Insect Navigation:
From Ants to Robots & Back Again

Cornelia Buehlmann & James Knight from the University of Sussex explain how we can combine behavioural and neuroscience experiments on ants with computational modelling & robotics.

Cataglyphis Velox, image by Cornelia Buehlmann.

Small-brained animals with fascinating navigational behaviours

As soon as the sun comes up, ants get to work, collecting food for their colony. Wood ants head to their favourite tree to find honeydew from aphids while desert ants try to find dead arthropods that have perished in the heat of the desert sun.

During such a foraging journey an ant worker can reach a position hundreds of meters away from her nest and must safely navigate back home (Buehlmann et al. 2014). Such an impressive task requires sophisticated navigational skills from an animal with a brain housing only around 250,000 neurons *(400,000 times fewer neurons than our own brains).* Multiple navigational strategies are used depending on the ants' sensory ecology, and it is this clever combination of innate navigational strategies and the learning of visual and olfactory information from the environment that is the key to ants' navigational success *(Wehner 2003; Collett et al. 2013; Knaden & Graham 2016).* While some ant species rely on pheromone trails, many others rely on path integration and information learnt from the environment. Path integration is an innate behaviour that allows individuals to explore unfamiliar terrain by using a 'sky compass' and a step counter to maintain a continuous estimate of the direct path back to the origin of a journey *(Heinze et al. 2018).* When ants are unfamiliar with the environment, path integration is vital, but ants complement this strategy by learning environmental features as they become familiar with their surroundings. Wood ants forage in dense, overgrown woods, and some desert ants inhabit cluttered environments rich in vegetation. Therefore, it is no surprise that these ants use learnt visual information to guide themselves along routes between the nest and foraging grounds. Routes that can be long and complex *(Kohler & Wehner 2005; Mangan & Webb 2012).*

Why it's so nice to study social insects

Navigation is a universal behaviour and all animals exhibit some form of navigational behaviour. Social insects, such as ants, play a key role in animal navigation research. Ant foragers are specialized for navigation and little else, which means they are practical to work with, as they spend their days shuttling between food and their nest. This robust, repeatable, and impressive natural foraging performance is thus a unique tool for unravelling the mechanisms of navigation. We can study their behaviour in natural habitats or under more controlled conditions in the lab, to understand natural behaviour or neural architecture, respectively. To go one step further in unpicking how behaviour emerges from the interactions between environment, brain, and behaviour, we can combine these behavioural and neuroscience experiments with computational modelling and robotics.

From behaviour to the brain

In insects, two brain centres are particularly exciting when it comes to navigation *(Figure 1 below).* The mushroom bodies (MB) are thought to be crucial for learning and memory and the central complex (CX) for orientation control *(Webb & Wystrach 2016).*

Sky-compass information from UV-sensitive receptors in the compound eye goes to the central complex – which is very similar across insects – reflecting a general need for insects to control their movement relative to external sensory information.

Another pathway transmits visual information from the eye to the mushroom body, ready for learning *(Roessler 2019).* The mushroom body is present in almost all insects and its role in olfactory learning has been extensively studied *(Cognigni et al. 2018)* and modelled *(Nowotny et al. 2005).* However, the visual input pathway is thought to have only evolved with the central-place foraging behaviour seen in hymenopteran insects, and is therefore not present in other insects. This reflects the high volume of visual learning required for social insect foragers.

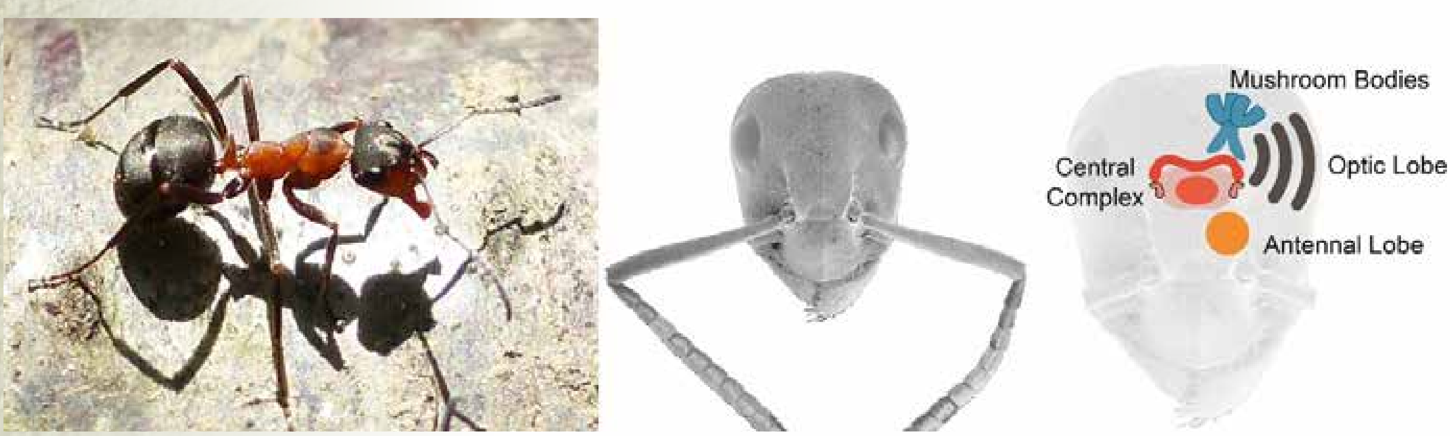

Figure 1: Left: Wood ant (Formica rufa). Middle: Ant head imaged by Craig Perl. Right: Schematic anatomy of the insect visual system.

