Nervous Systems: Myriad Variations on a Simple Theme

Brian McCabe 31 Oct 2021

By the phrase 'simple theme' in the title, I'm referring to the nerve cell – we each possess billions of them - which is special for a number of reasons. In personal terms, nerve cells impart our identity. More generally, they perform an indispensable function in multicellular animals: that of rapid communication.

There seem to be very few, if any, alternatives that are capable of performing this special function. A nerve cell in, say, a snail and a nerve cell in a human being work in essentially the same way. During the 600 million years or so since the time of our common ancestor, nerve cells seem to have been essential for all species in that particular evolutionary tree. Indeed, nerve cells almost certainly existed long beforehand. If alternative means of rapid communication arose in the course of evolution, they don't seem to have been successful. Given the constraints to which animal cells are subject, nerve cells do the job extremely well.

Why are they so good at it? Well, they're versatile.

- They can sense the environment in many ways: suitably modified, they can respond to electromagnetic radiation - light, ultraviolet and infrared, the angle of polarized light, sound, touch, electric fields, magnetic fields, many chemicals and tissue damage.
- They can communicate through extensions called nerve fibres for more than a metre. This is done electrically: usually by pulses of about a tenth of a volt travelling at speeds of up to about 200 miles per hour, often considerably slower.
- They can cause muscles to contract. They constitute a mode of communication that makes behaviour possible.

The junctions that nerve cells form with each other, the synapses, are special. Some synapses transmit nerve impulses by passing electric current from one nerve cell to the other, but most are chemical. That is, a chemical diffuses from one nerve cell to the other, to excite, inhibit or otherwise modify the recipient nerve cell. Importantly, information across a synapse travels in just one direction - somewhat like what happens in a valve - which has important consequences when nerve cells are connected by synapses in a network.

A particularly important property of some synapses is their ability to modify their own efficacy when their component nerve cells are active in particular temporal patterns, for example by being active simultaneously. A brief bout of conjoint activity can produce a change in synaptic efficacy lasting for several months and forge a functional pathway through a network of nerve cells in a sensory pathway. In this way, experience, particularly in the early years of life, can mould a sensory pathway and strongly influence how external events are subsequently represented in the brain. Such so-called activity-dependent synaptic modification may also be a mechanism for memory. It is, anyway, a principle employed in artificial neural networks, which influence so much of our lives today.

Nerve cells can, of course, connect together to form networks performing all sorts of complex functions: sensation, behaviour, speaking, thinking. When connected up appropriately, they can act as little analogue computers that are capable of arithmetic, differentiation, integration and logical operations. They also make quite good clocks, as controllers of our daily rhythms.

It's instructive to consider optical illusions such as the Kanizsa illusion[1]. Various angular figures that include the corners of a three-sided figure can give the strong illusion of a three-sided figure that does not actually exist. The illusion illustrates the point that when information about the outside world is incomplete – a common occurrence - neural networks can make a fairly good guess at what is missing. This inference could be wrong, but if correct, it can save your life if you make a correct inference about the partial outline of a nearby predator. Interestingly, this process is automatic – one needs no training to see it - but it is also different from many automatic processes, such as the maintenance of posture, that occur continually without our being aware of them. In contrast, the Kanizsa illusion is something of which we are consciously aware, and in the light of which we can make a conscious decision. This strikes me as a highly adaptive arrangement that has the best of both worlds: automaticity and the option of voluntary action.

Now, two case studies, which I think illustrate some further important principles:

What is the cognitive capacity of a new-born baby? What are the relative contributions of developmental programmes and the sensory environment?

If one presents a new-born human baby with a crude image of a face, the baby typically tracks the image for a high proportion of the time, and significantly more time than a jumble of the elements used to make up that face[2]. Babies are predisposed to preferentially attend to faces without having seen a face before. Subsequently, of course, the baby learns what its parents look like and develops a strong social bond with them. And this is helped by the baby's attention being directed towards faces.

We are therefore born with predispositions that orient us towards adaptive learning opportunities. What is thus learned can generate further adaptive behaviour, in what is typically a virtuous spiral, conducive to such things as social bonding and speech development.

There is evidence for a similar principle governing the development of sensory systems, at least in mammals, although the underlying neural mechanisms are not necessarily the same as those in the cognitive processes just mentioned. At birth, one a crude sensory capability is evident, which may be matched to the physical properties of the corresponding sensory organ, such as the eye. Future sensory performance may then be strongly influenced by activity in the sensory pathway of the young animal. Such is the case in the visual system, which has been particularly well studied in this respect.

The second example is a remarkable series of experiments, which relate a change in a single molecule to a complex pattern of behaviour[3].

The grasshopper mouse lives in the southwestern American desert. It is unusual in that it eats scorpions. This is an unusual dietary choice, even in California. Although a scorpion is a nutritious food source, most animals avoid it unless they are very hungry and very agile, since the venom from the sting can kill an animal the size of a mouse. If a human being is unfortunate enough to get stung, the sting is very painful indeed. The venom excites nerve cells (nociceptors) that normally respond to tissue damage, and which send nerve impulses to the parts of the central nervous system responsible for pain. Nerve cells in this sensory pathway bear, in their membranes, a protein that is critical for propagation of the nerve impulse – a sodium channel. In the grasshopper mouse, this sodium channel has a molecular structure unique to this nociceptive pathway.

A molecular accident occurred in a germ cell of an ancestor of the grasshopper mouse – an accident that caused DNA to encode a slightly modified sodium channel. In the grasshopper mouse, this sodium channel is locked shut by scorpion venom. When the animal is envenomed, no aversive information from the venom reaches the central nervous system. The mutation has changed the venom into a highly specific local anaesthetic.

A tiny molecular modification has thus opened up a new food source for the grasshopper mouse, a food source that is assiduously avoided by most or all of its competitors.

I wanted to discuss this experiment because it emphasises a second theme underling what I have been saying, namely the importance of interactions in the natural world. Interactions between nerve cells and their environment, between nerve cells themselves, between developmental programmes and the environment, between predator and prey, and between a molecular genetic change and the behavioural ecology of a species.

It is important occasionally to look up from the microscope, the oscilloscope and the DNA sequencer, to think how the tools at our disposal can improve our understanding of the interactions between living organisms. The importance of doing so is becoming increasingly apparent in view of the threat of extinction currently faced by so many species. Study of these interactions shows that life is complicated. But not to the extent that we can't usefully understand it.

Further information

1. https://www.illusionsindex.org/i/kanizsa-triangle

2. MH Johnson et al., Newborns' Preferential Tracking of Face-Like Stimuli and Its Subsequent Decline, *Cognition* 40: 1–19.
   https://doi.org/10.1016/0010-0277(91)90045-6
   (Free access from the cam.ac.uk domain)

3. https://en.wikipedia.org/wiki/Grasshopper_mouse