

a biofilm, bacteria stick to one another and to the underlying surface and keep in contact with other bacteria using quorum sensing. As part of a biofilm, bacteria act together so they can resist the body's immune system and antibiotics. If the bacteria accumulate in large numbers, for example at the site of a wound, they communicate and can become more mobile and more virulent.

Another species of bacteria that can form biofilms is *Staphylococcus aureus* (Figure 7.1.2). These bacterial biofilms can colonise equipment such as catheters in hospitals and cause serious infections.

Biofilms can contain more than one species of bacteria that live together. Quorum sensing plays an important role in the formation, maintenance and breakdown of biofilms like these.

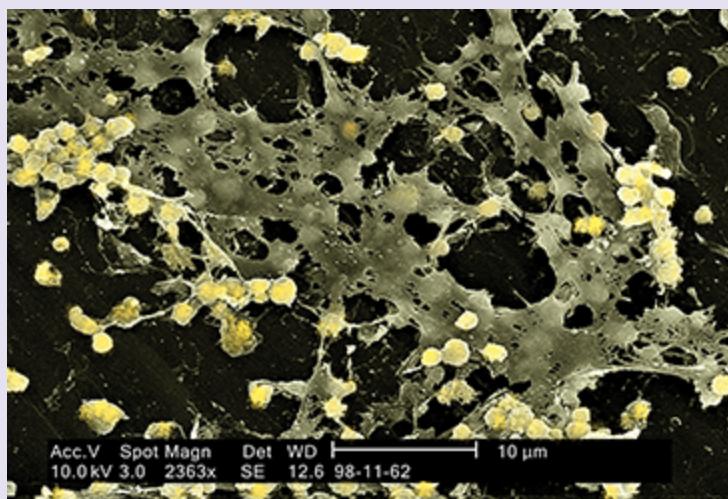


Figure 7.1.2: *S. aureus* biofilm.

7.1.3 Cell signalling in multicellular organisms

Cell signalling is vital to multicellular organisms. It means that they can coordinate the activities of their cells, tissues and organs so that the body works efficiently. Movement, growth, reproduction and homeostasis all happen because of cell signalling as one cell or group of cells influences the activities of others.

Emergent properties

One person playing the flute can produce a simple, recognisable tune but if several musicians with other instruments join in and play together as a group, they produce a wide variety of sounds and many different effects. New properties emerge in the cells of multicellular organisms in a similar way. Their cellular components interact so that the organism can carry out a range of more complicated functions. One cell can function on its own, but with other cells in a group, it can produce tissues and organs that carry out a range of roles in the organism. For example, lungs are made of many cells it is only when all these cells work as a unit that the lungs are able to perform their function. Cells form tissues, tissues form organs, organs form organ systems and organ systems work in synergy so that the whole organism can carry out a complex range of tasks and is greater than the composition of its parts.

Methods of communication

Cells use different substances including ions, neurotransmitters and hormones to communicate with one another (Table 7.1.1). These molecules move down concentration gradients either

within a cell or between one cell and another (Figure 7.1.1). Once a cell has received it, a messenger molecule is processed and the appropriate response can take place. Hormones are a diverse group of molecules that act as chemical messengers for cell signalling. Animal hormones circulate in the blood to reach specific target cells. Ions such as sodium and potassium are important in the transmission of nerve impulses and move in and out of nerve cells. Most animals have nervous systems consisting of nerve cells that transmit electrical impulses when ions cross their membranes. Neurotransmitter molecules enable nerve cells to communicate with other nearby nerve cells. You can read more about the transmission of nerve impulses in [Section 7.2](#) and more about the action of hormones in [Section 7.3](#).

Substance	Example	Method of movement	Action in communication
neurotransmitter	acetylcholine	diffuses between adjacent cells	enables synaptic signalling between different nerve cells
ions	sodium and potassium ions	diffuse down concentration gradients or are pumped into cells	maintains the action potential in nerve cells so that electrical messages can be transmitted
hormone	insulin, glucagon	carried in the bloodstream from the site	enables endocrine signalling

		of production to target cells	between cells that are not close together
cytokines	chemokines, interferon	small peptides that cannot cross the membrane and act through cell surface receptors	regulate humoral and cell-based immune responses, and maturation and growth of some cells

Table 7.1.1: Different molecules enable cells to communicate using electrical and chemical signalling.

