April 14, 2016

Scientists crack secrets of the monarch butterfly's internal compass

James Urton
News and Information

"Now where was I going?" *Flickr/Wikimedia Commons*

Each fall, monarch butterflies across Canada and the United States turn their orange, black and white-mottled wings toward the Rio Grande and migrate over 2,000 miles to the relative warmth of central Mexico.

Monarch Watch

This journey, repeated instinctively by generations of monarchs, continues even as monarch numbers have plummeted due to loss of their sole larval food source — milkweed. But amid this sad news, a research team believes they have cracked the secret of the internal, genetically encoded compass that the monarchs use to determine the direction — southwest — they should fly each fall.

"Their compass integrates two pieces of information — the time of day and the sun's position on the horizon — to find the southerly direction," said Eli Shlizerman, a University of Washington assistant professor.

While the nature of the monarch butterfly's ability to integrate the time of day and the sun's location in the sky are known from previous research, scientists have never understood how the monarch's brain receives and processes this information. Shlizerman, who has joint appointments in the Department of Applied Mathematics and the Department of Electrical Engineering, partnered with colleagues at the University of Michigan and the University of Massachusetts to model how the monarch's compass is organized within its brain.

"We wanted to understand how the monarch is processing these different types of information to yield this constant behavior — flying southwest each fall," said Shlizerman, who is lead author on the team's April 14 paper in the journal Cell Reports.

Monarchs use their large, complex eyes to monitor the sun's position in the sky. But the sun's position is not sufficient to determine direction. Each butterfly must also combine that information with the time of day to know where to go. Fortunately, like most animals including humans, monarchs possess an internal clock based on the rhythmic expression of key genes. This clock maintains a daily pattern of physiology and behavior. In the monarch butterfly, the clock is centered in the antennae, and its information travels via neurons to the brain.

Biologists have previously studied the rhythmic patterns in monarch antennae that control the internal clock, as well as how their compound eyes decipher the sun's position in the sky. Shlizerman's collaborators, including Steven Reppert at the University of Massachusetts, recorded signals from antennae nerves in monarchs as they transmitted clock information to the brain as well as light information from the eyes.

Shlizerman and colleagues modeled how the monarch brain integrates the time of day with the sun's position in the sky. *Eli Shlizerman*

"We created a model that incorporated this information — how the antennae and eyes send this information to the brain," said Shlizerman. "Our goal was to model what type of control mechanism would be at work within the brain, and then asked whether our model could guarantee sustained navigation in the southwest direction."

In their model, two neural mechanisms — one inhibitory and one excitatory — controlled signals from clock genes in the antennae. Their model had a similar system in place to discern the sun's position based on signals from the eyes. The balance between these control mechanisms would help the monarch brain decipher which direction was southwest.

Based on their model, it also appears that when making course corrections monarchs do not simply take the shortest turn to get back on route. Their model includes a unique feature — a separation point that would control whether the monarch turned right or left to head in the southwest direction.

"The location of this point in the monarch butterfly's visual field changes throughout the day," said Shlizerman. "And our model predicts that the monarch will not cross this point when it makes a course correction to head back southwest."

Based on their simulations, if a monarch gets off course due to a gust of wind or object in its path, it will turn whichever direction won't require it to cross the separation point.

Additional studies would need to confirm whether the researchers' model is consistent with monarch butterfly brain anatomy, physiology and behavior. So far, aspects of their model, such as the separation point, seem consistent with observed behaviors.

"In experiments with monarchs at different times of the day, you do see occasions where their turns in course corrections are unusually long, slow or meandering," said Shlizerman. "These could be cases where they can't do a shorter turn because it would require crossing the separation point."

Their model also suggests a simple explanation why monarch butterflies are able to reverse course in the spring and head northeast back to the United States and Canada. The four neural mechanisms that transmit information about the clock and the sun's position would simply need to reverse direction.

"And when that happens, their compass points northeast instead of southwest," said Shlizerman. "It's a simple, robust system to explain how these butterflies — generation after generation — make this remarkable migration."

