The Secret Life of the BRAIN

Unlocking the mysteries of the mind

Alfred David

Contents

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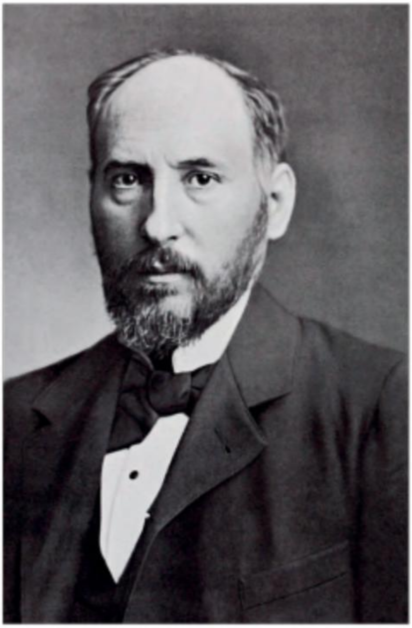
Select one of the chapters from the main contents list and you will be taken straight to that chapter.

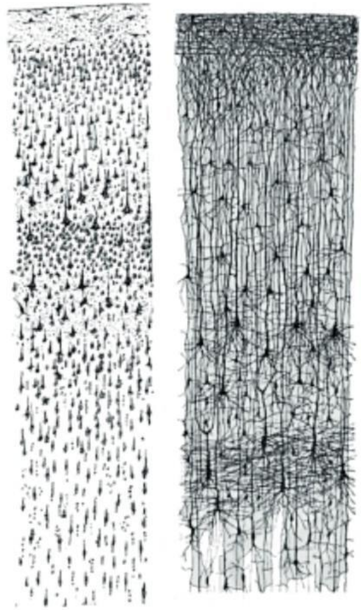
Look out for linked text (which is in blue) throughout the ebook that you can select to help you navigate between related sections.

You can double tap images to increase their size. To return to the original view, just tap the cross in the top left-hand corner of the screen.

Introduction

Through the centuries, anatomists and physicians have prodded, sliced and dissected their way through the brain, but its mysterious inner workings have proven difficult to uncover. The brain is essential for life, responsible for our thoughts and for our feelings. It makes us angry, scared or in love, and it is responsible for moments of stunning human creativity. Mozart's brain produced spine-tingling music. The brains of Newton, Einstein and Hawking probed their understanding of the universe. And Darwin's brain paved the way for understanding why we have a brain in the first place. But while organs such as the heart have obvious moving parts, with obvious signs of function, the brain's structure, variously described as having the texture and consistency of soft tofu, a ripe avocado or (even) scrambled eggs, seems to belie its ingenuity. It contains chambers with seeping fluids, and is supported by a vigorous blood supply, meaning that it is exceptionally demanding of food and oxygen. But the brain seems to be singularly static and silent. That is, until we clamp electrodes to a living scalp and see all the electrical activity generated by the organ within.





Spanish pathologist Santiago Ramón y Cajal (1852–1934) made hundreds of detailed drawings of the nerve networks he had discovered in the brain.

Function From Failure

Since the time of the ancient Greeks, anatomists have dissected bodies and mapped the parts of the brain, from its flabby lobes to its central stem, and given them names. They even managed to work out what some of them did by doing grisly experiment on living animals, cutting into parts of the nervous system to see what effect it had. Later, on the battlefield and elsewhere, physicians studied the unfortunate victims of specific brain damage. By seeing how injuries or lesions caused by disease affected the way their patients behaved, physicians slowly uncovered the secrets of the brain parts discovered by the anatomists. Post-mortems on damaged brains help to reveal how different parts of the brain are involved in speech, personality or even moral awareness. But exactly how this is all controlled, and what the brain actually did in a physical sense, was still a secret. Muscles work by twitching, blood works by flowing. But what causes a thought inside the brain? The microscope brought some answers.

Secrets Under Magnification

Towards the end of the nineteenth century, biologists around the world were perfecting techniques that would help them understand how living things worked at the microscopic level. Their work showed them that all parts of bodies were made up of tiny living structures called cells. Indeed, many people were now convinced that everything the body did – how it moved and even how it thought – depended on cells. In Barcelona, a young pathologist called Santiago Ramón y Cajal had made his name by studying cholera and tissues before turning to the brain. Using a special staining technique, Ramón y Cajal revealed single brain cells among their mass of neighbours. In this way, he helped to prove that the brain followed the rest of the body's rules of organization: it, too, was made up of communities of cells. This work laid the foundations of modern neuroscience. Today, biologists practically take it for granted that our bodies are made up of microscopic living cells: nowadays schoolchildren can peer down simple microscopes to look at cheek cells and onion cells. But not everyone in the past had been convinced. At the time of Ramón y Cajal, there was a competing theory as that the nervous system was made up of a single continuous network of tiny fibres. Ironically, in 1906 Ramón y Cajal shared a Nobel Prize for his work on the brain with an advocate of the network theory: Italian biologist Camillo Golgi dismissed the idea that the brain was made up of discrete cells. Golgi had, in fact, invented the very staining technique that Ramón y Cajal had used to make his discoveries. But in the end, there was no doubt that that brain – like any other organ – is made up of cells, and Ramón y Cajal's exquisite illustrations of branching brain cells are still shown to students today.