THEORY OF KNOWLEDGE

The systems approach

A system is defined as an assemblage of parts and the relationships between them. This makeup enables a system to work together as a functioning whole. The systems approach has long been used in engineering but for many years natural systems were examined from a reductionist point of view. We can see how the two approaches differ if we consider the study of a pond. A reductionist study of the pond would describe the organisms found there in terms of their features and characteristics; for example, whether they are vertebrates or invertebrates, plant or animal. But a reductionist study would not try to consider how the pond worked as a dynamic system.

A systems approach would take a holistic view of the pond that considers interrelationships such as food chains and nutrient cycling that occur between the various components of the pond. In this way a picture of the interdependence of the different parts of the pond – that is, the system's structure – could be built up.

In a study of cells and their components, the systems approach would consider a single cell in terms of the flows of energy and materials between the various structures within it. On a larger scale, groups of cells, an organ or even a whole organism can be studied using the systems approach so that the parts and the interactions between them can be viewed as a complete functioning entity. Emergent properties in any system can only be studied by means of a systems approach.

To consider:

- 1 What are the advantages and disadvantages of the systems approach compared with the reductionist approach to the study of cells and cell signalling?
- 2 In science, the reductionist and systems approach may use similar methods of study. What is the most important difference between the philosophies of the two approaches?

Signal transduction pathways

As we have seen, cells respond to signals from their environment through a process known as cell signalling. A signal is transmitted when a signalling molecule called a ligand binds to a receptor protein in the target cell.

This signal leads to a specific cellular response such as cell division, release or absorption of a substance or even cell death.

As signalling chemicals (ligands), bind to receptor sites, there are several possible outcomes which depend on the type of receptor and type of signalling molecule that is involved. The receptors involved in cell signalling can be broadly classified into two types: **cell-surface receptors** and **intracellular receptors**.

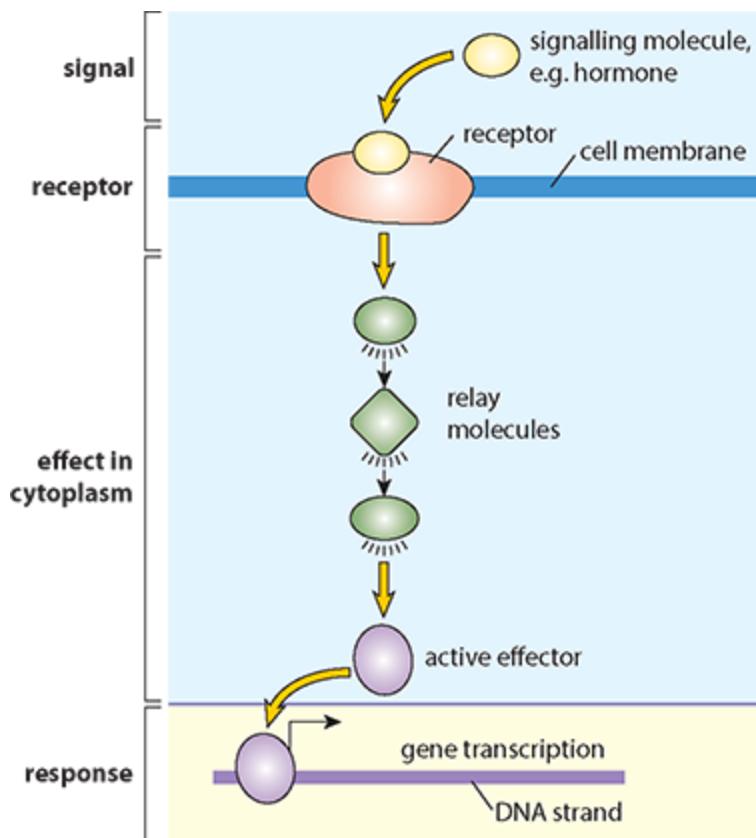


Figure 7.1.3: Some signalling molecules do not enter cells but stimulate reactions inside them.

Cell-surface receptors (transmembrane receptors) are integral to the plasma membrane with each receptor having an extracellular, transmembrane region and a part of their molecule in the

cytoplasm. When a ligand binds to a cell-surface receptor, extracellular signals are transformed into intracellular signals in a process called **signal transduction**.

Intracellular receptors (also known as internal receptors) are globular proteins that are found inside the cell not in the cell membrane.

If receptors are located on the cell membrane, the signal must be passed on through chains of molecules that make up **intracellular signal transduction pathways**.

