

Expanding Consciousness

Bees and other insects show signs of possessing complex self-awareness, but if the scope of consciousness is widened, where will it end?

Lars Chittka and Catherine Wilson

Consciousness is a state of awareness that allows us to close our eyes and picture our childhood home, or to perform the sort of planning, prediction and risk assessment required to gauge whether it's safe to jump over a stream of a given width. It allows us to solve problems by thinking, rather than simply by trial and error.

For centuries, scholars such as René Descartes (1596–1650) have argued that consciousness is a uniquely human attribute, perhaps facilitated by language, that allows us to communicate about our memories and feelings, and to coordinate plans for the future. In this view, nonhuman animals were regarded as merely cleverly-designed automatons with a toolkit of pre-programmed behaviors, each triggered by certain environmental stimuli.

Social insects such as bees and ants seemed to epitomize this viewpoint. Scientists knew that a large behavioral repertoire is required to construct their elaborate homes, defend them against intruders, provision their young with adequate nutrition—but it seemed plausible that these animals were nonetheless “reflex machines” without internal representation of the world or an ability to foresee even the immediate future. In this view, insects were

close to the notion of philosophical *zombies*—hypothetical robots that behave overtly like normal humans, but are entirely based on preprogrammed behavior routines and reflexes, without any self-awareness.

But there are now many indications that insects exhibit consciousness-like phenomena. Some lines of evidence are from experiments that have lain buried in the literature for decades, even centuries, without anyone recognizing their significance for consciousness.

Honeybees, for example, have a symbolic language by which they communicate about the precise coordinates of floral food sources or potential nest sites (see “Group Decision Making In Honey Bee Swarms,” May–June 2006). In this *dance language*, a scout bee returning from a flower patch performs a repetitive sequence of movements in the dark hive on the vertical comb. These movements are keenly attended by other bees. The successful forager moves forward in a straight line for a few centimeters, then a half circle to the left back to her starting point. She performs another straight run, and then circles to the right. The duration of the straight run tells other bees the distance to the food source (roughly one second of walking distance in the dance corresponds to a one-kilometer flight to the target). The direction of this run relative to gravity encodes the direction relative to the Sun—for example, if the run in the hive is straight up, this tells other bees to fly in the direction of the Sun.

Karl von Frisch made this discovery in 1945, for which he was later awarded the Nobel Prize in Physiology or Medicine. A decade later, one of his students, Martin Lindauer, peered into a beehive and discovered that some bees continued these discussions into the night. Before midnight, they “talked about” locations visited the previ-

ous evening, and in the hours before sunrise, they communicated locations visited on the former morning.

These bees retrieved their spatial memories entirely out of context, at a time at which there was no possibility of foraging and no need for communication. The function is unclear—they may have spontaneously thought about these spatial locations during the night, or perhaps this communication functioned as a strategy for spatial memory consolidation. Later studies have shown that a bee's memories of the previous day become strengthened when they are exposed to elements of these memories while they are deeply asleep. Perhaps bees dream about the experiences of the previous day?

The key implication in Lindauer's discovery is that bees are capable of *offline thinking* about spatial locations (and the ways in which the locations are linked to time), in the complete absence of any external trigger—a conclusion which does not align with the assumption that bees are zombies. Bees, then, appear to have at least some of the principal hallmarks of consciousness: representations of time and space.

The Evolution of Consciousness

Based on such evidence, many biologists and philosophers now suspect that consciousness-like phenomena might be evolutionarily ancient, perhaps dating back to the Cambrian Period (approximately 500 million years ago). This line of inquiry might seem like a slippery slope. Where should we draw the line? Do plants have some form of awareness? Or, as *panpsychists* would argue, do electrons, rocks, computers, or the universe have anything of the sort? If so, we are at risk of expanding the definition of consciousness to include ever more living and nonliving beings until the term becomes meaningless.

