NEUROSCIENCE

The Mind of an Octopus

Eight smart limbs plus a big brain add up to a weird and wondrous kind of intelligence

By Peter Godfrey-Smith on January 1, 2017

Credit: HENRIK SORENSEN Getty Images

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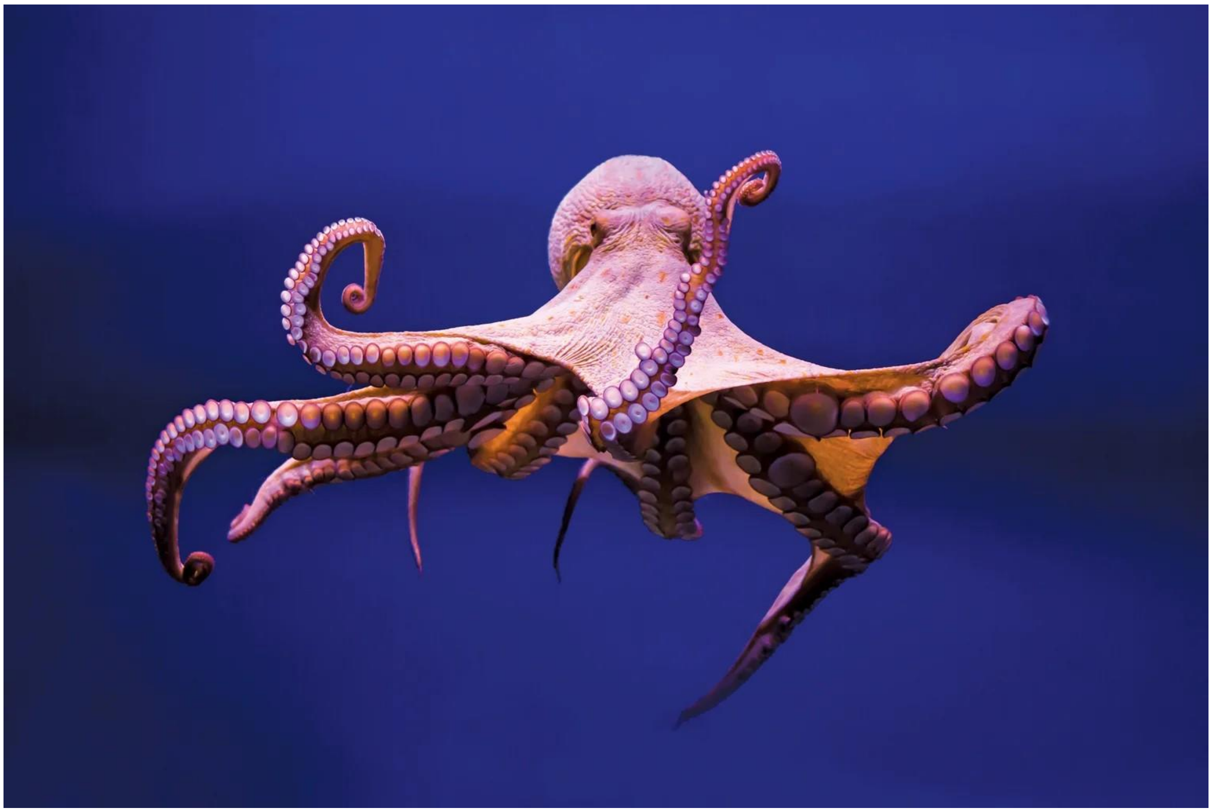
Someone is watching you, intently, but you can't see them. Then you notice, drawn somehow by their eyes. You're amid a sponge garden, the seafloor scattered with shrublike clumps of bright orange sponge. Tangled in one of these sponges and the gray-green seaweed around it is an animal about the size of a cat. Its body seems to be everywhere and nowhere. The only parts you can keep a fix on are a small head and the two eyes. As you make your way around the sponge, so, too, do those eyes, keeping their distance, keeping part of the sponge between the two of you. The creature's color perfectly matches the seaweed, except that some of its skin is folded into tiny, towerlike peaks with tips that match the orange of the sponge. Eventually it raises its head high, then rockets away under jet propulsion.