Brain Cells at Work

The demonstration that the brain is made of cells marked a seismic shift in neuroscience. It meant that the brain needed to be understood in terms of cellular things – like cytoplasm and membranes. As we shall see in the opening chapters of this book, this helps us appreciate how brains work, from the way they transmit the electrical impulses associated with thought processes and reactions to how they hold on to memories. In that respect, there is nothing mysterious about how the brain works: it all comes down to molecules and electrical charges, the stuff of any living matter. But the enormous organizational complexity of the billions of cells in a human brain means that understanding it is not easy. Brain cells are not randomly arranged: they are linked to one another in very particular ways. Their long, spindly fibres can connect to others over long distances through cable-like highways called tracts, while different regions of the brain are specialized in controlling vital functions, burdening our thought with emotion, and so on. This spatial organization is explained in the middle section of this book.

In social gatherings, our complex brains are constantly monitoring the subtle cues that we receive from others. Our brains allow us to read the emotions of others, to share their joy and to feel their pain.

Beyond Brain Cells

Brain cells are the vital components in the brain's electrical circuitry, but that is only part of the story when it comes to the secret life of the living brain. Brains do not work in isolation from the body's surroundings any more than they work isolated from other organs. Our brains react and respond to outside cues, some of which, in the complex world of our highly social species, come from other brains that are ticking over in other bodies. As we will see in later parts of this book, this means that our brains can get tuned in to the brains of our family and our companions. We behave differently in social settings and our brains are affected by the experience of things like parenthood.

It is an extraordinary thought, one of many that we can enjoy with our remarkable brain, that this entire gamut of complexity arises from an organ that develops like any other, beginning with a microscopic cluster of cells in a tiny embryo. In the close of this book, we will trace the life of a human brain from conception through to the rarefied wisdom of old age. In the womb, the growth of our brain in many respects parallels a far more ancient process that produced complex nervous systems out of simpler ones, millions of years ago. Our brain is not just a product of embryonic development, it is also the culmination of a process of evolution that has made our species so remarkable in its accomplishments, both good and bad. There are more than ten times the number of brain cells in a single modern human head than there are human beings on the face of the planet. That, in itself, is certainly food for cerebral thought.

Chapter 1

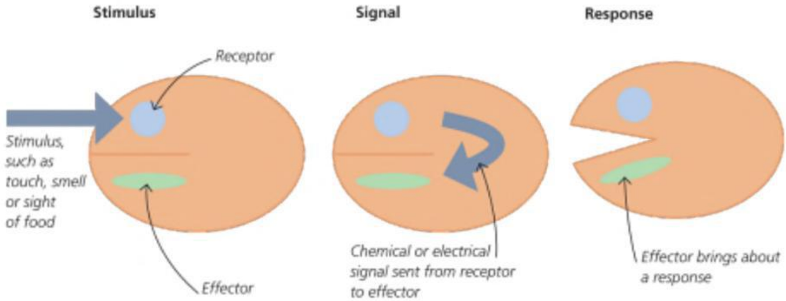
WHY HAVE A BRAIN?

Coordinating Bodies

The brain is part of an animal's nervous system, which has the job of controlling the activities of the living body. Although the simplest animals alive today lack a true brain, their nervous systems can still coordinate behaviour.

We share our planet with trillions of living things. Some are so small that you need a microscope to see them, but every one of them is busy controlling the complicated business of staying alive. For some, such as plants and bacteria, control depends upon chemical mixtures that signal a particular response. But the bodies of animals contain special cells that fire thought processes and trigger muscles to twitch into action. Compared to plants, animals move quickly and think hard. And most of them think with their heads: they have a brain. In complex animals, including humans, the brain is the ultimate organ of control. A hard-working human brain looks as unremarkable as a resting one, but each brain is capable, silently and secretly, of feats that are more impressive than those of the most powerful computer. Indeed, its microscopic arrangement, with billions of interconnected nerve cells, has been described as the most complicated working thing in the entire known universe. But brains are expensive to maintain, and use up a great deal of energy: in a human, the brain uses about a fifth of the body's total energy budget. And the fact that the simplest animals manage their bioelectric circuitry without any real brain begs the question: why have a brain at all? To answer that question, we need to begin by looking at an arrangement inside the body that is home for any working brain: the nervous system.

Even animals that do not have a brain, such as jellyfishes, have some electrical circuitry inside their bodies – a nervous system – that helps them to react to their surroundings.