In addition to Reppert, other co-authors on the paper were James Phillips-Portillo at the University of Massachusetts and Daniel Forger at the University of Michigan. Shlizerman's work was funded by the National Science Foundation and the Washington Research Fund.

Additional information can be found at the project's blog.

###

For more information, contact Shlizerman at 206-543-6658 or shlizee@uw.edu.

Grant number: DMS-1361145

Tag(s): College of Arts & Sciences • College of Engineering • Department of Applied Mathematics • Department of Electrical Engineering • ecology • Eli Shlizerman

We've Finally Solved the Mystery of How Monarch Butterflies Navigate Thousands of Miles

George Dvorsky
4/15/16 12:35pm Filed to: ANIMAL BEHAVIOR


Image: Flickr/Wikimedia Commons.

Each year, the migratory monarch butterfly embarks on an extraordinary journey from eastern North America to central Mexico. A multidisciplinary team of scientists has now created a model circuit that finally explains how these insects are able to navigate across such vast distances.

Migrating eastern North American monarchs have an internal compass that taps into the position of the sun, allowing the butterflies to maintain a steady northwestern trajectory. Scientists have known about this for years, but they had no idea how these signals are represented in the butterfly's brain, and how all this information—like the sun's position relative to the horizon and the time of day—are processed to produce flight control. New research from the University of Washington shows that monarchs are equipped with "cellular circuits" that drive this biological compass.

To understand how this navigation system works within the monarch brain, a team led by Eli Shlizerman took their knowledge of monarch physiology and neurology, and they emulated it in a model circuit. The researchers wanted to understand what kind of mathematical voodoo goes in the butterfly's brain that allows it to convert the incoming stream of data into a meaningful signal that consistently sends the insect in the right direction.

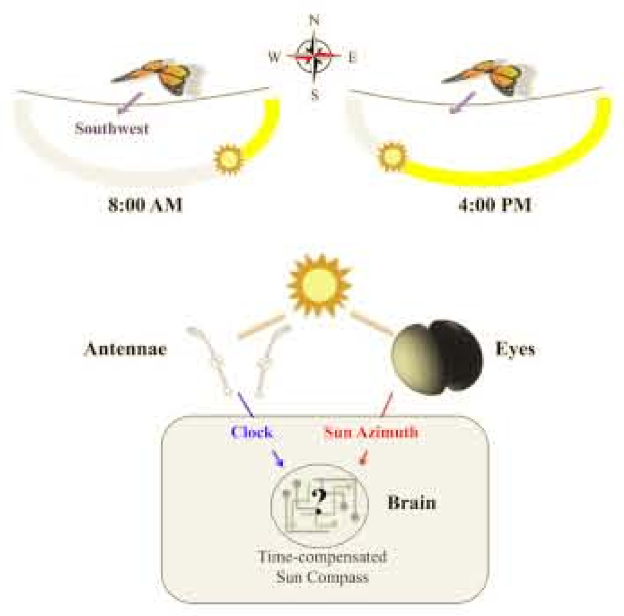

Image: Eli Shlizerman et al., 2016/Cell Reports

Monarchs are equipped with large, complex eyes that scan the sun's position in the sky. But that's not enough to determine direction; these bugs also need to know the time of day. To figure that out, monarchs have evolved an internal clock driven by the rhythmic expression of key genes. This "clock" is located in the antennae, and it sends this valuable information via neurons to the brain.

With the help of biologist Steven Reppert at the University of Massachusetts, the scientists were able to record these signals as they were being transmitted to the brain, along with the sunlight signals collected by the eyes.

"We created a model that incorporated this information—how the antennae and eyes send this information to the brain," Shlizerman said in a statement. "Our goal was to model what type of control mechanism would be at work within the brain, and then asked whether our model could guarantee sustained navigation in the southwest direction."

The resulting model consisted of two control mechanisms, one to monitor the time of day, and one to monitor the position of the sun.

"The circuit gets those two signals then matches them, according to how it's wired, to control signals that tell the system if a correction is needed to stay on the correct course," Shlizerman told the BBC. "It shows how behavior is produced by the integration of signals." The system simply goes into reverse to help with the journey home.

