My New Scientist

Root intelligence: Plants can think, feel and learn

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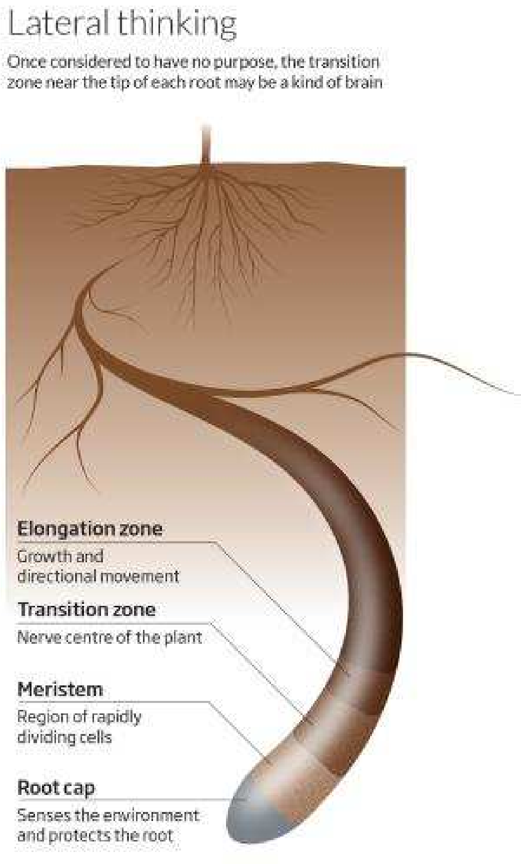
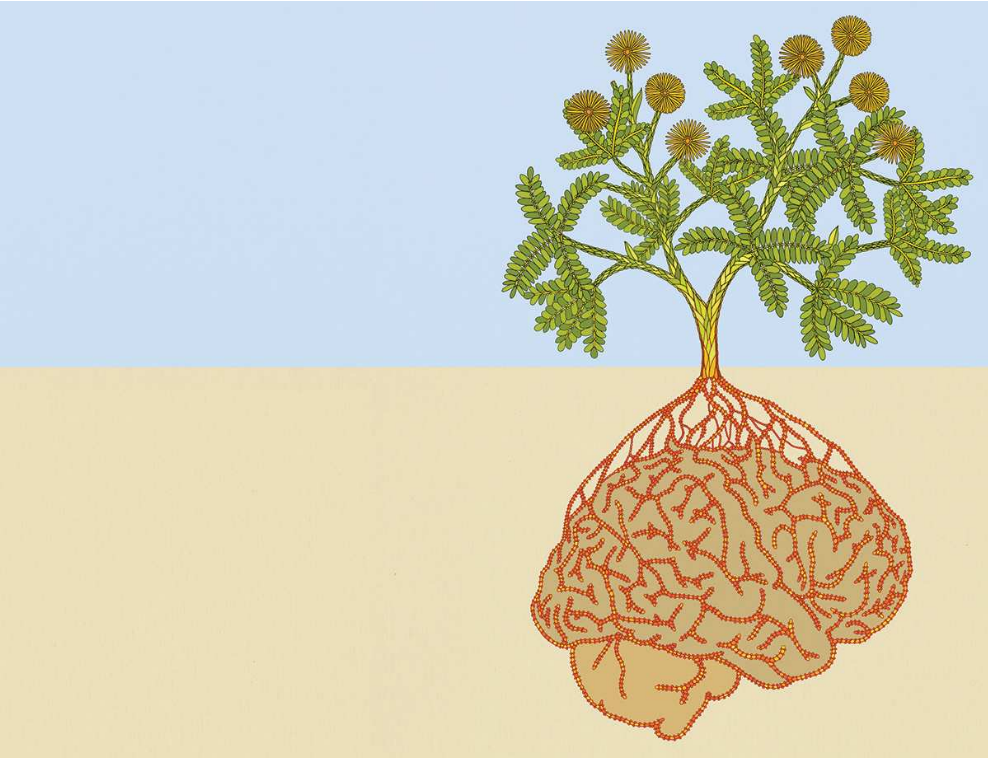
With an underground "brain network" and the ability to react and remember, plants have their own kind of intelligence – and may even cry out in pain



Lateral thinking

STEVE SILLETT has been hanging out with giants all his working life. He climbs and studies the canopies of giant redwoods along the coast of northern California. Sometimes, when traversing from the top of one tree to another, he is awestruck by the life that surrounds him. "There's this awareness of where you are, 90 metres up, in this breathing, living forest of ancient beings," says Sillett, who is at Humboldt State University, California. "You get into this space where you are interacting with another organism that functions completely differently."

Had Aristotle hung out among redwoods, he might not have consigned plants to the bottom rungs of his "ladder of life". But he didn't, and botanists have been tormented by his legacy. For centuries, few dared challenge his judgement. Now that's finally changing. In the past decade, researchers have been making the case for taking plants more seriously. They are finding that plants have a sophisticated awareness of their environment and of each other, and can communicate what they sense. There is also evidence that plants have memory, can integrate massive amounts of information and maybe pay attention. Some botanists ague that they are intelligent beings, with a "neurobiology" all of their own. There's even tentative talk of plant consciousness.