As a signalling molecule binds to a cell-surface receptor, the receptor changes shape. This may let it bond to other molecules or give it enzyme activity. Changes in the receptor set off a series of signals inside the cell. For example, the receptor may turn on another signalling molecule in the cell which can then activate its own target. The chain of reactions can lead to changes in cell activity or characteristics (Figures 7.1.3, 7.3.5 and 6).

Transmembrane protein receptors and their effects include:

- **G protein coupled receptors.** These are integral membrane proteins that are used by cells to convert extracellular signals into intracellular responses, including responses to some hormones, neurotransmitters, as well as responses to vision, olfaction and taste signals. One example is the receptor for the neurotransmitter acetylcholine, a membrane bound protein that changes shape to regulate the opening of the ion channels that allow positively charged ions to diffuse into nerve cells ([Section 7.2](#))

- **G protein and cyclic AMP.** cAMP (cyclic adenosine monophosphate) is a second messenger inside cells and this system is co-ordinates the body's response to the hormone epinephrine (adrenaline). cAMP is a small molecule made from ATP. In response to signals, an enzyme converts ATP into cAMP which can then activate an enzyme called protein kinase. Kinase goes on to phosphorylate target molecules and pass along the signal. Protein kinase is found in a variety of types of cells, and it has different target proteins in each. This allows cAMP second messenger to produce different responses in different cells.
- **Receptors with tyrosine kinase activity.** These receptors mediate the cells' responses to the protein hormone insulin, as well as many other hormones. As insulin binds to a receptor, tyrosine inside the cell is phosphorylated. Phosphate groups are linked to this amino acid which has a hydroxyl (-OH) group in its side chains. The transfer of the phosphate group is catalysed by an enzyme called a kinase. Phosphorylation switches on a series of reactions which cause vesicles containing glucose transporters (carriers) to move to the plasma membrane.

Intracellular receptors and their effects

Intracellular receptors are activated by signals (ligands) that can pass through the plasma membrane. Ligands are usually small, hydrophobic and non polar. The group includes receptors for steroid hormones such as oestradiol, which stimulates the hypothalamus to secrete GnRH, progesterone that targets cells of the endometrium (Ch 8), as well as testosterone and fat-soluble vitamins such as vitamin D. Steroid hormone receptors are structurally similar and work in similar ways. Unlike cell-surface receptors, ligands that bind to intracellular receptors can

easily diffuse across the plasma membrane so they do not need to transmit the signal to other receptors or messengers. They directly activate the intracellular receptor and as the receptors are stimulated, they bind to DNA and affect the transcription of certain genes.

Intracellular receptors share similar features because they work in similar ways. Most have three areas on their molecules: a ligand-binding area, a DNA-binding area, and a transcription-activating area.

Figure 7.1.3 shows how a peptide hormone affects the actions of its target cell in animals. This type of hormone does not enter cells but causes a response. It stimulates receptor molecules on the membrane that trigger a response inside the cell. Other steroid hormones do enter cells to bring about a response. You can read more about hormones in [Section 7.3](#).

Regulating signalling pathways

Cell signalling pathways may be regulated either by a positive feedback mechanism or by negative feedback. Positive feedback occurs to increase the change that takes place so that it happens more quickly. Negative feedback occurs to reduce the change, so the result of a reaction is reduced and the system returns to a stable state.

As you read about the hormone insulin ([Section 7.3](#)), notice that it works by negative feedback. When blood glucose levels rise, more insulin is released, and works to lower blood glucose, as this happens and glucose levels return to normal, insulin release is switched off. Thermoregulation (control of body temperature) and osmoregulation (control of body water levels) are also controlled by negative feedback.

Positive feedback is less common in biological systems but two examples of processes that have positive feedback are childbirth and lactation. During childbirth stretching of uterus walls causes contractions that stimulate the release of the hormone oxytocin. This hormone stimulates further contraction of the walls until the baby is born. During lactation, the hormone prolactin stimulates milk production and as the baby suckles more prolactin is released and causes further milk production. This continues until the baby is weaned and stops feeding on milk. You can read about these processes in [Chapter 8](#).

Phytohormones (plant growth regulators)

Plants produce growth regulator molecules, which act as signalling substances. These are sometimes called plant hormones or phytohormones, but they are different from animal hormones in structure and the way they work. Plant growth regulators are produced in very low concentrations but they control all aspects of plant growth and development, from embryogenesis, the sizes of different tissues and defence against disease to reproduction. You can read more about these substances in [Section 7.3](#).