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Helga Heilmann

The construction of honeycombs by *Apis mellifera* requires the coordinated and cooperative activities of many dozens of individuals. Workers manufacture and manipulate wax into a highly regular hexagonal pattern. In the process, they evaluate the space available and the current state of construction, and incorporate a diversity of communication signals from others. These rich instinctual repertoires had been thought to come at the expense of learning capacity; however, very few behavioral routines are fully hardwired, and even comb construction skills have to be partially learned by honeybees.

Solid proof of consciousness in anyone except oneself is of course unattainable. Everyone else may be a machine or a zombie. But then—say some philosophers—we may be brains in vats, as in the movie *The Matrix*.

One elementary phenomenon at the heart of biological consciousness is *self-recognition*: the ability to recognize oneself as distinct from another entity, as well as to plan, pay attention, recall memories of specific events, and take the perspective of another creature. If the image on your retina suddenly tilts by 45 degrees, you know that this is fine if it's the result of deliberately inclining your head—If not, you may be witnessing a major seismic event, and you had better run.

Animals are thought to tell the difference between these scenarios via what's known as an *efference copy*: an internal signal that communicates the consequences of the animal's own

actions, so that they can distinguish sensory changes caused by their movements from changes caused by external forces. Under normal conditions, animals expect the environment to move in a predictable manner when they turn their heads voluntarily. This expectation allows them to anticipate what will happen next, as a result of their own actions or intentions.

Early versions of efference copies were proposed in the 19th century, although the term was first coined by the German biologists Erich von Holst and Horst Mittelstaedt in their study of flies. In one of their experiments in 1950, they inverted the input to the fly's brain from the left and right eyes using a rather crude (and cruel) technique: The thin neck of the fly was twisted by 180 degrees, and its head then glued in place upside down. The result was that, when the animal turned left or right, the sensory signals

were the opposite of those it expected. Deprived of its ability to anticipate what it should see as a result of its own intentions, the fly behaved erratically. Insects, with their heads in the normal position, appear to have another of the key ingredients of consciousness: the ability to predict what will happen in the future as a result of self-generated movements, which allows them to move and act effectively.

At its evolutionary roots, we believe that consciousness is an adaptation that helped to solve the problem of how moving organisms can extract meaningful information from their sense organs. In an ever-changing and only semi-predictable environment, consciousness can solve this problem more efficiently than unconscious mechanisms possibly could. As the late zoologist Donald Griffin wrote in his book *Animal Minds* (1992), "Environmental conditions vary so much that for an animal's brain to have programmed specifications for optimal behavior in all situations would require an impossibly lengthy instruction book."

Bees provide further evidence that insects can cope with unusual challenges that no instruction book will an-



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The bumblebee on this thistle flower wears a radar transponder, which allows researchers to track its whereabouts for its entire lifetime. The transponder is only 15 milligrams (a bee can typically carry over 100 milligrams of nectar) and has not been shown to affect normal flight or behavior.

ticipate. More than 200 years ago, the Swiss naturalist François Huber (1750–1831) suggested that honeybees might display foresight in the construction of their honeycomb. Working with his wife Marie-Aimée Lullin and servant François Burnens, Huber conducted an experiment where they placed glass panes into the path of honeybees con-

structing a hive. Glass is a suboptimal surface to which to attach wax, so bees took corrective action long before they had reached the slippery surface: They turned the entire construction 90 degrees to attach the comb to the nearest wooden surface. Apparently, the bees had extrapolated from the direction of their current construction to the target

zone and foreseen a suboptimal result before it occurred.