A second meeting with an octopus: this one is in a den. Shells are strewn in front, arranged with some pieces of old glass. You stop in front of its house, and the two of you look at each other. This one is small, about the size of a tennis ball. You reach forward a hand and stretch out one finger, and one octopus arm slowly uncoils and comes out to touch you. The suckers grab your skin, and the hold is disconcertingly tight. It tugs your finger, tasting it as it pulls you gently in. The arm is packed with sensors, hundreds of them in each of the dozens of suckers. The arm itself is alive with neurons, a nest of nervous activity. Behind the arm, large round eyes watch you the whole time.

Octopuses and their relatives (cuttlefish and squid) represent an island of mental complexity in the sea of invertebrate animals. Since my first encounters with these creatures about a decade ago, I have been intrigued by the powerful sense of engagement that is possible when interacting with them. Our most recent common ancestor is so distant—more than twice as ancient as the first dinosaurs—that they represent an entirely independent experiment in the evolution of large brains and complex behavior. If we can connect with them as sentient beings, it is not because of a shared history, not because of kinship, but because evolution built minds twice over. They are probably the closest we will come to meeting an intelligent alien.

COMPARING BRAINS

Octopuses, cuttlefish and squid belong to a class of marine mollusks called cephalopods, along with now extinct creatures called ammonites and belemnites. The fossil record of octopuses remains skimpy. As the only cephalopods without an external or internal shell and no hard parts except for a beak, they do not preserve well. But at some stage during their evolution, they radiated—around 300 species are known at present, including deep-sea as well as reef-dwelling forms. They range from less than an inch in length to the giant Pacific octopus, which weighs in at 100 pounds and spans 20 feet from arm tip to arm tip.



Credit: Getty Images

As the cephalopod body evolved toward these modern forms—internalizing the shell or losing it altogether—another transformation occurred: some of the cephalopods became smart. “Smart” is a contentious term to use, so let's begin cautiously. First of all, these animals evolved large nervous systems, including large brains. Large in what sense? A common octopus (*Octopus vulgaris*) has about 500 million neurons in its body. That is a lot by almost any standard. Human beings have many more—something nearing 100 billion—but the octopus is in the same range as various mammals, close to the range of dogs, and cephalopods have much larger nervous systems than all other invertebrates.

