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A journey to find the origins of behaviour

Stanley Heinze has set out to explain why we perform certain tasks – why we do what we do – and helps us to understand the origins of behaviour.

During my PhD I was invited back to my old high-school to give a talk about what it was like to study Biology. After some general remarks, I revealed that my research focused on how a specific region in the brain of insects processes visual information. I did not get very far until a teacher in the audience asked whether insects really had actual brains - brains with different parts, that have different functions, just like we have? I realised at this point that insect neuroscience had been living in a pretty remote place, certainly far from the public. So, do insects have brains? Of course, and while they are indeed very small, they are no less fascinating and complex than our own brains, or that of a parrot, or that of a mouse. Actually, after dissecting an ant’s brain, Darwin himself wrote that: “It is certain that there may be extraordinary mental activity with an extremely small absolute mass of nervous matter: thus, the wonderfully diversified instincts, mental powers, and affections of ants are notorious, yet their cerebral ganglia are not so large as the quarter of a small pin’s head. Under this point of view, the brain of an ant is one of the most marvelous atoms of matter in the world, perhaps more so than the brain of a man.” (The Descent of Men, Darwin, 1871). And indeed, insects can achieve astonishing things with these tiny brains.

A challenge
Imagine you camp in the middle of a dense, tropical forest and you wander off for a few kilometers into various directions to collect fruit. Once you found what you needed, the plan is to return straight to the camp. Without GPS, or a map and compass, we all would be completely lost. Yet, small, solitary bees do this for a living; and if the outlined task was not already sufficiently challenging, they carry out these homing flights in the darkness of night. Neither do they have to merely find a camp, but a tiny hole at the end of a small stick (their nest) amidst the dense undergrowth of the forest. How can they excel where we fail so badly? By comparison, they have ca. 100,000 times fewer nerve cells in their brains. This brain processes information delivered by two compound eyes on either side of the head. While these eyes are highly sensitive to low light levels, they have much lower resolution, not allowing them to see details occupying an angle of visual space smaller than three degrees (we can resolve less than 0.02 degrees). Nevertheless, they rely on vision to maneuver their forest habitat. Visual information allows them to keep track of their convoluted paths during the search for food and also guides them along a straight path back to their nest.

A strategy
The process underlying this remarkable navigation ability is called path integration. This strategy continuously integrates the bee’s flight speed and direction of movement to update an internal estimate of its position relative to the nest. Insects with a fixed nest (ants, bees, wasps) and many other animals, including mammals, also use this strategy to explore novel surroundings and to return to a point of origin. Yet, it is still unknown how exactly the brain of any species carries out these tasks. While in mammals, neural recordings have shown that the hippocampus plays a major role for path integration, in insects, insights into potential mechanisms of path integration resulted largely from behavioural work. This work has revealed that both the sense of direction as well as the speed measurement, are driven by visual information. Direction is measured by observing compass cues in the sky, such as the position of the sun and the pattern of polarised light that surrounds the sun. Speed (and therefore also distance) is sensed by the amount of movement across the retina that the bees experience when they fly through their environment (optic flow).

Looking into the brain
The sense of direction was first explored in migratory locusts, as their brains are comparably large. During my PhD work I showed that a structure in the centre of the insect brain (called the central complex) contains an ordered array of neurons that change their activity when we showed polarised sunlight to the locust. Each cell has a preferred direction of polarisation and, combined, all cells encode the body orientation of the animal with respect to the sky as a bump of activity across the central complex. This essentially is an internal compass. Work in flies has since shown that this mapping of directions is likely a universally conserved feature that endows all insects with a sense of direction. Indeed, recently my lab confirmed the existence of similar neurons in the central complex of our tropical, forest-dwelling bees as well. More importantly, we also discovered cells in the same brain area that get highly excited when we show optic flow to the bees in a virtual reality arena. While we provided the bee with the sensory information it would experience during a foraging flight, we electrophysiologically recorded these cells and observed that their activity changed in
synchrony with the perceived changes in flight speed. We therefore found ‘speed cells’ in the same brain region that houses the ‘compass cells’ located there earlier.

**From bees to robots**

How do speed cells and compass cells interact to allow the bee to know the position of its nest? We still do not know for sure - but we have an idea. This idea was born out of an unusual combination of neuroanatomical work and robotics research. When we drew out all known neural projection patterns within the central complex (multiple cell types following highly regular, repeating patterns), the result looked oddly familiar. Indeed, ten years earlier, a robotics laboratory at the University of Edinburgh had used an evolutionary algorithm to find an optimal solution for the problem of path integration. This resulted in a computational model of a neural circuit, whose wiring turned out to be identical to our anatomical connection patterns in the insect central complex. A model designed by engineers to carry out path integration was therefore embedded in the neuroarchitecture of the insect brain, an astonishing finding.

We then went on to actually design a computational model of the anatomically identified neurons and indeed, the model enabled a virtual agent (as well as a physical robot) to robustly return to a point of origin after a random outbound trip. The model relies on specific neurons in the central complex to record flight speed over time, leading to an increase of their activity with further distances flown. One of these odometers exists for each compass direction, resulting in a population of 16 direction locked odometers. These generate a bump of activity across the width of the central complex that is highly similar to the head direction activity bump in the same region. Therefore, the central complex houses both a representation of the current flight direction as well as a representation of the target direction. As both are represented in the same format, they can easily be compared to one another. If the two patterns are misaligned, the bee has to initiate a turning movement to compensate for the mismatch and to get back on track towards its target. We indeed identified specific neurons in the central complex that have the correct anatomical properties to carry out this comparison and to serve as input to the actual steering system in the bee brain. This comparison would have to be performed at each moment in time to generate a continuous chain of elementary navigational decisions initiating right or left turns to maintain a target direction.

**Widening the scope**

In a broader context, this strategy could underly all directed movements, not only in insects, but in all animals. If behaviour is broken down into a moment to moment basis, even we as humans will mostly have to decide whether to turn right, left, or keep on moving straight ahead. What we do at each moment in time will depend on the sensory information from our environment, but also on our previous experience and our internal motivation (e.g. am I hungry?). All of these will determine what the current navigational goal is, and then match that goal to our current orientation in space. The complexity of our own behaviour then results from a multitude of factors that influences our target direction at each moment in time. Such directed behaviours would then be complemented by behavioural modules that can simply be switched on and off, for instance eating, sitting, or reading. How directed and undirected behaviours are coordinated, how internal motivation and previous experience are fed into the neural navigation circuits, and how coherent behavioural strategies emerge from elementary decisions, are the main question of the work in my group. To work towards these goals, we compare how the involved neural circuits have evolved in insect species with different navigation strategies and distinct sensory environments. We deploy a range of methods, from intracellular electrophysiology, multi-electrode recording, 3D electron microscopy and confocal microscopy, to behavioural experiments and computational modeling. Additionally, a global network of collaborators provides us with access to a wide range of species and key expertise. In the end, we hope to be able to use our understanding of the circuitry underlying navigational decisions in insects to extract the key principles of how brains in general make decisions that underly not only navigation behaviours, but any complex behaviour, including the decision that brought you here to read this article.

**Further reading**


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**Profile**

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