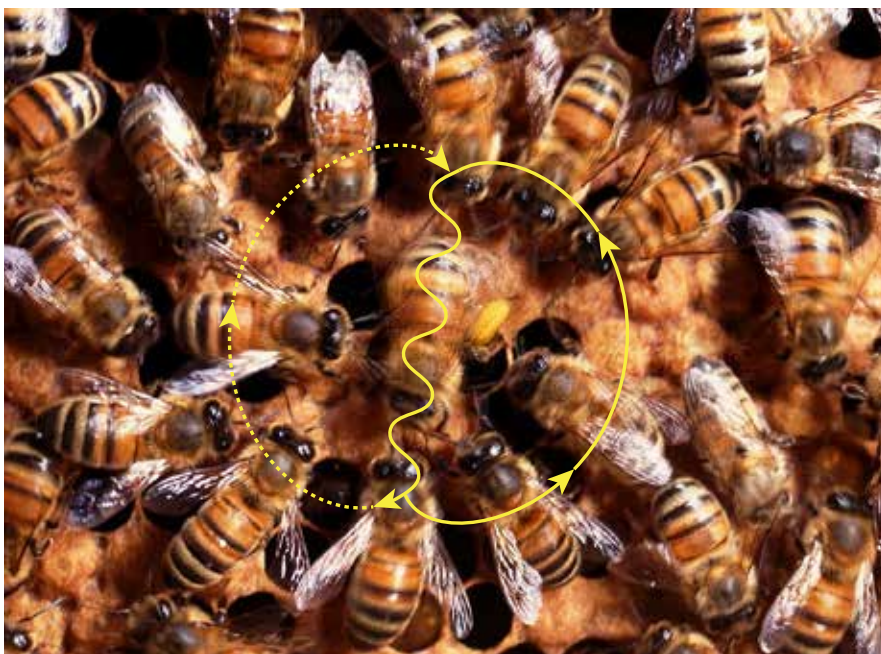
On another occasion, Huber’s team created an environment where the bees had no choice but to build their hive on a glass surface. The researchers observed that one of several combs broke off the ceiling of a hive during winter. Hive construction normally pauses during the winter months when the bees minimize their activity to ensure that their stores lasts until spring. However, on this occasion, not only did the bees become active to fortify the dislodged comb with a number of pillars and cross-beams made from wax, but they also reinforced the attachment zones of all the other combs on the glass ceiling, apparently to ensure that the problem would not recur. Such foresight, should it be confirmed experimentally with modern methods and sample sizes, is one of the hallmarks of consciousness, and in this case already extends beyond foreseeing just the immediate future.

The Inner Lives of Bees

One of us was part of a 2017 study of tool use among bumblebees where the insects were required to transport a small ball to a defined location in order to receive a sugar reward. Observer bees learned how to solve the task through social demonstration by skilled bees. When later tested on their own, the observer bees improved upon the technique of the demonstrators, choosing a ball closer to the center. They did this even when the closest ball was colored black instead of the trained yellow. Importantly, rolling a ball is not a behavior that bees perform in nature. The observers had no prior experience with rolling the balls themselves, and thus had no opportunity for trial-and-error learning. These results indicated that instead of “aping” a learned technique, bumblebees spontaneously improved upon the strategy used by the demonstrators, suggesting they had an appreciation of the outcome of their actions.

Can bees not only plan, but imagine? They can certainly learn to associate visual patterns (such as those presented on flowers) with nectar re-

The bee in the center of this image is communicating to the others through a *dance language*. Its movements can convey information such as the direction and distance to a particularly good flower patch.



