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Consciousness in a Cockroach

The insect nervous system provides clues to attention, consciousness, and the origin of the brain.

By Douglas Fox | Wednesday, January 10, 2007

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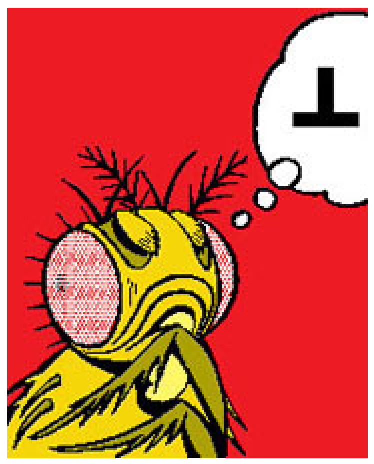


To Nicholas Strausfeld, a tiny brain is a beautiful thing. Over his 35-year career, the neurobiologist at the University of Arizona at Tucson has probed the minute brain structures of cockroaches, water bugs, velvet worms, brine shrimp, and dozens of other invertebrates. Using microscopes, tweezers, and hand-built electronics, he and his graduate students tease apart — ever so gently — the cell-by-cell workings of brain structures the size of several grains of salt. From this tedious analysis Strausfeld concludes that insects possess "the most sophisticated brains on this planet."

Strausfeld and his students are not alone in their devotion. Bruno van Swinderen, a researcher at the Neurosciences Institute (NSI) in San Diego, finds hints of higher cognitive functions in insects — clues to what one scientific journal called "the remote roots of consciousness."

"Many people would pooh-pooh the notion of insects having brains that are in any way comparable to those of primates," Strausfeld adds. "But one has to think of the principles underlying how you put a brain together, and those principles are likely to be universal."

The findings are controversial. "The evidence that I've seen so far has not convinced me," says Gilles Laurent, a neuroscientist at Caltech. But some researchers are considering possibilities that would shock most lay observers. "We have literally no idea at what level of brain complexity consciousness stops," says Christof Koch, another Caltech neuroscientist. "Most people say, 'For heaven's sake, a bug isn't conscious.' But how do we know? We're not sure anymore. I don't kill bugs needlessly anymore."

Heinrich Reichert of the University of Basel in Switzerland has become more and more interested in "the relatedness of all brains." Reichert's own studies of the brain's origin lead to a little-known ancestor, a humble creature called Urbilateria, which wriggled and swam nearly a billion years ago. The granddaddy of all bilaterally symmetrical animals, Urbilateria is the forebear of spiders, snails, insects, amphibians, fish, worms, birds, reptiles, mammals, crabs, clams — and yes, humans.

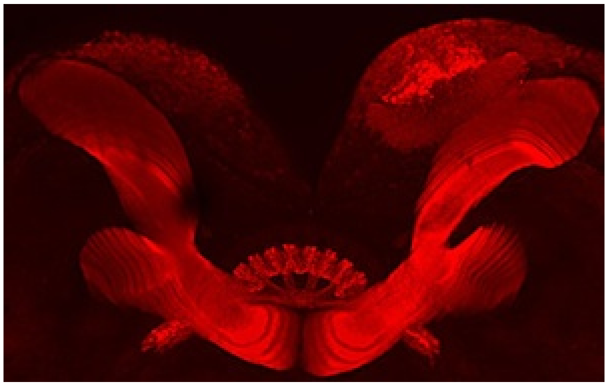
There is, of course, good reason to view insect brains as primitive — at least quantitatively. Humans possess 100,000,000,000 brain cells. A cockroach has nearly 1,000,000 brain cells; a fruit fly, only 250,000. Still, insects exercise impressive information management: They pack neurons into their brains 10 times more densely than mammals do. They also use each brain cell more flexibly than mammals. Several far-flung tendrils of a single neuron can each act independently — boosting computing power without increasing the number of cells. Somehow that circuitry allows a honeybee, with barely a million neurons on board, to meander six miles from its hive, find food, and make a beeline directly home. Few humans could do the same even with a map and a compass.

On the surface, the brains of insects and mammals look nothing alike. Only from studies of cell-by-cell connections does the astounding similarity emerge. One afternoon Christopher Theall, one of Strausfeld's Ph.D. students, shows me his own experimental setup for tapping into a portion of the cockroach brain known as the mushroom body. This mushroom-shaped brain structure is thought to be analogous to the mammalian hippocampus, a brain component involved in forming memories of places.

"What we're trying to do," says Theall, as we enter a cramped laboratory, "is scale down the techniques that have been used in rat and primate brains — scale them down to a brain that's a thousandth the size."

