mountains that runs 150 to 300 km inland from the eastern coast of Australia. When the moths encounter this range, they might use it as a navigational cue and follow it slightly south-westwards towards the aestivation sites, if they're coming from the north. If they're coming from western Victoria, they would end up hitting the mountain range slightly south of the aestivation sites and have to go northwards to the Alps. The areas where you find the aestivation caves are classic alpine areas above about 1850 m. There are large rolling smooth mountain tops and meadows full of flowers and lakes, absolutely beautiful. We don't know if bogong moths fly individually or in groups, because they are small, dark coloured and fly in the dark, so that makes it difficult for us to determine, but when we catch them with a light trap during the migration, we get large numbers turning up within a 5 to 10 minute period, and then nothing happens for an hour before another pile comes, so it seems like they travel together in large groups.

What happens when the moths arrive at their caves?

We have set up cameras where we've watched the moths with time lapse over many weeks. You can see the build-up of the moths inside the cave, you see them growing in number, the walls disappearing and then at some point, towards the end of the season, the population in the cave starts to thin, the patches become smaller until they're gone. I have a friend who has been in the mountains just west of Canberra where there are a couple of aestivation sites where the moths arrive at the beginning of the spring, and he's seen the first moth arrive on the cave wall. The fascinating thing is that it's exactly the same place where the first moth arrived the previous year. I think it's 'point zero', which the first moth always homes to, and I don't understand why. It's almost miraculous, because the moth has never been there before, cannot have learned about this location and will only ever be there once in its life.

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What senses do the moths rely on when navigating?

There are three potential navigational senses that we've identified so far. The first is the magnetic sense (magnetoreception) that senses the Earth's magnetic field, which they use as a compass. The second is the visual sense and the third is the olfactory sense – the sense of smell. They use the visual sense to distinguish constellations of stars, or they might use the Milky Way. We don't know exactly which aspect of the night sky they are using, but they can use it as a compass, which tells them a direction relative to north to travel to a distant place 1000 km away, which they've never been to before. We also have preliminary evidence that cave odours might be guiding spring migrants to the caves, that odours might be acting as a navigational beacon for the moths, but the jury is still out.

How do the moths know their current location?

There are two things they could do. If you know your position all the time, you are a so-called 'true navigator'. You not only have a compass but also have a map, and animals that researchers have studied that do this have a geomagnetic map – they can detect the local magnetic field intensity and inclination angle. Those two things vary smoothly and systematically across the surface of the Earth; each location is marked by a unique combination of field strength and inclination angle and that gives you the map. Sea turtles and night migratory birds have these maps, but I don't think that bogong moths are true navigators. They could get away with just having a compass if they know instinctively at birth which direction to fly in. My hypothesis is that they do something called 'vector navigation', where the journey is maybe a sequence of vectors (directions in which they travel). Each vector has a start and a finish and at the end of a vector there are sensory cues, which they instinctively recognise and which indicate that they have arrived at a particular position. Then they pick up the next vector to go to another place along the migration route, where a new set of sensory cues that uniquely identifies that location awaits, and so on.

How do the moths manage to navigate by the dim light of stars?

Bogong moths have incredibly sensitive vision. They have a type of compound eye that is about 1000 times more sensitive to light than that of day-active insects, which allows them to see the colours of objects illuminated by the tiny quantities of light from the stars, so the image on their retina is probably at least 15 times brighter than in our own dark-adapted eyes. But their eyes are very tiny. They certainly see a lot fewer stars than we do, but they'd see the Milky Way more brightly than we do, so they probably use the Milky Way

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mostly for navigation – which, in the southern hemisphere, has a gradient in light intensity from the northern sky to the southern part of the sky, getting brighter towards the south. The moths all come from different directions, so the Milky Way is not necessarily pointing in the right direction for all of them. The other complicating factor is that during the night, the Milky Way turns by about 90 deg, so it doesn't point in one direction. We don't know how they use the night sky, but we know that the rotation of the night sky does not cause them trouble and neither does a full sky of cloud – they still migrate in the correct direction, which means they default to their magnetic compass when stars are not available.