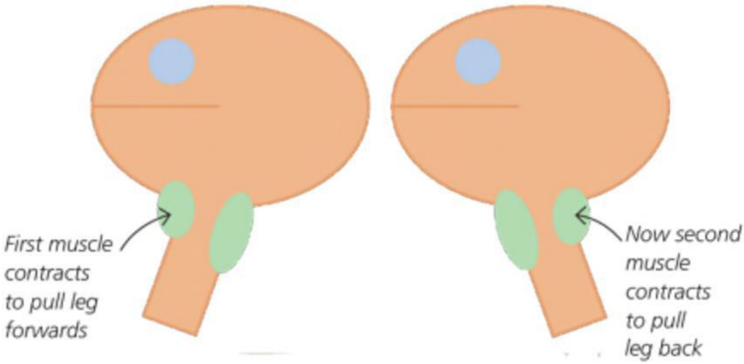
The simplest control system in an organism provokes an automatic response when a receptor (sensor) is stimulated. It involves a chemical or electrical signal being sent from the receptor to the part of the body that responds. This effector could be a gland or a muscle.

How to Control a Body

What do we mean by "control"? Life processes, such as using food, breathing and growing, involve countless chemical reactions that occur simultaneously, and a fine balance is needed to get them to work. On top of everything, the living body is exposed to constant changes, and it has to react to these changes to keep working properly. For a beating heart, this could mean speeding up when the body starts exercise, or just pumping at the right pace when at rest. For a hungry animal, it means moving towards food, but also not straying too close to danger. In countless ways, the body has to control what it is doing.

All living things sense their surroundings in one way or another. They have special sensory cells that can detect stimuli: changes in their surroundings that can trigger a bodily response. A chain reaction in the body ensures that each stimulus leads to an appropriate response. The simplest chain might involve the sensory cells releasing a chemical that seeps through the body, and this chemical causing other body parts to respond. This is what happens in plants when their shoots bend towards light. It happens all the time right inside our own bodies when hormones flood through our blood, such as when a meal prompts the body to deal with the sudden surge of sugar. But a faster communication between sensor and responder is possible when it involves the flow of a bioelectric impulse. Nervous systems, found uniquely in animals, including us, do just that. And they explain why animals are usually quicker at responding to stimuli than plants. Over large distances, bioelectric impulses are much faster than seeping chemicals.

A nervous system is made up of special cells that can carry electrical signals. They provide the link between sensory cells and cells called effectors that can bring about the response. A brain is part of this nervous system. Some effectors are glands that, upon being triggered, give off chemicals that themselves act as more triggers. But other effectors have a more dramatic, observable effect: these are the twitching muscles.



Most muscles can only ever contract (shorten) when stimulated by the nervous system, before returning to their relaxed (longer) state. This means that the nervous system must coordinate different muscles to move a part of the body one way and then back again. The simple act of a human walking upright on two legs involves the nervous system collecting information from many different sensors and coordinating many muscle groups.

Twitching Muscles

Among all living things, only animals can consistently and quickly move in the way they do. This movement is possible because an animal's nervous system is linked to muscles. Each muscle is made up of long, tapering cells that are stacked together and, like the nerve cells, can carry bioelectric signals. But when the nervous system triggers a muscle, it moves. More precisely, it shortens in a twitching motion called contraction. By controlling muscles in different parts of the body, an animal's nervous system can control all its movement in a coordinated way. For instance, in a walking animal, bioelectric triggers from the nervous system ensure that different muscles of the leg contract in just the right sequence so that it bends and straightens, and the animal ends up putting one foot in front of the other.

Nervous Systems Without Brains

The simplest kind of nervous system imaginable would involve a single nerve cell between a sensor and a muscle. Such a system would be very good at producing a rapid-firing response: whenever the sensor was stimulated, the muscle would twitch. But the system would be automatic and would lack any flexibility. The animal would have no choice in the matter of whether the muscle should twitch or not.

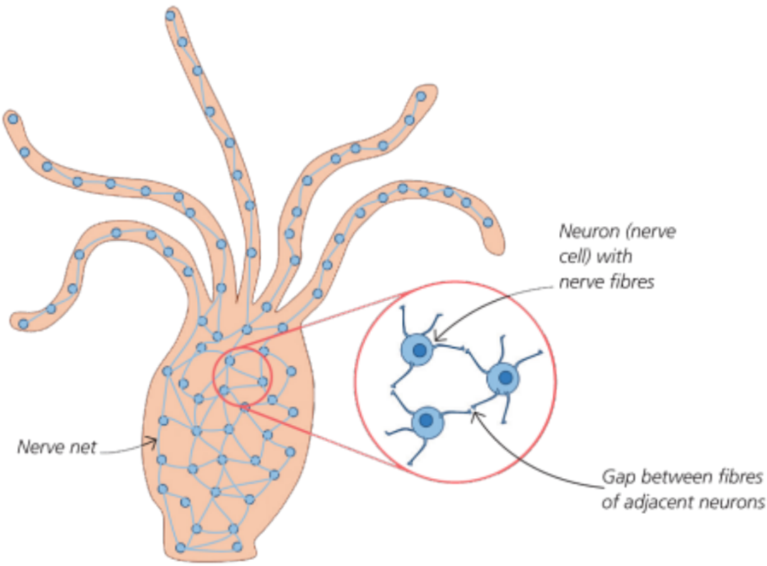
In reality, even the simplest nervous systems are made up of many nerve cells that interconnect to form a network. Nerve cells, called neurons, can do this because each one is armed with spindly fibres that radiate outwards from the main cell body, carrying their electrical signals with them. The fibres of adjacent neurons appear to touch and interconnect, but as we will see in the next chapter, there are tiny gaps where they meet. A network of neurons like this immediately offers more possibilities for controlling behaviour. There is now no longer a single pathway between one sensor and one muscle. Instead, the signal from one sensor has the option of travelling through a number of possible routes to make different muscles respond. Our brains contain complicated networks of densely packed connections, but the principle works even in the simplest animals without a brain, albeit on a smaller scale.