Theall's experimental apparatus rests on a table that floats on vibration-absorbing pressurized air. Even a cart rattling in the hallway outside could undermine the experiment. Because Theall needs to record nerve impulses amounting to just one ^{1}/10,0000 of a volt, the table is enclosed in a cage that blocks electromagnetic interference from the room's lights. Working under a microscope with tweezers, steady hands, and held breath, Theall fashions copper wire only twice the diameter of a red blood cell into electrodes that he will insert into the cockroach's brain.

"They're fragile," he says. "Even a breeze from a door opening can ruin a couple hours of work."

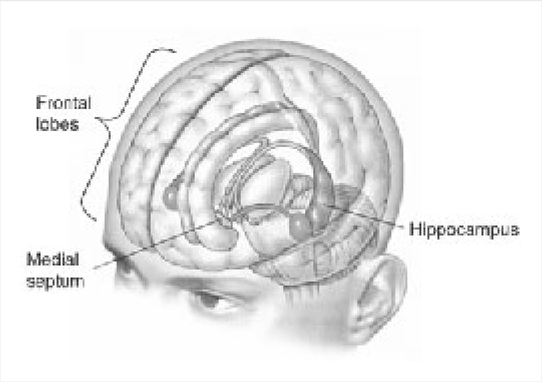


Paired structures called mushroom bodies in a cockroach brain play a key role in navigation.

After 20 hours of prep, Theall is ready to do the experiment. Twisting a knob while gazing into the microscope, he sinks the electrode into the roach's brain until it rests in one of the mushroom bodies. During the experiment, Theall will train this cockroach to earn a reward: If the insect points its antenna toward certain landmarks, it will receive thrilling puffs of peanut-butter odor. Theall wants to eavesdrop on neurons to determine how they contribute to learning the location of those landmarks.

The final step of the experiment — dissection of the mushroom body — allows Theall to see the two or three cells he has monitored. Because the cells have absorbed copper released from the electrode, he can tell them apart from the 200,000 other brain cells in the mushroom body. Theall then traces the structure of each cell using pen, paper, and a light box. It is like drawing a gnarled oak tree down to the last twig, and reconstructing a single cell can take two days. Theall, a typical student in Strausfeld's lab, will perform hundreds of experiments like these before his Ph.D. is complete.

Theall and Strausfeld never know which of the tens of thousands of cells they're going to hit when they tap into a roach's mushroom body. By repeating the experiment over and over, however, they are assembling a picture of what types of cells exist, how those cells function during tasks of place memory, and what kinds of connections they form with other cells. Cell by cell, they hope to piece together the structure's circuitry.



During a chat in his office, Strausfeld sketches a mushroom body, pointing out several parallels to the hippocampus, the brain center devoted to memory and place location in mammals. The base consists of thousands of parallel nerve fibers running together like the grain in a piece of wood. Further up from the base, the fibers send out connections in loops that look like jug handles on a freeway; this is the shape that has earned this part of the brain the name "mushroom body." The connections rejoin the fibers higher up, near the top. Strausfeld suspects these looping pathways bring together related pieces of information, like the sights and smells of various landmarks that a roach encounters, one after another, as it travels to and from its home.

"The geometry of the structure," he says, "is so strangely reminiscent of the [human] hippocampus." Strausfeld and others are looking for clues as to whether the similarities result from a deep and ancient kinship or simply from analogous solutions that evolved independently to aid survival.

In his underground laboratory at the Neurosciences Institute, van Swinderen is observing a fly suspended in what amounts to a miniature IMAX theater. The setup is designed to monitor the focus of attention in a fly's brain. An LED screen wraps around the fly, displaying a sequence of flashing objects in front of its eyes, two objects at a time. Right now, it's an X and a square. The X is flickering 12 times per second and the square 15 times per second.


Two electrodes in a fly's brain monitor signals involved in attention.

"You can use these flickers," van Swinderen tells me, "to extract what the fly is attending to. At the moment," he says, "it's paying attention to the X."

Van Swinderen has inserted an electrode into the fly's brain to monitor its neural activity. The jagged brain waves percolating through the electrode scroll across a computer screen. Buried deep in the jumble of jagged peaks are two tiny signals: one wave rising and falling 12 times per second and another rising and falling 15 times per second. Those two waves are emanating from thousands of brain cells responding to the two flickering objects. The greater the number of cells firing in unison to a given object, the higher the corresponding wave. By noting which wave is higher, van Swinderen can tell which target the fly is directing more attention to.

Van Swinderen prefers to call it "salience" rather than "attention," because he does not want to imply that flies are conscious. But whatever that perceptual focus is called, finding it in a fly has huge implications for understanding the roots of consciousness in humans. Every second we are flooded by sensory information from our eyes, ears, nose, and every inch of our skin. The roving spotlight of attention — our mind's eye — determines which tiny fraction of this influx we actually admit into our consciousness and, just possibly, file away as memory.

