Do Plants Have Brains?

Some biologists argue that “neurobiology” has been too narrowly defined. Mimosa pudica, also called sensitive plant or touch-me-not, folds its leaves rapidly when mechanically disturbed. Few plants exhibit such quick movements, although many—such as those that open and close their blooms according to the time of day—respond with slower movements to environmental stimuli.

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Some people think that plants respond to talking, the playing of music, and other forms of human attention. And although plants more than likely do not process human language, they are nonetheless highly aware of their surroundings and are very capable of communication among their cells. Furthermore, some scientists think that a plant's internal communication system is very close to what we could legitimately call a nervous system. After all, some mimosas are famous for retracting rapidly after being disturbed, and Venus flytraps react swiftly to the presence of insects in their capture devices. Charles Darwin made comparable observations and proposed similar ideas about plants. In one of his less well known works, The Power of Movement in Plants (1880), he wrote about the radicle, the embryonic root in a plant, and the sensitivity of its tip to diverse kinds of stimulation:

It is hardly an exaggeration to say that the tip of the radicle thus endowed, and having the power of directing the movements of the adjoining parts, acts like the brain of one of the lower animals; the brain being seated within the anterior end of the body, receiving impressions from the sense organs, and directing the several movements.

Darwin was saying that the radicle not only behaves like a brain by directing the functions of other cells, but is also positioned in the corresponding place in the anatomy of the plant. Some modern botanists have extended this idea. In 2005, the first international plant neurobiology meeting was held in Florence, Italy, and a brand-new journal, Plant
Signaling and Behavior, was launched in 2006. Just what are the plant neurobiologists proposing?

The idea that plants have nervous systems stems from several sources of information. First, plants have genes that are similar to those that specify components of animal nervous systems. Such components include receptors for glutamate, an amino acid that is one of the building blocks of proteins but that also functions as a neurotransmitter. Other components are neurotransmitter pathway activators, such as those known as G-box proteins, and a family of “14-3-3” proteins, which act to bind various signaling proteins. All these proteins have been observed in animals, in which they have been shown to have distinct roles in neural function. Yet they are also found in plants.

Second, although those proteins more than likely do not have “neural” functions in plants, some plant proteins do behave in ways very similar to neural molecules. Third, some plants seem to show synapse-like regions between cells, across which neurotransmitter molecules facilitate cell-to-cell communication. Included in the requirement for comparison is that the regions should have the same characteristics as animal synapses, such as the formation of vesicles, small bubbles that store the neurotransmitters that are to be released across the synapse. Fourth, many plants have vascular systems that look like they could act as conduits for the “impulses” that they need to transmit throughout the body of the plant. Last, some plant cells display what could be interpreted as action potentials—events in which the electrical polarity across the cell membrane does a quick, temporary reversal, as occurs in animal neural cells.

Illustration from The Power of Movement in Plants shows one of Darwin’s experiments with a bean radicle. (A) A little square of card attached near the tip causes bending away from the card, as if the radicle has encountered an obstacle. (B) In time, the bending, which is effected not by growth at the tip but by cells farther
up the radicle, increases to a right angle. (C) Eventually the tip begins to bend downward through the action of geotropism. With the radicle suspended in mid-air, the cells in the region of the bend are not directly sensing compression against an obstacle, so it is the sensitive apex that initiates their response.

Let's look at these various kinds of information and at what they may imply for the existence of brain-like functions in plants.

It is hardly surprising to find genes in plants that are related to animal genes involved in the nervous system. Indeed, confirmation of this fact was one of the first really interesting results of the various genome projects. The reason why it isn't surprising is that all life on the planet is united through common ancestry. To find genes in common among broadly divergent organisms is what you'd expect with descent from common ancestors. Thus a typical bacterial genome turns out to have the equivalent of 2 percent or so of its genes in the human genome. For plants the number is about 17 percent, and for such organisms as flies and worms the number jumps to between 30 and 40 percent. Another way to measure similarity of genomes is to ask how much the actual sequences of bases in the genes of a genome vary. For vertebrates, when sequence similarity is examined, the number ranges from about 85 percent, for such distant relatives as fish, to 98.7 percent, for the chimpanzee, and 99.7 percent for our close extinct relative, Homo neanderthalensis. What was not so expected, though, is the broad distribution of major gene categories that are represented in both plants and animals.