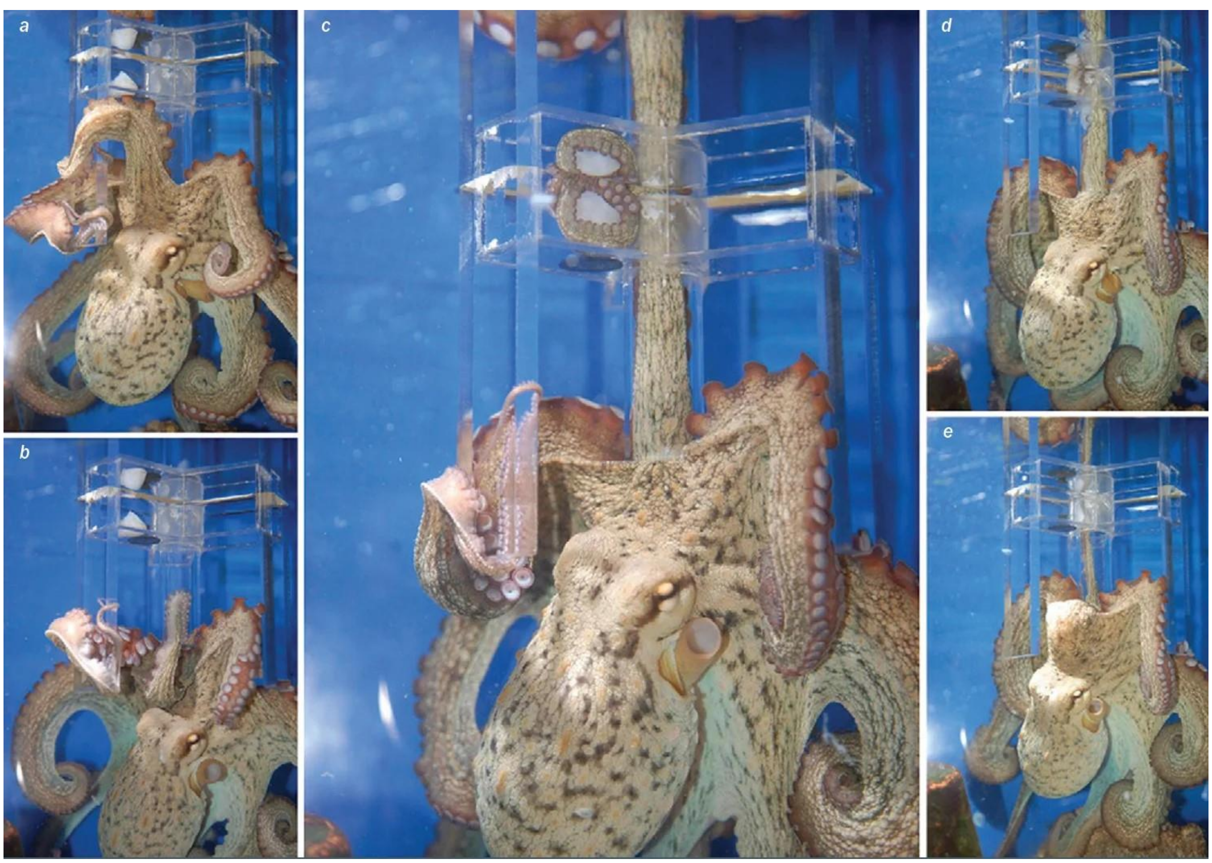
Absolute size is important, but it is usually regarded as less informative than relative size—the size of the brain as a fraction of the size of the body. This tells us how much an animal is “investing” in its brain. Octopuses also score high by this measure, roughly in the range of vertebrates, though not as high as mammals. Biologists regard all these assessments of size, however, as only a very rough guide to the brainpower an animal has. Some brains are organized differently from others, with more or fewer synapses, which can also be more or less complicated. The most startling finding in recent work on animal intelligence is how smart some birds are, especially parrots and crows. Birds have quite small brains in absolute terms, though very high-powered ones.

When we try to compare one animal's brainpower with another's, we also run into the problem that there is no single scale on which intelligence can be sensibly measured. Different animals are good at different things, as makes sense given the different lives they live. When cephalopods are compared with mammals, the lack of any common anatomy only increases the difficulties. Vertebrate brains all have a common architecture. But when vertebrate brains are compared with octopus brains, all bets—or rather all mappings—are off. Octopuses have not even collected the majority of their neurons inside their brains; most of the neurons are in their arms.

Given all this, the way to work out how smart octopuses are is to look at what they can do. Octopuses have done fairly well on tests of their intelligence in the laboratory, without showing themselves to be Einsteins. They can learn to navigate simple mazes. They can use visual cues to discriminate between two familiar environments and then take the best route toward some reward. They can learn to unscrew jars to obtain the food inside—even from the inside out. But octopuses are slow learners in all these contexts. Against this background of mixed experimental results, however, there are countless anecdotes suggesting that a lot more is going on.

ESCAPE AND THIEVERY

The most famous octopus tales involve escape and thievery, in which roving aquarium octopuses raid neighboring tanks at night for food. Those stories—the basis for octopod hijinks in the 2016 Disney-Pixar film *Finding Dory*—are not especially indicative of high intelligence. Neighboring tanks are not so different from tide pools, even if the entrance and exit take more effort. But here is a behavior I find more intriguing: in at least two aquariums, octopuses have learned to turn off the lights by squirting jets of water at the bulbs and shortcircuiting the power supply. At the University of Otago in New Zealand, this game became so expensive that the octopus had to be released back to the wild.



An octopus's arm can taste, touch and move without oversight from the brain. To test if the brain also has centralized, top-down control over the limbs, scientists designed a transparent maze. To reach a treat in the upper left compartment (a and b), the animals had to send an arm out of the water (c), losing guidance from their chemical sensors. They then had to rely on their eyes to direct the arm (d). Most succeeded (e). Credit: From “Octopus Vulgaris Useds Visual Information to Determine the Location of its Arm,” by Tamar Gutnick et al., in Current Biology, Vol. 21, No. 6; March 22, 2011

This story illustrates a more general fact: octopuses have an ability to adapt to the special circumstances of captivity and to their interactions with human keepers. Anecdotally at least, it has long appeared that captive octopuses can recognize and behave differently toward individual human keepers. In the same lab in New Zealand that had the “lights-out” problem, an octopus took a dislike to one member of the staff, for no obvious reason. Whenever that person passed by on the walkway behind the tank, she received a half-gallon jet of water down the back of her neck.