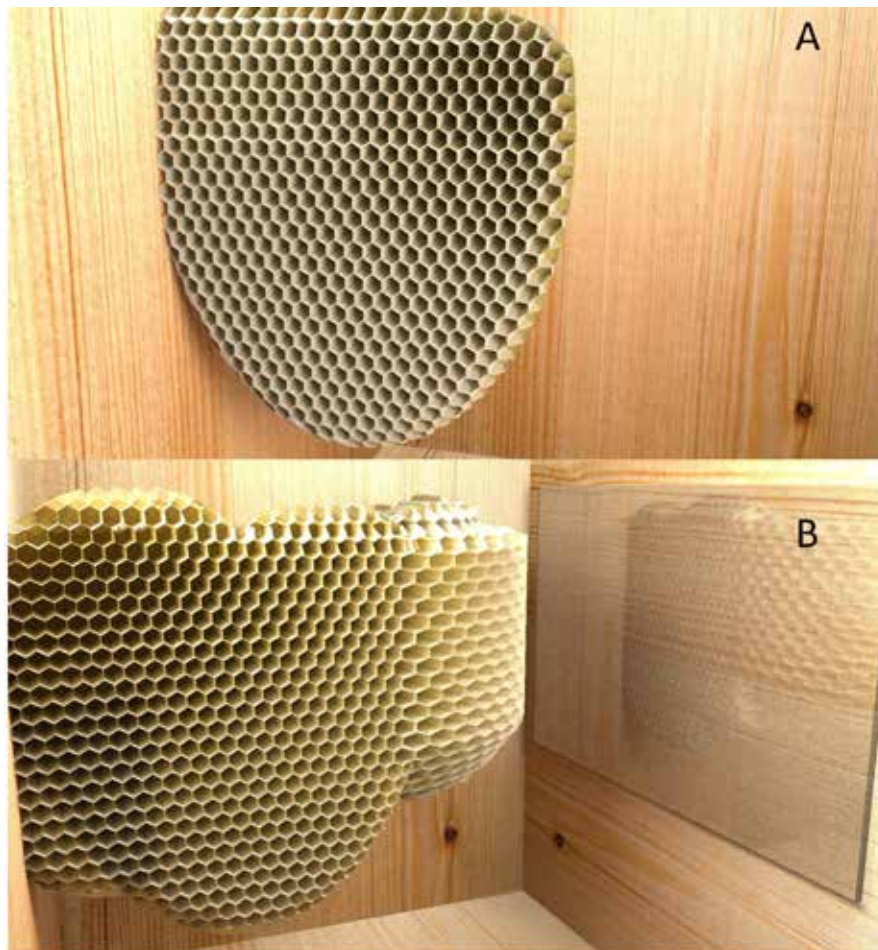
Warren Photographic

wards, but this does not necessarily imply that they have an image of such flowers floating around in their heads. In fact, neural network analyses show that even complex visual patterns (that consist, for example, of differently oriented stripes in all four quadrants of the pattern) can be recognized with just two simple feature detectors that sample information across the visual field—without the need to store the actual image in the bee’s memory.

But an experiment one of us published in 2018 indicates that bees might indeed be able to picture the spatial arrangements of features in a pattern. In this experiment, bees were first trained to distinguish two types of artificial flowers that were visually identical, but which had “invisible patterns” made up of small scented holes that were arranged either in a circle or in a cross. The bees were able to figure out these patterns by using their feelers. But the most exciting finding was that, if these patterns were suddenly made visible by the experimenter (so that the flowers now displayed visual circles or crosses), bees instantly recognized the image that formerly was just an ephemeral pattern in the air. This indicates that the bees might indeed have a mental representation of the shape, rather than recognizing patterns based on simple feature-detectors in their visual system.

Bees also display optimistic and pessimistic emotional states, at least when their behavior is evaluated by the same criteria by which domestic animals are commonly assessed. In such tests, bees first learned that one stimulus (such as the color blue) is linked to a sugar reward, while another (such as green) is not. They were then faced with an intermediate stimulus (in this example, turquoise). Fascinatingly, they responded to this ambiguous stimulus in a “glass half full” (optimistic) manner, if they had encountered a surprise reward (a tiny droplet of sucrose solution) on the way to the experiment. If an adverse stimulus is unexpectedly experienced, they respond in a “glass half empty” (pessimistic) manner.

Further evidence that qualitative experience is available to a range of animals is furnished by consideration of mind- or mood-altering drugs. Not only mammals (think of the effects of catnip), but some insects indulge in them. Volatile anesthetics, appetite suppressing stimulants, depres-



Vincent Gallo

This computer-generated image recreates Swiss entomologist François Huber’s experiments to probe honeybees’ flexibility in comb construction. When faced with a space that had a glass ceiling and floor, the bees began their construction on one of the side walls (a). If a glass pane was placed over one of the walls before the comb reached it, the bees introduced a curve that revised the direction of the hive to a more suitable target area for attachment (b).

sants, and hallucinogens are naturally produced by plants and fungi. These chemicals are not only accidental by-products of their biomolecular machinery, but also are for their own defense in deterring herbivores. But they do not always deter: Bees, for example, prefer flowers whose nectar is laced with low levels of nicotine.