Although they are brainless, jellyfishes, sea anemones and corals have a network of neurons. It runs through the flesh of the animal to control parts such as moving tentacles. And although it is nowhere near as densely packed as the neurons of our brain, this "nerve net" is clearly adequate for their purposes. When tiny planktonic animals drift within reach, sensors are triggered and the nerve net springs into action to coordinate a set of muscles that makes the tentacles squirm towards their prey. In a swimming jellyfish, a more regular coordinated pattern of action helps cause the pulsating movements that drives the animal through the water.

Forward-Thinking

The reason jellyfishes and anemones do not have a brain might seem obvious: they don't even have a head. Each animal consists of a "stem" with a single gut opening at one end that functions as both a mouth and an anus, surrounded by a ring of tentacles. Jellyfishes swim through water, with their mouth-anus facing downwards, while anemones sit on the seabed with theirs facing up. But neither has a head. In fact, they don't really have a front end and back end. Their bodies are radially symmetrical, and they have a sense of "up" and "down", but not "forwards" and "backwards". For them, a spreading nerve net works well because it helps the animal pick out stimulation coming from all directions at once.

Half a billion years ago, when animals were first evolving, those like the jellyfishes and anemones, adopted radial symmetry as their way of life and stuck to it. But some worm-like creatures evolved to move forwards instead. They became bilaterally symmetrical, meaning that the body could be divided down the middle into two halves that were mirror images of one another. One end became the front (with the mouth) and the other became the back (with the anus). When moving forwards, it was better for them to concentrate many of their sensors at the front end – the end that would be facing any new stimuli. And with a bigger frontal battery of sensors, the nervous system at the front swelled to process this incoming information. A head evolved to accommodate the swelling, which became the brain. Today, most animals, including humans, have a forward-facing head packed with sense organs and a brain. Ultimately, a brain is the legacy of our ancestors choosing to move forwards through the world.



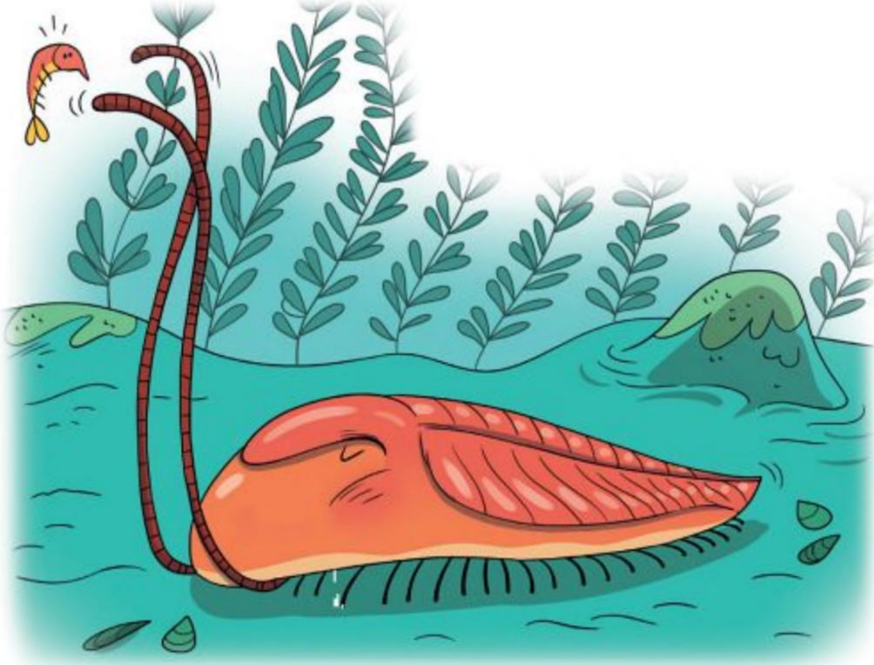
The nerve net of a sea anemone helps its electrical signals travel through all parts of the body, and provides multiple pathways for sending the signals from different sensors to different responding effectors. This means that lots of alternative responses are possible from single stimuli.

A Brain in the Driving Seat

In forward-moving animals, the brain inside the head is the control centre of the entire nervous system, while nerve cells communicate between the brain, sensors and muscles.

Although practically every part of our body has sensors and nerve cells, our head is the primary place concerned with processing the information that we gather from the world around us. The evolution of a head in animals was, literally, a forward-facing innovation. There is even a term for it: cephalization. Animals with brain-packed heads are the best at moving forwards: crawling on the ocean floor, swimming in open water, or moving over land or in the air. It is far better to have a control centre at the front of the body, which is the first part to encounter information from newly explored places. Cephalization was a breakthrough in the evolution of animal life.