In the future, this model circuit could be installed in a robotic butterfly or other robotic insects. The researchers say these hypothetical mechanical brethren could follow monarchs on their annual journey and track their entire migration. Such a project could go a long way in helping this species, which has suffered significant population decline over the last several years.

[Cell Reports]

George Dvorsky @dvorsky
George is a contributing editor at Gizmodo and io9.

SCIENCE

Scientists crack mystery of migrating monarch navigation

The uncanny mechanisms that monarch butterflies use to navigate thousands of miles each year, back and forth from their wintering grounds in Mexico has long baffled scientists. A new study suggests how they may process information to determine which way to go.

By Eva Botkin-Kowacki | APRIL 15, 2016

Save for later

Michael Fiala/Reuters/File | View Caption

Monarch butterflies migrate thousands of miles from the northern United States and southern Canada to spend the winter in more temperate climates in southern Mexico. The insects may not have a GPS to navigate their way south, but they do have a compass of sorts.

Previous research found that the insects use the position of the sun in the sky combined with an internal clock to determine which way is south, in what's called a time-compensated sun compass.

But scientists puzzled over how this information was integrated and turned into action inside the butterfly's brain. So a team of researchers set out to create a model that might explain the neurological mechanism. That model is described in a paper published Thursday in the journal Cell Reports.

Recommended: **14 animals declared extinct in the 21st century**

"We have the pieces. They have to connect someplace," one of the researchers, Steven Reppert, a neurobiologist at the University of Massachusetts Medical School, tells The Christian Science Monitor in a phone interview. Now, "we have an idea of how those connections should potentially occur."

So how does it work?

As a monarch butterfly flies along on a sunny day, its eyes are constantly registering where the sun is in relation to the horizon. Although the sun travels east to west, the butterfly needs to be able to determine which is which at a given moment. That's where the circadian clock comes in.

Embedded within the insect's antennae are these biological clocks. They help the butterfly determine what time it is. So if the sun is close to the horizon, these clocks indicate whether it is rising or setting and therefore if it is in the east or west.

Then, if the sun is in the east, for example, the butterfly flies with the sun on its left to go south.

14 animals declared extinct in the 21st century

IN PICTURES | Protecting the butterflies' forest

PHOTOS OF THE DAY | Photos of the weekend

But how those two sets of data work together to create a directional adjustment in the butterflies has been unclear, and that's where this new research comes in.

"This work provides a big step forward in thinking about how these different pieces of information that we knew had to talk to each other are likely to do that," Marcus Kronforst, an ecologist at the University of Chicago who was not part of this study, tells the Monitor in a phone interview.

These two senses feed into the center of the butterfly's brain, into a sort of compass. But what are the signals that enter the brain and how do they interact?

The researchers fed the data they already knew about how this whole navigation system works into their computational model. Using those parameters, they developed what might be the neural mechanism.

As the receptive fields in the eyes detect the sun's position, an oscillating neuronal signal is sent through to the brain. Meanwhile, the circadian clock is also sending oscillations.

The rate and combination of these neuronal signals tell the brain what signal to send to the body to adjust course. It dictates how much of an angle to change and whether it should turn left or right.

And if a butterfly is blown too far away from the necessary southerly direction, they adjust in a more dramatic way.

The researchers found that if the butterflies are pushed off course past a certain angle (which changes throughout the day), they will actually rotate their bodies around in a full circle as a sort of resetting method. Interestingly, that angle is tighter to the southerly track during the morning and evening, so the researchers suggest these rotational corrections likely occur more frequently then.

This phenomenon didn't just appear in the model, the first author of the study, Eli Shlizerman, an applied mathematics researcher at the University of Washington, tells the Monitor in a phone interview. When they tested the actual butterflies, they would see them perform similar rotations to adjust.

But that's not all. What happens when the butterflies need to return north for the summer?

When the researchers were investigating what different arrangements of neuronal wiring might fit the data to explain how the butterflies navigate, they found just two viable options. One helps the monarchs fly southwest, and the other helps it return northeast.