Figure 2: Natural foraging ground of wood ants. The same image is shown in high resolution (top) and low resolution (bottom). Black, vertical bars in upper image represent 210° field of view in humans. Ants have a low resolution but an almost 360° panoramic view of the world.

From behaviour and brains to computational models and robots *(and back again)*

To a human being, ants experience a very alien view of the world *(Figure 2 above)*. Their compound eyes capture an almost 360° panoramic view of the world, but this is sampled at a very low resolution. With minimal processing, these wide-field panoramic views provide reliable information on whether a visual scene is familiar, whilst being useless for recognising individual objects *(Graham & Cheng 2009)*. Bioinspired models of how insects and robots might use views for navigation have a long history. In simple 'homing' models of visual navigation, simulated insects had a single view of their nest and moved so as to minimize the difference between the nest view and their current view of the world *(Cartwright & Collett 1983)*. However, in natural environments, the 'catchment area' around a single view is small and it is difficult to determine exactly what movements the simulated ant has to make to return home from any given point. To address these issues, models have been extended to store a number of views representing complex routes *(Baddeley et al. 2012)*. With such models, a simulated ant can follow a route by periodically scanning and, at each point in the scan, comparing the current view to all of the stored views and simply moving in the direction in which the view is most similar to her memories. This model has been implemented using both artificial neural networks and computational models of the mushroom body *(Ardin et al. 2016)* suggesting that not only

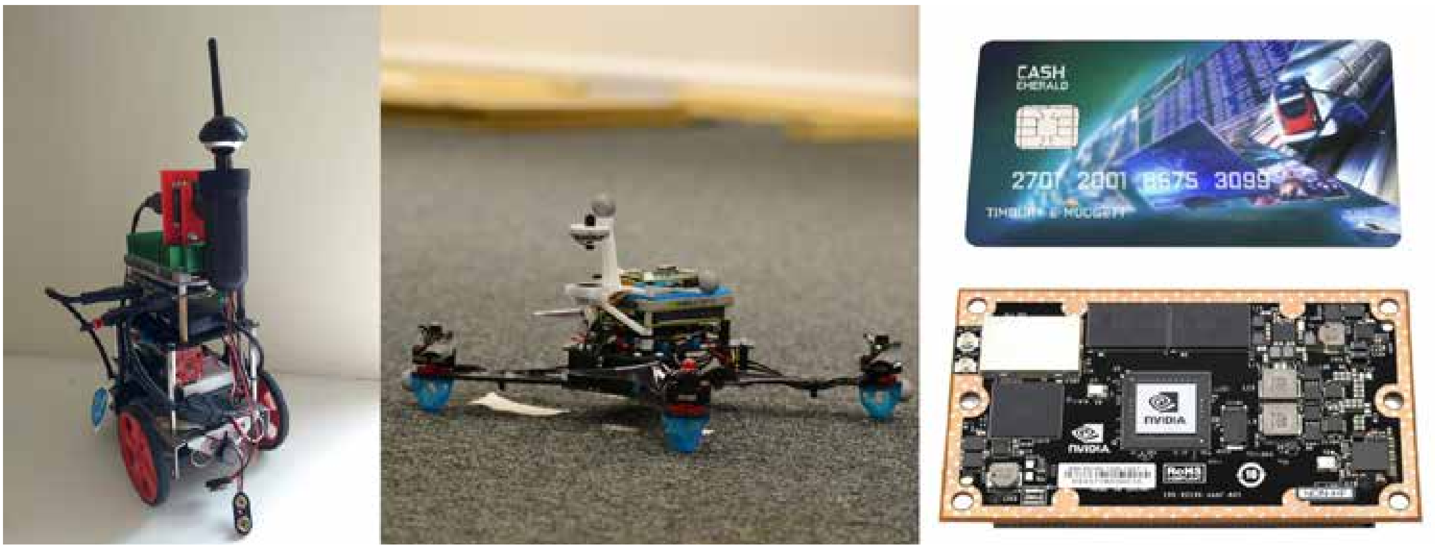

Figure 3: Left: Ant robot. Middle: Bee robot. Image taken by Alex Cope. Right: Robot brain JETSON TX1.

does it reproduce the behaviour seen in ants, but it can also be mapped to the neural 'hardware' they have available.

The path integration behaviour of insects can also now be mapped onto specific circuits in the central complex of insects and, by implementing this circuit on a wheeled robot, the neuroethology loop can be closed, allowing the behaviour of the model to be directly compared to the behaviour of the animal it all started with (Stone et al. 2017).

Historically, the MB and CX – the important navigational centres of the brain – were studied in isolation. However, recent theoretical models describe how the central complex and mushroom bodies could potentially work together in navigating ants (Collett & Collett 2018). The view-based navigation signal from the MB provides target headings along a learnt route and the CX maintains these headings by controlling the motor system based on the ant's sky compass.

In our research projects at the University of Sussex, funded by both the Biotechnology and Biological Sciences Research Council (BBSRC) and Engineering and Physical Sciences Research Council (EPSRC) (http://www.sussex.ac.uk/lifesci/insectnavigation/index), we aim to better understand what information ants extract from complex natural scenes as well as how visual navigation is actually implemented in the insect brain by doing direct manipulations of the specific pathways described above. But we want to go further and, in the Brains on Board project (http://brainsonboard.co.uk/research/), we aim to build autonomous robots based on the principles outlined here that will navigate around dynamic environments and seek changing goals. Figure 3 shows two prototype robots developed by the project - a wheeled 'ant' and a flying 'bee'. Both come equipped with panoramic vision sensors and the latest NVIDIA Jetson embedded GPUs which, using our own GeNN software (Knight & Nowotny 2018), are able to use simulated brain models to control their motors.


Wood Ants, image courtesy of the University of Sussex

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