Still, evolution can facilitate some remarkable "variations on themes" with genes. If a gene makes a protein involved in a particular process in plants, the corresponding gene in an animal or a fungus doesn't necessarily have to make a protein that has the same function. An instructive example is glutamate receptors, which are involved in the animal neural synapse and interact with the neurotransmitter glutamate. Plants have glutamate receptors too, but whether they serve anything like a "neural" function is another matter. An examination of the distribution of this gene family in the genomes of plants and animals will show us how gene families can diverge and how the functions of these genes can diverge too.

In animals these receptors are found primarily in the receiving end of nerve cells—their "postsynaptic" region. Glutamate is transported across the synapse, encounters the receptors, and so excites an action potential, or firing of the nerve cell. It happens that two major kinds of glutamate receptors are recognized on the basis of how they promote the postsynaptic impulse. The first kind is "ionotropic": glutamate receptors line the ion channel pores across the cell membrane of the recipient nerve cell, and when the receptors bind to glutamate, the pores are activated and ions flow through them. In "metabotropic" receptors, the ion channels are activated more indirectly, through signaling
cascades that are usually linked to G-proteins (which bind guanine, one of the four nucleic acid bases).

For the process to work, the glutamate receptors also have to bind what are called agonists. There are three major kinds of agonists that interact with ionotropic glutamate receptors: AMPA (alpha-amino-3-hydroxy-5-methyl4-isoxazole propionate), NMDA (N-methyl-D-aspartic acid), and kainate. Other agonists interact with metabotropic receptors. There are also several versions of the glutamate receptors for both the ionotropic and metabotropic functions, as well as several within those functional categories that are specific for different agonists. So there are multiple versions of genes for the proteins in animals (that is what is called a gene family). For instance, most mammals have sixteen ionotropic glutamate receptors: four that use AMPA as an agonist, seven that use NMDA as the agonist, and five that use kainate as the agonist. Likewise, mice and humans have eight metabotropic glutamate receptors, each of which uses a variety of agonists.

Plants have glutamate receptors that are more similar to the ionotropic kind. *Arabidopsis thaliana* (thale cress), a workhorse of plant genetics and genomics, has twenty members of this gene family, a number in the same ballpark, curiously, as those sixteen ionotropic glutamate receptors in mammals. Moreover, three major categories of glutamate receptors have been discovered in plants, recalling that there are three major categories of ionotropic animal glutamate receptors (those that use AMPA, NMDA, and kainite as agonists). But do the subgroups of animal ionotropic glutamate receptors roughly correspond to those in plants? In other words, are the animal glutamate receptors that use AMPA as an agonist more closely related to a particular subset of plant glutamate receptors than they are to any other animal or plant receptors?

In fact, the three categories of plant glutamate receptors bear no resemblance at all to these animal categories. For one thing, animals apparently all evolved the same genes in this gene family via duplications in common ancestors, whereas plant glutamate receptors all appear to be evolved from a single common ancestor that existed before plants and animals diverged. That means that the very specific glutamate receptors of animals do not have a one-to-one relationship with plant glutamate receptors. Nor do the receptors in plants display a relationship to distinct organs, as they do in animals.

Further, apart from any similarity in the genes, we may turn to our second seeming similarity, that of the function of the proteins specified by the genes. In fact it is true that plant glutamate receptors can interfere with animal glutamate receptors, suggesting that the plant receptors still have some equivalent function in animal nerve cells. There is, for instance, the strange case on the island of Guam of human ingestion of cycad material
(plants rich in a glutamate-like amino acid) causing neurodegenerative symptoms similar to those of Alzheimer’s, Parkinson’s, and Lou Gehrig’s diseases. And the expression of plant glutamate receptors is specific to the root, the very location that some scientists find most suggestive of plant nervous systems. While a small subset of these receptors does appear to be important in early development of the roots, however, the different receptors in plants do not generally display a relationship to distinct organs, as they do in animals.

Still, **if glutamate receptors don’t serve nervous system functions in plants, why are they there?** The most common argument for their retention in plants is that they serve as defense proteins to ward off invading insect species.