Alcohol is widely present in nature in the form of fermented fruits. Molecular biologist Galit Shohat-Ophir of Bar-Ilan University in Israel and her colleagues discovered that fruit flies stressed by being deprived of mating opportunities seek out alcohol. This activity suggests that intentional *sensation adjustment* or even *mood adjustment*, as well as involuntary susceptibility to psychotropics, is widespread across the animal kingdom—which strongly implies that animals have inner experiences. It will be important to rule out alternative explanations, in

which behavior is modified via direct effects on neurotransmission or the digestive system, but it is nonetheless a promising avenue for future research. Why would an organism seek out mind-altering substances when there isn’t a mind to alter?

Physiological Ties to Consciousness

One objection to the hypothesis of insect consciousness is that their brains are simply too small. But at the time of writing, the much-sought-after *neural correlate of consciousness* (NCC) has not been identified in humans; thus one cannot argue that certain animals don’t have human-type NCC. What we can say is that insect nervous systems are anything but simple: Although a bee brain has only about 1 million nerve cells (compared to around 80 billion in a human brain), some individual neurons have a complexity of branching that rivals a fully grown oak tree. A



Lars Chittka

Marking bees with number tags allows researchers to track individual bees, which reveals differences in their behaviors. For example, some individuals work throughout the day, whereas others visit flowers only in the morning or afternoon. Certain individuals even innovate novel solutions to nectar harvesting, while some simply copy other bees' flower exploitation methods.

bee brain has about 1 billion *synapses* (connections between neural wires that can be shaped by experience).

In addition to their intricacy, insect brains also have other physiological properties required for consciousness. If they operated solely by reflex, the

flow of information would be expected to go from the sense organs to the mechanisms responsible for motor control. But in insects, there are many top-down processes at work, in which neural cables send messages from the central brain to the sensory periphery.

Such top-down processes are involved in attention-like phenomena. Attention allows animals to focus specifically on important stimuli (such as a flower known to have plentiful nectar, if you're a bee) and disregard others (flowers with less nectar). The neuroscientist Bruno van Swinderen at the University of Queensland in Australia has discovered specific neural signatures of attentive states in insects. He also found evidence that a bee knows what visual stimuli to expect next, thereby demonstrating that its neural activity is not simply generated as a result of stimuli "trickling down" from the sense organs to the central brain. Any activity generated from "within the brain" (meaning in the absence of external stimulation) is of particular interest in the context of consciousness.

Significantly, van Swinderen also discovered that flies' brains have several types of neural signal oscillations, including when they are asleep. As in humans, where different oscillations accompany deep sleep and REM sleep, flies have different patterns of oscillations in various sleep phases. The insect brain is never "switched off"—

thus there may be dreamlike states in both flies and bees.

Neuroscientists Tzvetan Popov and Paul Szyszka from the University of Konstanz in Germany recently discovered that honeybees have the kinds of neural oscillations synchronized across the brain that, at least in humans, are associated with conscious states. Although neural oscillations alone do not create consciousness, it is widely agreed that certain types of such oscillations are a key ingredient of conscious states. And nervous systems would have generated some form of oscillations right from the start of animal evolution because they are key to the rhythmic muscle contractions that form the basis of locomotion. During later evolutionary elaboration of nervous systems, brains might have coopted such pre-existing neural pacemakers to generate spontaneous activity from within the brain, ultimately leading to phenomena such as conscious thought.

The anatomical and functional parallels between the *central complex* of the insect brain and the *basal ganglia* of vertebrates are striking and point to a common genetic origin. Defects in both these systems produce motor problems, impaired memory, attention deficits, emotional disorders, and sleep disturbance. According to biologist Andrew Barron of Macquarie University in Australia and philosopher Colin Klein of the Australian National University, the central complex is a likely contender for mediating subjective experience in insects.

Limits of Universal Consciousness

What about the possibility of consciousness in even simpler animals, and indeed beyond animals? In the mid-19th century, Charles Darwin wrote about not only the moral and emotional feelings of animals but also their appreciation of beauty and the recruitment of that susceptibility in sexual selection. He speculated that because *Planaria* (flatworms) have a central nervous system, they must have some form of consciousness. In *The Power of Movement in Plants* (1880), he went on to compare the animal brain and the plant's *root radicle* or taproot. This taproot must find its way, by some form of sampling and evaluation, to the best sources of anchorage and nourishment.