Neuroscientist Shelley Adamo of Dalhousie University in Nova Scotia also had one cuttlefish that reliably squirted streams of water at all new visitors to the lab but not at people who were often around. In 2010 the late biologist Roland C. Anderson and his colleagues at the Seattle Aquarium tested recognition in giant Pacific octopuses in an experiment that involved a “nice” keeper who regularly fed eight animals and a “mean” keeper who touched them with a bristly stick. After two weeks, all the octopuses behaved differently toward the two keepers, confirming that they can distinguish among individual people, even when they wear identical uniforms.

Philosopher Stefan Linquist of the University of Guelph in Ontario, who once studied octopus behavior, puts it like this: “When you work with fish, they have no idea they are in a tank, somewhere unnatural. With octopuses it is totally different. They know that they are inside this special place, and you are outside it. All their behaviors are affected by their awareness of captivity.” Linquist's octopuses would mess around with their tank and deliberately plug the outflow valves by poking in their arms, perhaps to increase the water level. Of course, this flooded the entire lab.

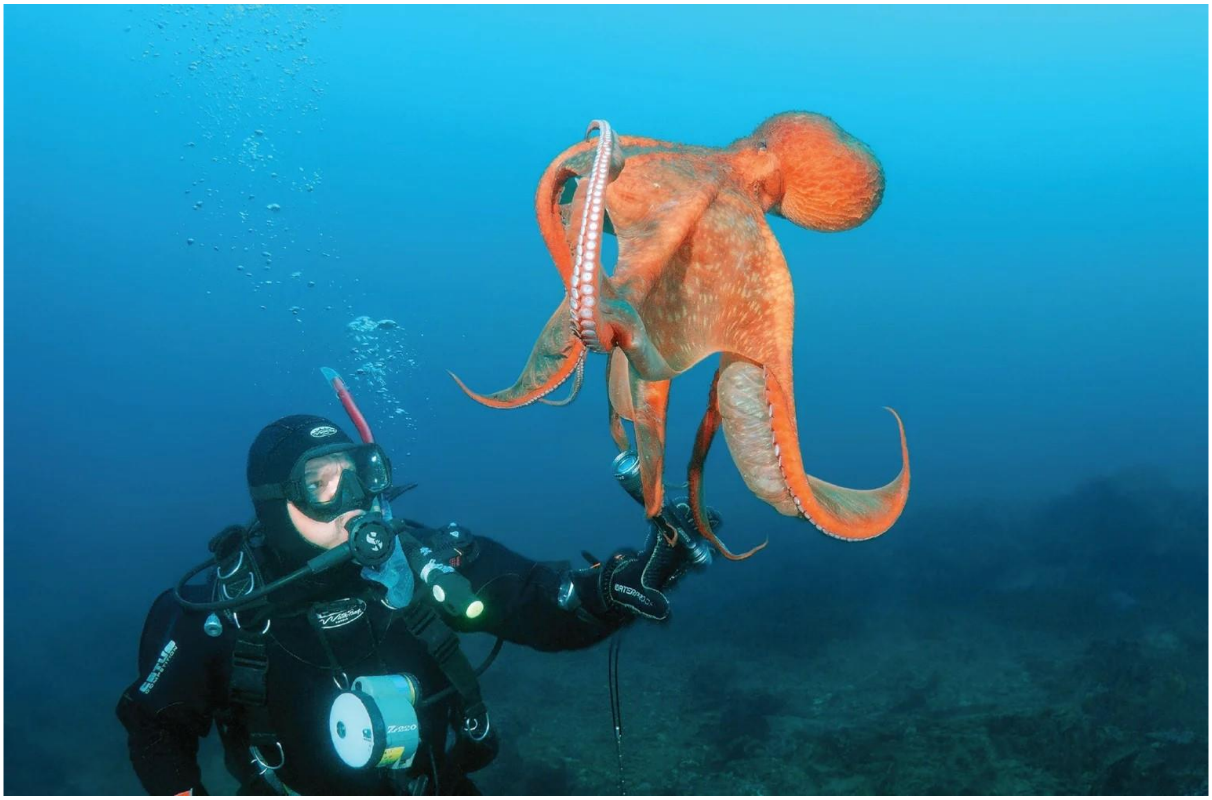
The tales of octopuses squirting experimenters reminded me of something I had seen myself. Captive octopuses often try to escape, and when they do, they seem unerringly able to pick the one moment you are not watching them. I thought I might be imagining this tendency, until I heard a talk a few years ago by marine biologist David Scheel of Alaska Pacific University, who works with octopuses full-time. He, too, said that octopuses seem to track in subtle ways whether he is watching them or not, and they make their move when he is not. I suppose this makes sense as a natural behavior in octopuses; you want to make a run for it when the barracuda is not looking at you. But the fact that octopuses can so quickly do this with humans—both with scuba mask and without—is impressive.