Third, given all this, are there plant structures that behave like synapses, along with molecules that behave like neurotransmitters active in the “synaptic” region? For this to mean anything, a few characteristics of plants need to be confirmed. Synaptic communication must be shown, implemented by neurotransmitters and neural transmitter receptors in the same way as in animal neurotransmission—for example, by way of vesicles near the synapse. One neurotransmitter candidate is auxin (indole-3-acetic acid), a small molecule that some botanists feel is the best argument for neurological behavior in plants. There are also transporters for auxin that behave a lot like receptors, in that they assist the movement of auxin across the cell membrane. But does the auxin system act like neurotransmission? Some scientists would actually argue yes. Molecular botanist Gerd Jürgens at the Max Planck Institute for Developmental Biology, for example, has shown that auxin transport is accomplished through “vesicle trafficking,” a process involving cellular vesicles (small lipid-encased bubbles) that has animal neurotransmitter—like features.

Still, auxin is not found in animals, and it appears to be a plant-specific protein that regulates growth. To some, Jürgens’s observations suggest that the vesicle structures might be similar enough to make a good argument. When the kinds of “synapses” made in plants are examined, two junction types turn out to have protein domains embedded in the cell membrane. The auxin transport system, accomplished through vesicle trafficking, is influenced by light and gravity to control cell-to-cell communication, and it uses auxin as a transmitter, behaving in much the same way as a neurotransmitter.

The other “synapse” behaves like the interconnection between an animal immune cell and a pathogenic cell. In animals, this system implements the immune response and the destruction of the invading pathogen. In plants, it allows the individual not only to deal with pathogens but also to stabilize interactions with symbionts—an important function. Plants establish useful two-way interactions with a lot of microorganisms such as bacteria and fungi, and in some cases these microbes accomplish tasks that the plant is unable to do
on its own. Some plants cannot process environmental nitrogen, so they form a symbiotic relationship with bacteria from the genus *Rhizobium* to do the trick, and the synapse-like attachment is essential for the relationship. In the process, the rhizobia get the benefit of being fed by the plant.

Then, to address the fourth and fifth points raised above concerning the existence of plant neural systems, what about electrical impulses or action potentials in plants, and their possible pathways as part of the plant vascular system? Oddly enough, electrical conductivity in plants was discovered a few years before Luigi Galvani did his ghoulish 1780s frogleg experiments showing electrical impulses in animals. So there is no doubt that electrical signals or perhaps even action potentials exist in plants. It is also pretty clear that, as Eric Davies at North Carolina State University put it, “the fundamental reason plants have electrical signals is that they permit very rapid and systemic information transmission, so that the entire plant is informed almost instantly even though only one region may have been perturbed.” Still, the nature of the action potential is quite different in plants and animals, though both involve their cells’ ion channels. Whereas animals produce the action potential by an exchange of sodium and potassium ions, plant potentials are produced with calcium transport that is enhanced by chloride and reduced by potassium.

**So what do we conclude?**

The notion that plants have brains in some sense is both interesting and thought-provoking. So provocative, indeed, that in 2007 thirty-six investigators from thirty-three institutions published an open letter in the journal *Trends in Plant Science* maintaining “that plant neurobiology does not add to our understanding of plant physiology, plant cell biology or signaling,” and imploring the proponents of the initiative to “to reevaluate critically the concept and to develop an intellectually rigorous foundation for it”—a nice way of saying, “just cut it out.”

Overall, the response from the plant neurobiologists on the matter of plant “brains” has been rather conflicted. Anthony Trewavas of the University of Edinburgh suggested that “plant neurobiology is a metaphor”—and nothing more. His focus was on the term itself, and his interest was principally in its importance in driving science to understand the cell biology of plants and the mysteries of plant cell-to-cell communication and signaling. But the biologists František Baluška of the University of Bonn and Stefano Mancuso of the University of Florence strenuously argued for the literal existence of nervous systems in plants, suggesting that “removing the old Aristotelian schism between plants and animals will unify all multicellular organisms under one conceptual ‘umbrella.’”
Obviously, both perspectives cannot be right. Trewavas seems to us to call it what it is: simply a case of discussing similarities. It is the metaphor itself that makes statements about the similarity of plant and animal systems so interesting. But to make it useful, you have to acknowledge that it is metaphor. To unify plants and animals under a single “conceptual umbrella” when there really isn’t one, creates a genuine problem. For one thing, there is good evidence that plants and animals do not share a common ancestor to the exclusion of all other organisms on the planet. Fungi and the many single-celled organisms that have nuclei get in the way. A unifying umbrella would both disguise this reality and undermine the utility of the metaphor. When a metaphor is no longer recognized as such, fallacy becomes the rule of the day.