And, as Dr. Kronforst explains, the butterflies don't fly around aimlessly to find their initial direction when it is time to migrate. Instead, they set off in the right direction right away. So these two wirings likely appear somehow in the neurobiology of the monarch butterflies.

This model doesn't explain all the mechanisms likely involved in monarch migration navigation, admits Dr. Reppert. This model just looks at the mechanism for when the sun is in clear view in the sky. But the butterflies are known to be able to use polarized light on partly cloudy days to calculate the position of the sun. And they still fly in the right direction on completely overcast days. This is likely thanks to a sort of magnetic compass also in the insect's brain, Reppert says.

It's still unclear how these different mechanisms work together, Reppert says, but the sun compass is likely the primary cue that the butterflies use to determine direction.

To confirm their model, the researchers will next need to dig into the biology of butterflies and see if the model matches the structures actually in their brains.

"It is really an incredible feat that these little butterflies are able to make that amazing long-distance migration," Kronforst says. "That's why it's important for people to try and understand how this happens."

This research won't just help scientists understand monarch migrations, he adds. It also could yield clues into the navigational tools of other migratory animals too.

Popular Now

1 FIRST LOOK First-time video captures rare True's beaked whale up from the depths

2 FIRST LOOK The tortoise: Blue Origins sees small steps as key to space business

3 FIRST LOOK Feud over Mississippi flag moves to federal appeals court

4 FIRST LOOK Poachers shoot and kill a rhino ... outside Paris (+video)

5 After Trump tweets, pressure grows for full Russia investigation (+video)

Great monarch butterfly migration mystery solved

By Victoria Gill
Science reporter, BBC News

14 April 2016 | Science & Environment   Share

The researchers peered inside the brains of butterflies to learn their secrets

Scientists have built a model circuit that solves the mystery of one of nature's most famous journeys - the great migration of monarch butterflies from Canada to Mexico.

Monarchs are the only insects to migrate such a vast distance.

So, by teaming up with biologists, mathematicians set out to recreate the internal compass they use to navigate on that journey.

The findings are **published in the journal Cell Reports**.

Lead researcher Prof Eli Shlizerman, from the University of Washington, explained that, as a mathematician, he wants to know how neurobiological systems are wired and what rules we can learn from them.

"Monarch butterflies [complete their journey] in such an optimal, predetermined way," he told BBC News.

"They end up in a particular location in Central Mexico after two months of flight, saving energy and only using a few cues."

Prof Shlizerman worked with biologist colleagues, including Steven Reppert at the University of Massachusetts, to record directly from neurons in the butterflies' antennae and eyes.

"We identified that the input cues depend entirely on the Sun," explained Prof Shlizerman.

"One is the horizontal position of the Sun and the other is keeping the time of day.

"This gives [the insects] an internal Sun compass for travelling southerly throughout the day."

Having worked out the inputs for this internal compass, Prof Shlizerman then created a model system to simulate it.

This consisted of two control mechanisms - one based on the timekeeping "clock" neurons in the butterflies' antennae and the other from what are called azimuth neurons in their eyes. These monitor the position of the Sun.

"The circuit gets those two signals then matches them, according to how it's wired, to control signals that tell the system if a correction is needed to stay on the correct course," explained Prof Shlizerman.

"For me this is very exciting - it shows how a behaviour is produced by the integration of signals," he added.

"We can take these concepts to produce robotic versions of these systems - something [that is] powered by and that navigates by the Sun."

Prof Shlizerman said that one of his team's goals was to build a robotic monarch butterfly that could follow the insects and track their entire migration.

"It's a very interesting application that could follow the butterflies and even help maintain them.

"Their numbers are decreasing, so we want to keep this insect - the only one that migrates these huge distances - with us for many years."

Prof Matthew Cobb from the University of Manchester told BBC News that the study showed that "something as astounding as the monarch migration can be understood in terms of cellular circuitry".

"Our current robots are far cruder than even the simplest nervous system," he added.

Follow Victoria **F on Twitter**

Related Topics

Evolution