Roots as brains? *(Image: Claire Scully)*

Charles Darwin would have approved. He was the first to seriously question Aristotelian ideas that plants don't have the stuff of life that animates us and other animals, simply because they don't move. One of his books, published in 1880, was provocatively titled *The Power of Movement in Plants*. But despite this patronage, plants didn't catch the fancy of biologists pondering intelligent life for more than a century.

Then, in 1900, Indian biophysicist Jagdish Chandra Bose began a series of experiments that laid the groundwork for what some today call "plant neurobiology". He argued that plants actively explore their environments, and are capable of learning and modifying their behaviour to suit their purposes. Key to all this, he said, was a plant nervous system. Located primarily in the phloem, the vascular tissue used to transport nutrients, Bose believed this allowed information to travel around the organism via electrical signals.

Bose was also well ahead of his time. It wasn't until 1992 that his idea of widespread electrical signalling in plants received strong support when researchers discovered that wounding a tomato plant results in a plant-wide production of certain proteins – and the speed of the response could only be due to electrical signals and not chemical signals travelling via the phloem as had been assumed. The door to the study of plant behaviour was opened.

Slow but not stupid

Even then, it would be another decade before Anthony Trewavas at the University of Edinburgh, UK, became the first person to seriously broach the topic of plant intelligence. Trewavas defines intelligence as the ability to sense one's environment, to process and integrate such sensory perceptions, and decide on how to behave. "The great problem of plant behaviour has always been that you can't see it going on," he says. There are a few exceptions, such as the snap of the Venus flytrap. "But the most visible plant behaviour is simply growth, and growth is a very slow business," he says. This problem has been reduced with the advent of time-lapse video and photography.

Take the parasitic vine Cuscuta, also known as dodder. In time-lapse, a dodder seedling seems to sniff the air looking for a host, and when it finds one, it lunges and wraps itself around its victim. It even shows a preference, choosing tomato over wheat, for example. "It is remarkably snakelike in the way it behaves," says Trewavas. "You'll stop doubting that plants aren't intelligent organisms, because they are behaving in ways that you expect animals to behave."

Once Trewavas mooted the idea of plant intelligence, others soon backed him up. So much so that in 2005, the Society for Plant Neurobiology was formed to foster debate and change the way we think about plants. "There is a kind of brain chauvinism," says Stefano Mancuso, one of the founders based at the University of Florence, Italy. "We think that a brain is something that is absolutely needed to have intelligence." Not so. Despite a lack of neurons and an animal-like nervous system, plants are perfectly capable of processing and integrating information to generate behaviour that can be called intelligent. Mancuso and society co-founder Frantisek Baluska at the University of Bonn, Germany, believe that roots are the key.

A root is a complex assemblage. There's the root cap, which protects the root as it navigates through soil, but also senses a wide range of physical properties, such as gravity, humidity, light, oxygen and nutrients. Behind this is the meristem, a region of rapidly dividing cells. Further back is the elongation zone, where cells grow in length, allowing the root to lengthen and bend. And between the meristem and the elongation zone is a curious region called the transition zone (see diagram). Traditionally, it was thought to have no purpose, but Baluska and Mancuso think it is actually the nerve centre of the plant.

Underground intelligence

They have found that the transition zone is electrically active. What's more, within it a hormone called auxin, which regulates plant growth, is ferried around in protein containers called vesicles that are reused once they have released their load. This is similar to the transport of neurotransmitters in animal brains, where vesicle recycling is thought to be important for the efficient and precise information exchange across synapses. The transition zone is also a major consumer of oxygen, in another curious analogy to the human brain. All of which leads Baluska and Mancuso to suggest that this is where sensory information gathered by the root cap is translated into commands for the elongation zone – and so control of root behaviour.

Intriguingly, this ties in with Darwin's "root brain" hypothesis. In the last paragraph of *The Power of Movement in Plants*, he dared readers to think of the root as the intelligent end of a plant. Referring to a plant's primary root, or radicle, he wrote: "It is hardly an exaggeration to say that the tip of the radicle... acts like the brain of one of the lower animals."

"He was right once more," says Mancuso. "If we need to find an integrative processing part of the plant, we need to look at the roots."

Parallels with animal intelligence don't end there. Besides the tantalising brain-like behaviour of the root's transition zone, many plant cells are capable of neuron-like activity. "In plants, almost every cell is able to produce and propagate electric signals. In roots, every single living cell is able to," says Mancuso. Likewise, the phloem is extremely electrically active, and capable of fast electrical signalling. "It is some kind of huge axon, running from the shoot tip to the root tip," says Baluska.

There's also the curious fact that plants produce chemicals that in animal brains act as hormones and neurotransmitters, such as serotonin, GABA and melatonin. Nobody quite knows the significance of these chemicals in plants – it could simply be that evolution has come up with similar molecules for very different purposes in plants and animals. Nevertheless, Susan Murch of the University of British Columbia in Kelowna, Canada, has shown that drugs like Prozac, Ritalin and methamphetamines, which disrupt neurotransmitters in our brains, can do the same in plants. "If you really mess with a plant's ability to either transport or make melatonin or serotonin, root development is very strange – they are malformed and disjointed," she says.