Although the head is not discretely separate in many animals (in the sense that they have no neck), practically all animals alive today that are more complex than a jellyfish or anemone have some sort of brain.

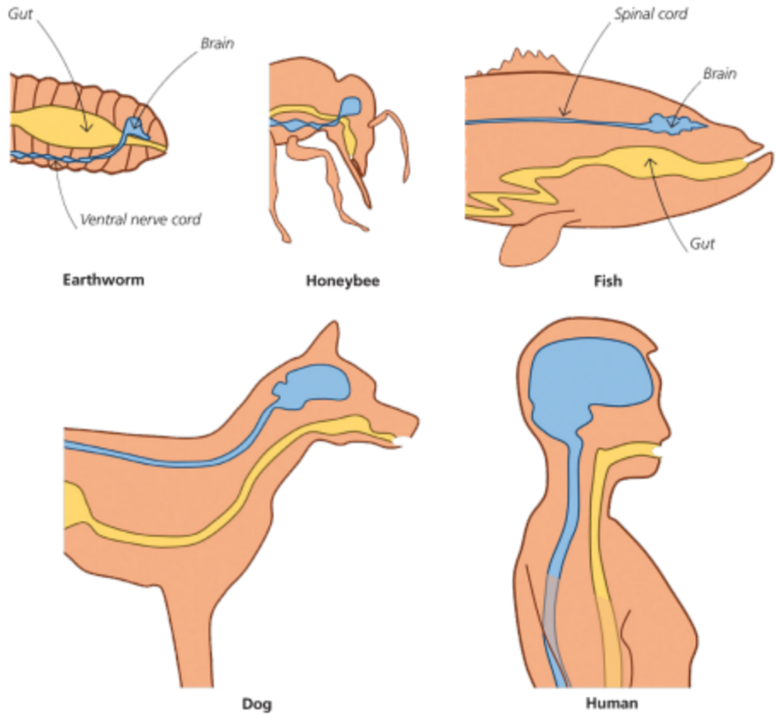


Animals moving forwards in search of food have their sensors packed in their front end, which will be the first part of the body to come across a potential meal.

What is a Brain?

As forward-facing animals evolved to become bigger and more complex, their nervous systems became more complex, too, and the part of the nervous system at the front end, bearing the brunt of the sensory barrage, became more complex than other parts: it became the brain. In the simplest sense, a brain is a dense mass of nerve cells that controls and coordinates behaviour: it receives signals from sensors around the body and sends out other signals to parts of the body, such as muscles, that can respond. It can also store information, in the form of memories, which can affect what an animal does.

Animals without a backbone, known as invertebrates, include animals such as worms, insects and snails. The brains of most invertebrates are little more than a small blob of nerve cells, although they still have considerable processing power. Some scientists prefer to use a different term for an invertebrate mini-brain: they call it a cerebral ganglion. However, in this book, we shall define any central coordinating "blob" in the head of an animal as a brain.

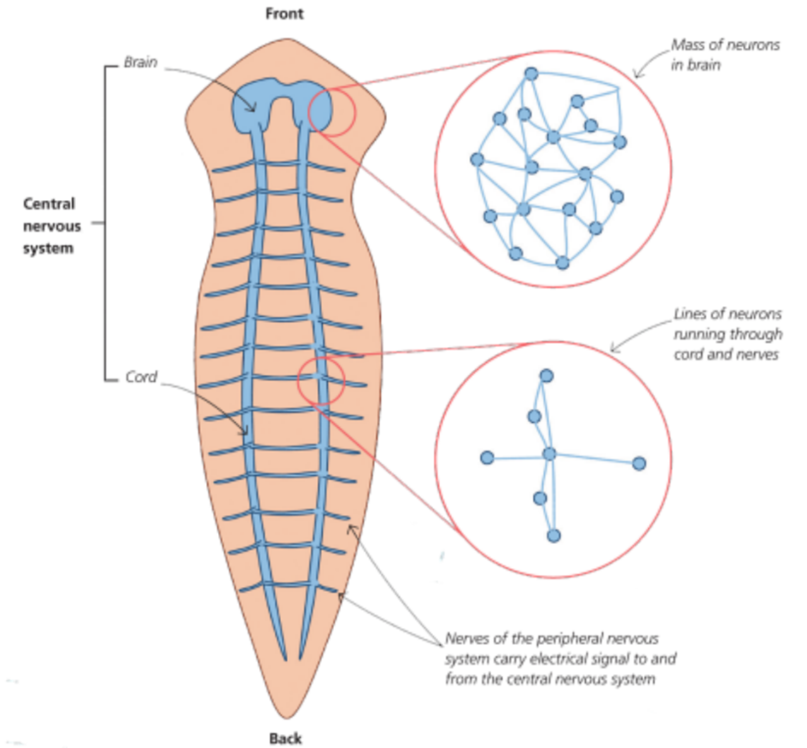


The brains of animals vary a great deal in size and complexity. Invertebrates (animals without a backbone, such as earthworms and honeybees) have smaller brains in proportion to the size of their body than most vertebrates (animals with a backbone, such as fishes, dogs and humans).