Another octopus behavior that has made its way from anecdote to experimental investigation is play. An innovator in cephalopod research, Jennifer Mather of the University of Lethbridge in Alberta, along with Anderson, did the first studies of this behavior, and it has now been investigated in detail. Some octopuses—and only some—will spend time blowing pill bottles around their tank with their jet, “bouncing” the bottle back and forth on the stream of water coming from the tank's intake valve. In general, the initial interest an octopus takes in any new object is gustatory—can I eat it? But once an object is found to be inedible, that does not always mean it is uninteresting. Work by Michael Kuba, now at the Okinawa Institute of Science and Technology in Japan, has confirmed that octopuses can quickly tell that some items are not food and are often still quite interested in exploring and manipulating them.

THINKING ON THEIR FEET

Let's look more closely now at how the nervous system behind these behaviors evolved. The history of large brains has, very roughly, the shape of a letter Y. At the branching center of the Y is the last common ancestor of vertebrates and mollusks—some 600 million years ago. That ancestor was probably a flattened, wormlike creature with a simple nervous system. It may have had simple eyes. Its neurons may have been partly bunched together at its front, but there would not have been much of a brain there.

From that stage the evolution of nervous systems proceeds independently in many lines, including two that led to large brains of different design. On our lineage, the chordate design emerges, with a cord of nerves down the middle of the animal's back and a brain at one end. This design is seen in fish, reptiles, birds and mammals.



When you approach an octopus in the wild, it is not unusual for the animal to send out one of its arms to inspect you. The arm's suckers—each of which may contain 10,000 neurons—latch on tightly, trying to pull you in closer and taste you at the same time. Credit: Andrey Nekrasov
Alamy

On the other side, the cephalopods' side, a different body plan evolved and a different kind of nervous system. Invertebrates' neurons are often collected into many ganglia, little knots that are spread through the body and connected to one another. The ganglia can be arranged in pairs, linked by connectors that run along the body and across it, like lines of latitude and longitude. This is sometimes called a ladderlike nervous system.

As cephalopods evolved, some ganglia became large and complex, and new ones were added. Neurons concentrated at the front of the animal, forming something more and more like a brain. The old ladderlike design was partly submerged, but only partly. For instance, in an octopus, the majority of neurons are in the arms themselves—nearly twice as many in total as in the central brain. The arms have their own sensors and controllers. They have not only the sense of touch but also the capacity to sense chemicals—to smell or taste. Each sucker on an octopus's arm may have 10,000 neurons to handle taste and touch. Even an arm that has been surgically removed can perform various basic motions, such as reaching and grasping.

The internal coordination of each arm can be quite graceful, too. When an octopus pulls in a piece of food, the grasping by the very end of the arm creates two waves of muscle activation, one heading inward from the tip and the other heading outward from the base. Where these two waves meet, a joint is formed that is something like a temporary elbow. The nervous systems in each arm also include loops in the neurons (recurrent connections, in the jargon) that may give the arm a simple form of short-term memory, although it is not known what this system does for the octopus.