Although this proposal has been taken up recently by František Baluška



Iida Loukola

This bumblebee has learned to move a ball by walking backwards, holding onto the ball with its front legs. It knows that when it places the ball in a certain location, it will receive a sugar reward. Other bees can learn this task by observing skilled workers, in a manner that indicates an understanding of the goal of the task.

at the University of Bonn in Germany, and by Anthony Trewavas at the University of Edinburgh, the case for plant consciousness is more difficult to make than the one for insect consciousness. Trewavas argues that parts of plants move to approach an object or to avoid

obvious that—despite the wonders of unconscious processing—no human being can nourish itself, escape predation, reproduce, engage in a social life, or find the way to a new destination without consciousness of a world outside the body.

Bees spontaneously improved upon the strategy used by the demonstrator, suggesting they had an appreciation of the outcome of their actions.

an obstacle, and their stems can probe, twine, or lean, but their movement timescale is so slow that we may be simply overlooking the rudiments of intentionality in their behavior. However, plants do not move their bodies as a unit, and therefore don't need (or have) a central nervous system enabling the whole body to navigate in space. And as we've argued above, we believe that a central nervous system is critical for the first stages of development of a conscious distinction between self and world.

Another objection needs to be addressed before one credits too many organisms with consciousness. Much of human behavior depends upon subconscious processing of which we are unaware. Our actions in the world depend to a surprising extent upon stimuli we haven't consciously noticed, and the experience of volition has been found to follow our actions after a time-lag rather than preceding them or being simultaneous with them. One could interpret this gap between many human actions and conscious thought as showing that consciousness has no causal input into behavior. According to this theory, it is supposed, the brain collects and weighs environmental stimuli and data from memory, computes the best option, and makes the behavioral choice for us by initiating an action. If consciousness is causally ineffective, the argument that animals need it for living is unavailable. Or perhaps what *we* need consciousness for is fully automated in *them*.

However, these arguments do not diminish the case for widespread consciousness in the animal kingdom. It is

What about the pansychist notion that the universe, computers, electrons, and other lifeless beings might possess consciousness? We hold that because these entities do not face decisions requiring agency, it would be astonishing if they had experiences. The challenges that come with survival and self-replication faced by a moving, living organism are most efficiently implemented through emotions, a rich representation of the world, and the ability to anticipate at least the immediate future.

It might seem like prejudice to tie consciousness to life. Increased computing power and machine learning have enabled the automation of pattern recognition, including the recognition of faces and human speech, the simulation of meaningful conversation, automated theorem-proving in logic and mathematics, and even the creation of fine art (see "*AI Is Blurring the Definition of Artist*," *January–February*). As artificial devices acquire more and more of these competencies, why shouldn't there come a moment when they "wake up" into consciousness? (See *Computing Science*, 346–349.)

But why should they wake up? We have no reason to think that consciousness must appear when automated performance of activities that are significant to humans, such as chess playing, reaches a high point of development. The more likely outcome is that we are unable to produce a fully competent living robot unless and until we can discover, and replicate synthetically, the elusive NCCs.

If we could generate self-repairing, self-replicating robots with evolvable

software and let them roam freely under competitive conditions, would the most successful ones ultimately be those with subjective experiences, emotions, the ability to predict the results of their behaviors, and relatively flexible problem-solving skills? Or would conventional robots with a versatile toolkit of highly efficient but preconfigured, hard-wired responses fare better?

If, as we have argued, consciousness is an evolutionary invention—akin to wings or lungs—that is useful to *us*, it is most likely useful to other organisms with traits deeply homologous to ours. They share with us the difficulties of moving, probing the environment, remembering, predicting the future and coping with unforeseen challenges. If the same behavioral and cognitive criteria are applied as to much larger-brained vertebrates, then some insects qualify as conscious agents, with no less certainty than dogs or cats.

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