A Centralized Nervous System

With its front-facing brain, the nervous system of a worm and other front–back animals differs from that of a radial jellyfish is another important way: it has become centralized. Instead of a mesh of nerve cells spreading through the body, nerve cells are concentrated not only into a brain, but also in its conduits. Running down the length of the body, from brain to rear, are solid cords of nerve cells. The simplest worms have two or more cords, but in more complex animals there is a single cord. The brain and cord (or cords) make up the animal's central nervous system (CNS). All along the CNS, finer branches, called nerves, extend out from the brain and cord to penetrate, or innervate, the rest of the body. These nerves carry signals from the body's sensors into the CNS, as well as other signals coming away from the CNS towards the muscles. Altogether, the nerves make up the peripheral nervous system (PNS). The job of the CNS is to control and coordinate these signals as they pass from sensors to muscle. The brain contains more nerve cells with more complex interconnections, so it plays a bigger role in this process than the cords.

In invertebrates such as insects the nerve cord runs down through the underside of the animal, from its head, through the belly beneath its guts and other major soft organs, right to its rear end. By contrast, in the bodies of vertebrates – animals with a backbone (fishes, amphibians, reptiles, birds and mammals) – the single cord runs down the back. The entire CNS of a vertebrate animal is protected within parts of the hard skeleton. The brain is encased in the skull, while the cord is encased in the spine. This is why the cord of backboned animals is properly called the "spinal cord".



The nervous system of animals with front and back ends, such as this flatworm, is centralized, with the brain in the head and one or more nerve cords running down the length of the body. Branches from this central nervous system are nerves of the peripheral nervous system.

What Can Complex Brains Do?

In the most complex animal brains, including ours, there is far more going on than automatically coordinating responses to incoming information. Certainly, the most vital processes of life, such as heartbeat or breathing, are rigidly controlled in this way, but brains have "higher" centres too that make our behaviour much more complicated than that. Bigger brains with more neurons are better at storing memories, while their processing powers help with decision-making so that responses are not always fixed and automatic. In short, brains help animals solve problems, such as "where is the best place to find food in this forest?" or "what is the answer to this exam question?" The most complex brains of all – the brains inside the heads of humans and our closest living relatives – also produce sensations such as pleasure and fear. This means that the brainiest creatures experience emotions and even have individual personalities. How the brain does all these things is a big part of this book.


After collecting nectar, bees return to their hives and tell other bees where the flowers are by performing a "waggle dance". The dance communicates the direction and distance to the flowers. These are complex behaviours, but it appears that the bees have little choice but to perform them.

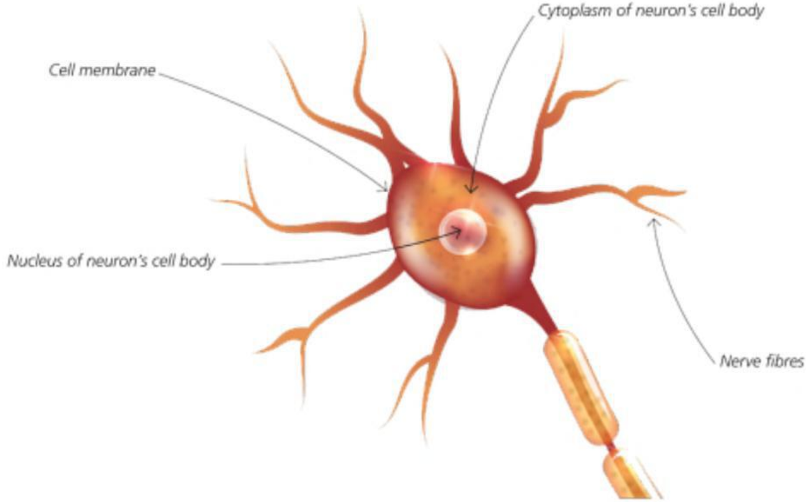
Chapter 2
HOW NERVE CELLS WORK

Nerve Cells

The nervous system is made up of microscopic nerve cells called neurons. We can only properly understand how the nervous system works by taking a closer look at the workings of these individual cells.

Practically every part of a living body is made up of microscopic cells, and the brain is packed with more than most: there are about 100 billion of them in an adult human brain. Its neurons work by passing on signals, but that is only part of the story. The incredible complexity of a brain, allowing it to react to stimuli, store memories, make us feel emotions and give us a sense of "self", ultimately comes down to the bioelectric activity of its cells and how they communicate with one another.

All animal cells contain the same kinds of components. Each one is filled with a runny jelly-like cytoplasm that is bound on the outside by a very thin layer called the cell membrane. Inside the cytoplasm, most kinds of cell have a nucleus, which contains DNA, the cells' genetic material. Inherited through generations, DNA controls what cells and bodies do and how they develop. But the fate of every cell inside the body is also determined by the conditions it is exposed to in its surroundings. In this way, cells become specialized in what they do as the body develops. The brain cells of a human are human because of their DNA, and they control distinctly human-like behaviour. But they are also bathed in chemicals that can affect how you feel. By looking at the shape, structure and workings of these cells, we can begin to understand the capabilities of the brain.