Van Swinderen often records brain waves simultaneously from three locations in a large insect brain region called the medial protocerebrum. At first glance, the jumbled waves from those areas might seem as varied as the sounds of Mozart, the Sex Pistols, and Tuvan throat singing. But as long as the fly is alert and attending to something, there exists within that jumble a chorus of neurons chiming the same wave pattern in concert across all three areas. That wave pattern represents the thing the fly is attending to, and as its attention shifts from one thing to another, the wave pattern also changes. Van Swinderen can detect the chorus because he has carefully designed his experiment with its little IMAX theater to determine what the fly will attend to. It is a beautiful illustration of attention: every neuron singing the same song — the song of the square.

"Attention," says van Swinderen, "is a whole-brain phenomenon. A thing is not purely visual, not purely olfactory. It's a binding together of different parts that for us signify one thing. Why couldn't the fly's mechanism [of attention] be directed to a succession of its memories?" he asks. "That, to me, is just a short hop, skip, and a jump away from what might be consciousness." The difference between the memories of a fly and a human might be a matter of degree. The human can store a lot more memories and can therefore maintain a more sophisticated personal narrative of his past and present. But van Swinderen believes "it could be exactly the same mechanism in a fly and a human." Although there is still no evidence to decide either way, the result could be consciousness.

"Probably what consciousness requires," says Koch of Caltech, "is a sufficiently complicated system with massive feedback. Insects have that. If you look at the mushroom bodies, they're massively parallel and have feedback."

Chemical clues confirm that at least some fundamental brain processes are the same in humans and insects. Van Swinderen and Rozi Andretic, a neuroscientist at NSI, have found that mutant flies producing too little of the neurotransmitter dopamine have impaired salience responses. Feeding the mutant flies methamphetamine — a chemical related to drugs used to treat attention-deficit/hyperactivity disorder — relieves the dopamine shortage and normalizes the flies' attention. But give meth to a normal fly and it cannot attend as well. "Similar mechanisms are present in vertebrates and flies," Andretic told me. "You need optimal concentrations of dopamine, and if you have too little or too much, you will be impaired." In both humans and flies, dopamine-releasing cells may help coordinate distant brain regions involved in the phenomenon of attention.

When you consider that neurons themselves are strikingly similar across the animal kingdom, it all begins to make sense. "You have the same basic building blocks for vertebrates and invertebrates," says Strausfeld, "and there are certain ways you can put these building blocks together [into brains]." So when it came to building a brain center like the hippocampus that can recognize places, there might have been only one way to wire those quirky neurons together to do the job — and evolution arrived at that same solution multiple times independently, just as the genetic instructions for wings evolved multiple times in distinct lineages.

The more startling possibility is that the brain might have evolved only once in the history of life. Distant cousins — cockroaches and humans — could have inherited the basic blueprint from a common ancestor, Urbilateria, the last common forebear of all bilaterally symmetrical animals. No fossils of this creature are known to survive, but by estimating how long it took for DNA sequences to diverge between flies and mice, geneticists estimate that Urbilateria lived 600 million to 1 billion years ago.

By analogy to marine invertebrates today, some scientists believe that Urbilateria burrowed on the sea bottom as an adult and swam as a larva, with simple eyes like those in many living marine larvae.

Clues to Urbilateria's brain plan come from studying the embryonic development of creatures alive today. In both mouse and fruit fly embryos, Detlev Arendt, an evolutionary biologist at the European Molecular Biology Laboratory in Heidelberg, Germany, has found that cells involved in forming the brain and nerve cord divide into three columns of cells. At least some of the genes that govern the column formation are the same in flies and mice. "This pattern is so specific," says Arendt, "that clearly the last common ancestor must have had these three columns."

Heinrich Reichert of the University of Basel has turned up another striking similarity. During embryonic growth, a gene that is similar in both flies and mice (and, by implication, humans) triggers the brain to divide into front, middle, and rear segments. Mice lacking the gene develop severe brain abnormalities. But swapping the fly version of the gene into these mutant mice corrects most of those abnormalities. "It reveals," says Reichert, "a deep relatedness in the brains of flies and fish and mice and men that certainly was not expected by just looking at the superficial anatomy."

Of course, these genes act early, while the embryo is primitive. So Urbilateria could have possessed them and still have had almost no brain. The ultimate answer will come from identifying and comparing dozens more insect and mammal genes. Of particular interest are those involved in forming complex structures that play similar roles, like mushroom bodies and the hippocampus.

"The million-dollar question," Strausfeld says, "would be whether the genes involved in the development of these structures are shared between mouse and fly. That would, of course, be thrilling."