TEST YOUR UNDERSTANDING

- 1** List three substances that may act as cell signalling molecules.
- 2** Explain what is meant by the term ‘emergent properties’.
- 3** Outline the importance of cell signalling to multicellular organisms.
- 4** Give an example of a negative feedback effect in cell signalling.

5 Name a ligand that binds to an intracellular receptor.

Link

- What are other advantages of being multicellular? (Chapter 8.1)

7.2 Neural signalling

LEARNING OBJECTIVES

In this section you will:

- recognise that animals have a nervous system consisting of cells called neurons that transmit electrical impulses
- understand that the brain integrates and co-ordinates information
- recognise that the spinal cord integrates unconscious processes
- describe the structure of a typical sensory neuron and a typical motor neuron
- learn that many nerve fibres are covered with myelin sheaths
- learn that sodium and potassium ions are pumped across the membranes of neurons to generate a resting potential
- understand that an action potential consists of the rapid depolarisation and repolarisation of the neuron membrane
- recognise that nerve impulses are action potentials that are propagated along the axons of neurons
- discover that a nerve impulse is transmitted as a result of local currents that cause each successive part of the axon to reach the threshold potential

- define a synapse as the junction between two neurons or between neurons and receptor or effector cells
- understand that pre-synaptic neurons release a neurotransmitter into the synapse when they are depolarised
- learn that cholinergic synapses use acetylcholine as their neurotransmitter, which is the most common neurotransmitter in vertebrates and invertebrates
 - recognise that neonicotinoid pesticides block synaptic transmission in insects
 - discover that the speed of transmission of action potentials is increased by myelination, saltatory conduction and increased diameter of axons
 - recognise that depolarisation and repolarisation occur during action potentials
 - understand that local currents propagate an action potential along a nerve fibre
 - learn that myelinated fibres have gated and non-gated ion channels at the nodes of Ranvier
 - discover that neurotransmitters can be excitatory or inhibitory and that initiation or inhibition of an action potential results from summation of the two
 - learn that drugs and other chemicals can stimulate or depress post-synaptic transmission

- understand that free nerve endings in the skin send pain messages to the brain
- discover that consciousness is a consequence of nerve interactions in the brain

GUIDING QUESTIONS

How does the nervous system of animals rely on electrical and chemical signals?

Most animals have nervous systems consisting of nerve cells called neurons. They transmit signals in the form of nerve impulses from one part of the body to another. In the human body there are about 85 billion neurons but a simple animal such as *Hydra* has only about 6000. Nervous systems have evolved to receive sensory inputs, integrate them and send out motor signals. A nervous system allows animals to perceive signals from its environment and to respond to them in a number of different ways such as moving in an organised way.

7.2.1 The structure of nervous systems

Most animals have nervous systems consisting of nerve cells called neurons that transmit electrical nerve impulses through their bodies. The simplest, sedentary multicellular animals, the sponges (Porifera), do not have nerves but simple cnidarians such as *Hydra* have a nerve net that runs throughout their body (Figure 7.2.1). More active invertebrates such as arthropods have a concentration of neurons in the head and these coordinate signals from the animal's body so that it can move and respond to stimuli in an organised way.

The human nervous system is more complex: it consists of a central nervous system, or CNS, is made up of the neurons of the brain and the spinal cord. The CNS receives information from sensory receptors all over the body. Information is processed and interpreted before the CNS initiates suitable responses.

The peripheral nerves are the networks of neurons that carry information to and from the CNS. Peripheral nerves include sensory neurons, which carry information to the CNS, and motor neurons, which transmit impulses from the CNS to muscles and glands that then cause a response.

The brain processes information that it receives from all the peripheral nerves. Different parts of the brain are responsible for different functions, the cerebral hemispheres co-ordinate learning, memory, language, speech and reasoning, while the cerebellum co-ordinates movement posture and balance. The hypothalamus in the centre of the brain (Figure 7.2.3) co-ordinates the endocrine and nervous system by regulating the secretions of the pituitary gland which lies just underneath it. The medulla oblongata (brain stem) controls automatic and

homeostatic activity such as breathing swallowing, digestion and heart rate (see [Chapter 9](#)).