A typical multi-fibre neuron consists of a central cell body that contains most of the components needed to keep the cell alive (such as its nucleus) and an array of nerve fibres.

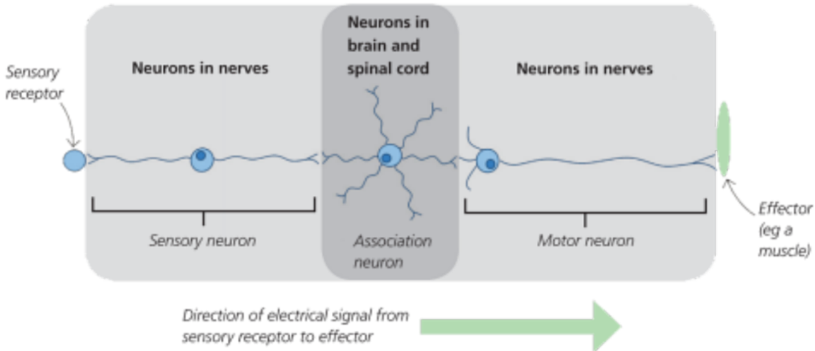
Parts of a Neuron

The most prominent feature of a neuron (nerve cell) is its arrangement of long, thin fibres. A neuron looks as though someone has taken an ordinary-looking cell and pulled points of its cytoplasm out into very long spindly threads. As a result, a neuron consists of a cell body that contains the nucleus and other essential structures, and an attached arrangement of thread-like nerve fibres.

Each thread is still bound by the oily cell membrane (something that is especially important, as we shall see), so the oily surface of a typical neuron is very big indeed. The fibres of some kinds of neurons can be a phenomenal length: the fibres of neurons running through our limbs can be more than 1 metre (3 ft) long.

Neurons are easily the longest kinds of cell in existence. The record-breaking fibres of a neuron serve an obvious purpose: they carry the bioelectric signals of the nervous system over long distances uninterrupted. This helps to explain why the nervous system can react so quickly to stimuli. But the arrangement of fibres also varies among neurons. Some have a single extra-long fibre with a cell body at one end. Others have two long fibres, with the cell body in the middle, or have a multitude of fibres. Nerve cells in the brain generally have the most fibres of all. Remarkably, each cell can have hundreds or even thousands of fibres radiating from a central cell body, ready to communicate with their neighbours.

In bright light, your pupils contract in a reflex action. Sensory neurons send a signal from the eye to the brain, which fires motor neurons to contract certain muscles in the iris.

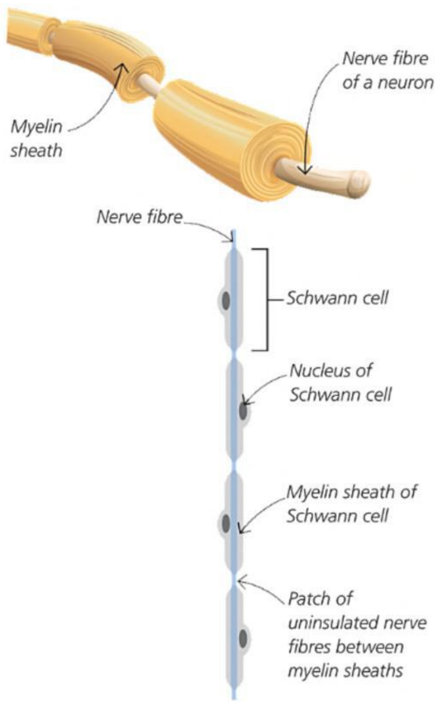


Sensory and motor neuron fibres occur in nerves of the peripheral nervous system. Associations neurons are found in the brain and spinal cord: the central nervous system.