How does an octopus's brain relate to its arms? Early work looking at both behavior and anatomy gave the impression that the arms enjoyed considerable independence. As Roger T. Hanlon and John B. Messenger put it in their 1996 book *Cephalopod Behaviour*, the arms seemed “curiously divorced” from the brain, at least in the control of basic motions. But octopuses can pull themselves together in some contexts. As I mentioned earlier, when you approach an octopus in the wild, in at least some species the octopus sends out one arm to inspect you—behavior that suggests a kind of deliberateness, an action guided by the brain.

In fact, some kind of mixture of localized and top-down control might be at work. The best experimental research I know that bears on this topic comes out of the lab of neurobiologist Binyamin Hochner of the Hebrew University of Jerusalem. In 2011 researchers Tamar Gutnick and Ruth Byrne, along with Hochner and Kuba, conducted a very clever experiment to test whether an octopus could learn to guide a single arm along a mazelike path to a specific place to obtain food. The task was set up so that the arm's own chemical sensors would not suffice to guide it to the food; the arm would have to leave the water at one point to reach the target location. But the maze walls were transparent, so the target location could be seen. The octopus would have to guide an arm through the maze with its eyes.

It took a long while for the octopuses to learn to do this, but in the end, nearly all the animals tested succeeded. The eyes can guide the arms. At the same time, the paper also noted that when octopuses are doing well with this task, the arm that is finding the food appears to do its own local exploration as it goes, crawling and feeling around. So it seems that two forms of control are operating in tandem: there is central control of the arm's overall path, via the eyes, combined with a fine-tuning of the search by the arm itself.

COMMON GROUND

Despite their many differences, cephalopods bear some striking similarities to vertebrates. For instance, vertebrates and cephalopods separately evolved “camera” eyes, with a lens that focuses an image on a retina. The capacity for learning of several kinds is also seen on both sides. Learning by attending to reward and punishment, by tracking what works and what does not work, seems to have been invented independently several times in evolution. If, on the other hand, it was present in the human/octopus common ancestor, it was greatly elaborated down each of the two lines.

There are also more subtle psychological similarities. Research indicates that octopuses, like us, seem to have a distinct short- and long-term memory. They seem to have something like sleep. And a 2012 study led by Jean G. Boal of Millersville University in Pennsylvania discovered that cuttlefish appear to have a form of rapid eye movement (REM) sleep, similar to the sleep in which we dream. (It is still unclear whether octopuses share this REM-like sleep.) Other similarities are even more abstract, such as recognizing individual humans. This ability makes sense if an animal is social or monogamous, but octopuses are not monogamous, have haphazard sex lives and do not seem to be very social.

Even so, there is a lesson here about the ways that smart animals handle the stuff of their world. They carve it up into objects that can be remembered and identified despite changes in how those objects present themselves. This, too, is a striking feature of the octopus mind—striking in its familiarity and similarity to how we two-legged types make sense of our world.

EMBODIED WISDOM?

With no hard body parts apart from a beak, an octopus can morph into a dazzling array of shapes and squeeze through openings only slightly bigger than one of its eyes. Credit: Frank Stratton Getty Images

The octopus is sometimes said to be a good illustration of the importance of a theoretical movement in psychology known as embodied cognition. One of its central ideas is that our body, rather than our brain, is responsible for some of the "smartness" with which we handle the world. The joints and angles of our limbs, for example, make motions such as walking naturally arise. Knowing how to walk is partly a matter of having the right body.

But the doctrines of the embodied cognition movement do not really fit well with the strangeness of the octopus's way of being. Defenders of embodied cognition often say that the body's shape and organization encode information. But that requires that there be a shape to the body. An octopus can stand tall on its arms, squeeze through a hole little bigger than one of its eyes, become a streamlined missile or fold itself to fit into a jar.

Further, in an octopus, it is not clear where the brain itself begins and ends. The octopus is suffused with nervousness; the body is not a separate thing that is controlled by the brain or nervous system. The usual debate is between those who see the brain as an all-powerful CEO and those who emphasize the intelligence stored in the body itself. But the octopus lives outside both the usual pictures.

It has a body—but one that is protean, all possibility; it has none of the costs and gains of a constraining and action-guiding body. The octopus lives outside the usual body/brain divide. —*P.G.-S.*

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