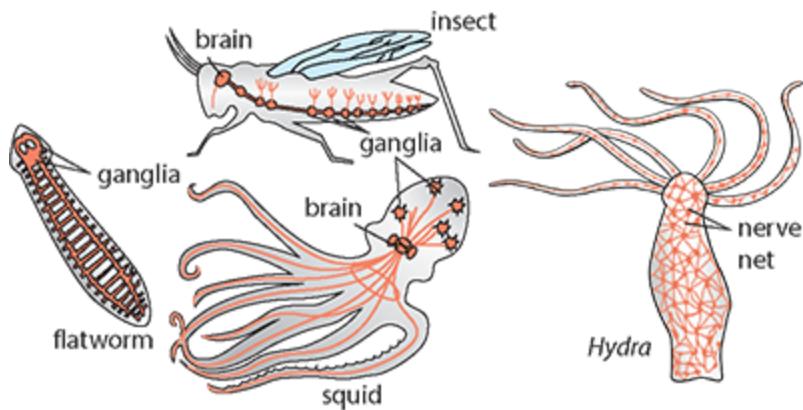


Figure 7.2.1: Examples of invertebrates with nervous systems include simple cnidarians such as *Hydra*, molluscs such as squid, and arthropods such as insects.

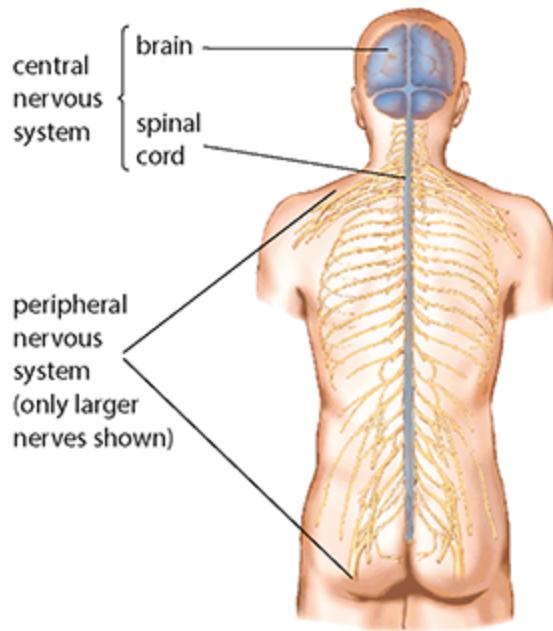


Figure 7.2.2: The human nervous system.

The spinal cord integrates unconscious processes which are those that take place without us thinking about them. Reflex actions such as the knee jerk reflex that contracts the muscles in the leg when the tendon below the knee cap is tapped, are co-ordinated by the spinal cord which receives and transmits messages to make the leg kick out.

Conscious actions are those which we are aware of, they require us to think or consider our actions and to make intentional responses to a situation. Conscious actions are coordinated by the brain.

Consciousness is a feature of the human brain which results from the interaction of many individual neurons in the brain. It is another example of an emergent property which is a consequence of interactions of different cells and chemicals in the brain.

You can read more about voluntary and involuntary control of actions in [Chapter 9](#). Fig 9.1.5 shows the relationship between the different parts of the nervous system that are involved.

Three types of neuron are found in the nervous system. **Sensory neurons** and **motor neurons** transmit information to and from the CNS, while **relay neurons** within the CNS form connections between them.