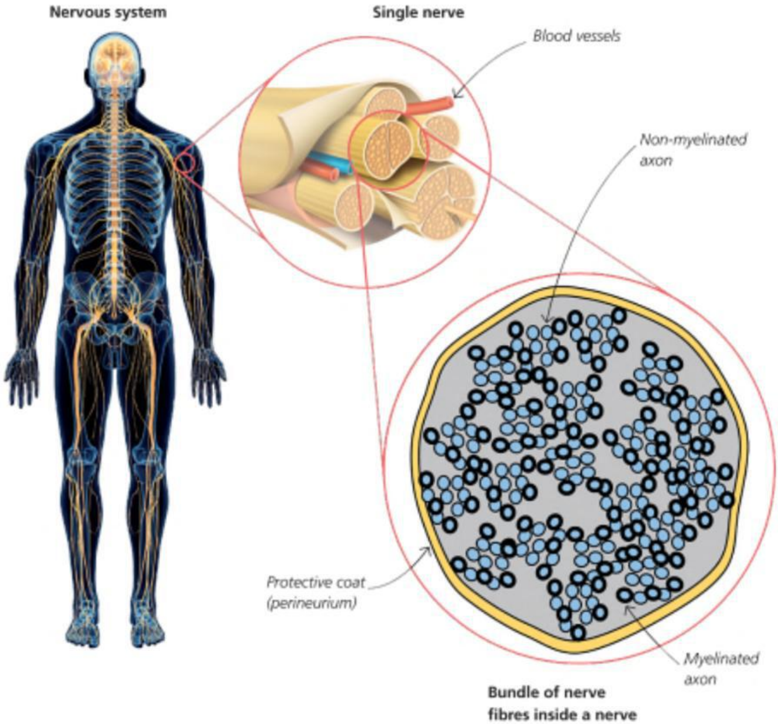
Insulated Neurons

Outside the brain and spinal cord, most of the long-distance signalling along nerve fibres is aided by a special feature that helps to speed up the transmission. Each fibre is enclosed in a glistening coat of fatty material called the myelin sheath. Electrical charges cannot easily pass through fat, which means that the myelin sheath serves to insulate the fibres, just like the plastic insulation that protects electrical wiring. In this way, the sheath stops the electrical charges from escaping from the fibres, ensuring that they are properly funnelled through the nervous circuitry. As we shall see, it also makes the signals move even faster in their passage between the CNS and sensors or muscles.

These insulated fibres are also found in parts of the central nervous system, where dense concentrations of myelin make the tissue look white and glistening, giving it its name "white matter". The parts of the CNS that are not myelinated are, instead, packed more with cell bodies. The tissue here looks darker and is called "grey matter".



Fatty layers of insulation are wrapped around many nerve fibres of the nervous system. The layers are formed from special supporting cells called Schwann cells that clasp the length of a nerve fibre, with small uninsulated spaces between them.



A nerve is an electrical cable containing bundles of microscopic nerve fibres called axons that carry electrical signals to and from the brain or spinal cord.

How Nerve Fibres are Arranged into Nerves

The longest nerve fibres of a neuron usually carry electrical signals away from the cell body. These are called axons. Bundles of axons are bound together inside thicker cables, which are the nerves. Each bundle is wrapped inside a protective coating and several such bundles are packed together along with blood vessels to make a single nerve. The blood vessels provide food and oxygen for the working neurons. Generating the electrical activity necessary for a nerve fibre to carry bioelectric signals demands a lot of energy. This is provided by energy-rich food, such as sugar, which releases energy in chemical processes that use oxygen, called respiration.

The body contains a fixed arrangement of nerves that is set in place during early development. Some nerves carry only fibres of sensory neurons or motor neurons, but others have a mixture of both. Most of the main nerves, called spinal nerves, emerge and branch from the spinal cord. But others, called cranial nerves, such as the optic nerves that link to the eye, connect directly with the brain.

comparison. Cell membranes contain special kinds of protein molecules that keep the membrane charged up by, for instance, pumping out more positive charge than they bring inside. But given that cells expend energy doing so, what purpose does it serve?

Many organisms use the charge difference across their membranes as a potential store of energy, a bit like a battery. By letting opposite charges flow through at discrete points, they can use them to do work. But for fast-reacting animals, charged cell membranes also do something else: they carry signals. And these signals form the basis of the entire nervous system, including the brain.

The fastest movements in the animal kingdom, such as that of a chameleon's tongue, are possible because of the rapid-firing electrical signals of neurons and muscle cells. These same signals are responsible for the fast-acting thought processes in the brain.

Excitable Cells

Signal-carrying animal cells include neurons and muscle cells. In neurons, the charged cell membranes send a signal from one end of the cell to the other. In muscle cells, as a signal is transmitted, this is accompanied by a twitching of the cell, making the muscle contract. In each case, the nature of the electrical charge is much the same.

Neurons and muscle cells perform their extraordinary feats because they are excitable. This means that their charges flip when they are stimulated, such as by touch or exposure to a chemical. The flip occurs because the stimulus affects the charge-generating proteins embedded in the cell membrane. These proteins are extraordinarily sensitive, and a slight disturbance will alter what they do. As a result, their usual routine, making positive charges flow out, is changed. Positive charges instead are blocked and accumulate on the inner surface of the membrane, and the charges are flipped around. A stimulus has made the inner surface positive and, in comparison, the outer surface negative.

The charge reversal doesn't stop there. The sensitive membrane proteins are scattered along the length of the cell, and this causes a domino effect. The charge reversal stimulates more proteins that are nearby, and very quickly the charge reversal zips right along the neuron from one end to another. In other words, the cell becomes "excited". In nerve fibres that are insulated with a myelin sheath, the charges are concentrated at the gaps, called "nodes", between one insulating Schwann cell and the next. This makes the signal "jump" from node to node to make things even faster. All this would be enough to explain the lightning-fast movements of any signal, but there is a problem. If the entire membrane suffers a reversal of charge in this way, surely that would block any further stimulus from having an effect? The nervous system has an answer to this problem: the membrane proteins can recover their original state.

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