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How important is the bogong moth for First Nations people?

The First Nations tribes that lived in the alpine areas of southeastern Australia before Europeans came and disturbed everything lived on both sides of the mountains: on the coastal side and on the inland side. They knew about the arrival of the moths in the mountains and so, during the summer, the First Nations people from the two sides of the mountains would migrate up to where the caves are and spend 2 to 3 months feasting on the moths; they arranged marriages, they did business and they socialised. The bogong moth became a really important part of First Nations people's cultural heritage; it's part of their art, their stories, their songs and their Dreaming – which is their complex system of beliefs. They named the moth, which means 'brown' in the Dhudhuroa language.

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How do the moths contribute to the ecology of their summer aestivation sites?

They contribute an enormous amount of food for the endemic marsupial species that live in the mountains, like the mountain pygmy possum, the antechinus and the broad-toothed rat. Lots of alpine marsupials live in the mountains all year, some of them hibernate even, and when the snow is thawing in the spring the first food that they get is this influx of moths, so they're highly dependent on the moths. They can turn to other food sources later in the spring and in the summer, when the snow is fully melted and things start to get going, but the moths are really the first food that arrives. Probably lots of moths perish in the mountains as well and their bodies can provide quite a lot of fertiliser for alpine plants.

The moths are really the first food that arrives

How have recent changes affected the bogong moth population?

There's been a slow decline in moth numbers in the alpine areas since they were first quantified in the early 1950s, but when we had our drought a few years ago, the population plummeted by about 99.5%, which is pretty nasty. We don't really know what caused the slow decline, but there are a few smoking guns that could be responsible: loss of habitat where the caterpillars develop over winter due to expanding agricultural practices; it could be due also to the use of neonicotinoid pesticides. The other obvious big killer is climate change. The semi-arid areas of southeastern Australia, where the caterpillars develop and eat new vegetation as a result of winter rainfall, are very susceptible to long periods of severe drought. It's almost certain that the population crash that we had during our last drought (2017–2020) occurred because there was nothing for the caterpillars to eat in the winter and they just died. In Australia, the frequency and intensity of these types of droughts are predicted to increase, so this doesn't bode well. I'm worried. One possible way to protect the moths is to try to set aside areas that are not used for agriculture – they could just be left, even though agriculture is one of the minor drivers. But I think that a warming climate is the biggest threat, so it's a case of stopping using fossil fuels and moving to alternative energy sources. That's where the solution lies.

Have cities and the light they produce impacted the moths and their ability to navigate?

From what I can tell, no. During the last 150 years, towns have sprung up everywhere producing light on the ground at night, but there has not been an obvious decline in the moths because of the light. However, they are attracted to Canberra sometimes. My hypothesis is that they suddenly get into an unexpected and unfavourable wind system that blows them across the mountains into the city. There have been bogong moth invasions so massive in Canberra that they've shut down Parliament, which I think is incredible. The parliament building was completely infested, with aestivating Bogong moths short circuiting the lifts and blowing out the electricity. The last time this happened was in 2013 and it lasted about 2 or 3 weeks. For the moths it's a 'pit stop', a temporary aggregation of moths on their journey, which they do naturally anyway. The moths normally arrive at lower mountain elevations a bit earlier in the spring, when the higher caves are still blocked by snow, and they tend to make a slow upwards journey, aggregating temporarily in sheltered spots along the way, which we call camps. Sometimes they just use Canberra as a camp, but we've noticed no major effect on the numbers that ultimately reach the caves in those years. The Bogong moth is really one of the most amazing insects! Despite having a brain a tenth of the volume of a grain of rice and very small eyes, it pulls off a feat of navigation that rivals those of vertebrate animals with much larger brains.

Eric Warrant was interviewed by Kathryn Knight. The interview has been edited and condensed with the interviewee's approval.