Despite all this, the term "plant neurobiology" is controversial even among some of the most vocal advocates of plants. Daniel Chamovitz at Tel Aviv University in Israel says it's an oxymoron. "Plants just don't have neurons. It's like saying 'human floral biology'," he says. Indeed, the Society for Plant Neurobiology met with so much resistance that its founders were forced to change its name to the less controversial Society of Plant Signaling and Behavior.

Nevertheless, Chamovitz and others don't dispute that plants are extremely aware of their environment, and are able to process and integrate information in sophisticated ways. In fact, a plant's awareness of its environment is often keener than an animal's precisely because plants cannot flee from danger and so must sense and adapt to it. For instance, while animals have a handful of photoreceptors to sense light, plants have about 15. "Plants are acutely aware of their environment," says Chamovitz. "They are aware of the direction of the light and quality of the light. They communicate with each other with chemicals, whether we want to call this taste, or smell, or pheromones. Plants 'know' when they are being touched, or when they are being shook by the wind. They integrate all of this information precisely. And they do all of this integration in the absence of a neural system."

The Venus fly trap remembers a touch and only shuts if touched again within 30 seconds *(Image: Ojo Images Ltd/Alamy)*

Plants also manage to remember things without the benefit of neurons. Memory can be defined, according to Chamovitz, as "recording an event, storing that event and recalling it at a later time in order to do something". And plants certainly do this. For example, just one touch isn't enough to spring the jaws of a Venus flytrap. Instead, it remembers the first touch and if it senses another within 30 seconds it snaps shut. That's because the first touch causes molecules to build up in the trap's sensory hairs and the second touch pushes the concentration of these across a threshold, resulting in an electrical impulse that activates the trap.

Smarty plants

There is even evidence that plants have long-term memories. *Mimosa pudica*, the touch-me-not plant, can close its leaflets when touched, but this defensive behaviour requires energy, therefore the plant doesn't indulge in it unnecessarily. When Mancuso and colleagues dropped potted mimosas on to foam from a height of 15 centimetres, the plants closed their leaves in response to the fall. But after just four to six drops they stopped doing this – as if they realised that the fall posed no danger. However, they continued to close their leaves in response to a physical touch, which would normally presage being damaged or eaten. "Even after one month, they were able to discriminate and be able to understand whether the stimulus was dangerous or not," says Mancuso.

This is all very clever, but it's not intelligence, says Chamovitz: "I don't like the term plant intelligence. We don't even know what intelligence is for humans. If you get five psychologists together you will get 20 different definitions."

Murch agrees. She acknowledges that plants seem to possess the various elements that make intelligence possible – sensing, awareness, integration of information, long-term memory and adaptive learning – but she is not convinced this adds up to intelligence. And despite years spent among towering redwoods, Sillett is also doubtful. "I wouldn't call it intelligence, but awareness. These trees are keenly aware of their environment, and they respond to it in many ways that we can measure as performance."

But while many researchers are cautious, others are keen to push the way that we think about plants into even more disputed territory. Baluska suggests that plants may even feel pain, and argues that this is a sign that they have a kind of consciousness. An animal can be knocked out with anaesthetics, including the gas ethylene. Plants produce ethylene to regulate everything from seed germination to fruit ripening. They also release it when stressed – when under attack by predators or being cut by humans, for example – and nearby plants can sense it. "Ethylene is the plant equivalent of a scream," says Murch. But Baluska goes a step further, pointing out that the gas is produced in large quantities by fruit when it's ready to be eaten. "If you consider ethylene as an anaesthetic, and if some organism is producing an anaesthetic under stress then you could get ideas that plants maybe feel some pain," he says.

Such notions are extremely controversial and, even Baluska agrees, speculative. To avoid simply pitting one side against another in the debate, we need a different framework to start thinking about notions of intelligence and consciousness, says Michael Marder of the University of the Basque Country in Vitoria-Gasteiz, Spain. The lone plant philosopher for now, he argues for a phenomenological approach to understanding plants, which involves asking: what does the world look like from the standpoint of plant life?

"Our task is to think about these concepts of attention, consciousness and intelligence in a way that becomes somehow decoupled from the figure of the human," he says. "I want [us] to rethink the concept of intelligence in such a way that human intelligence, plant intelligence and animal intelligence are different sub-species of that broader concept, which can somehow encompass these different life forms."

Murch has begun engaging with such questions in one of her classes, which brings together biochemistry and creative writing students to ponder plant intelligence. "Inevitably, there is a vegan in the audience who goes, 'Then what will I eat?'" she says.

That might seem like a flippant response, but contemplating whether plants are intelligent could lead us to change the way we live. As Marder points out, the sessile nature of plants means they don't exist in opposition to the place they grow. Rather, they become a focal point for myriad organisms. "Maybe we can use that model for ourselves, to temper a little bit the excessive separation from our environment that has led in large part to the profound environmental crisis we find ourselves in," he says.

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Lateral thinking

Once considered to have no purpose, the transition zone near the tip of each root may be a kind of brain