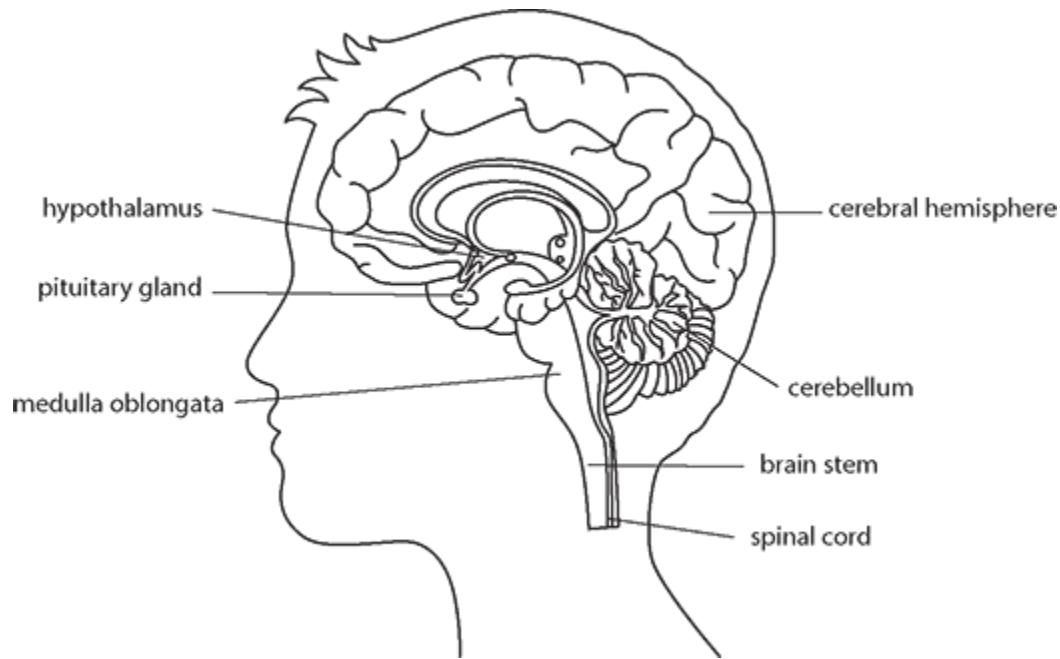


Figure 7.2.3: The human brain

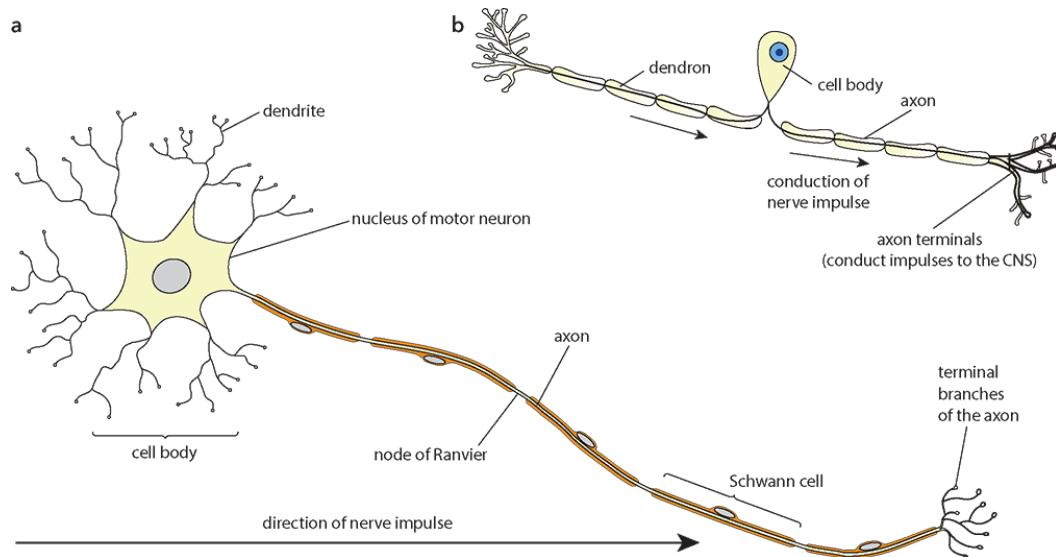


Figure 7.2.4: a A motor neuron. b A sensory neuron.

The structure of a typical motor neuron is shown in Figure 7.2.4a and a typical sensory neuron in Figure 7.2.4b. In motor neuron many small dendrites receive information from relay neurons and transmit the impulses to the cell body. One long axon then carries

impulses away. The cell body contains the nucleus and most of the cytoplasm of the cell. The axon is covered by a myelin sheath formed from Schwann cells, which wrap themselves around it. Myelin has a high lipid content and forms an electrical insulation layer that speeds the transmission of impulses along the axon.

7.2.2 Transmission of nerve impulses

Resting potential

Neurons transmit information in the form of impulses, which are short-lived changes in electrical potential across the membrane of a neuron. All neurons contain sodium (Na^+) and potassium (K^+) ions. Impulses occur as these important ions move in and out through the plasma membrane.

When a neuron is not transmitting an impulse, it is said to be at its **resting potential**. The resting potential is the potential difference across the plasma membrane when it is not being stimulated: for most neurons, this potential is -70 mV . The inside of the axon is negatively charged with respect to the outside (Figure 7.2.5).

As a nerve impulse occurs, the distribution of charge across the membrane is reversed. For a millisecond, the membrane is said to be **depolarised**. As charge is reversed in one area of the axon, local currents depolarise the next region so that the impulse spreads along the axon (Figure 7.2.6). An impulse that travels in this way is known as an action potential.

Action potential

KEY POINT

action potential is the reversal (depolarisation) and restoration (repolarisation) of the resting potential across the plasma membrane of a neuron as an electrical impulse passes along it.

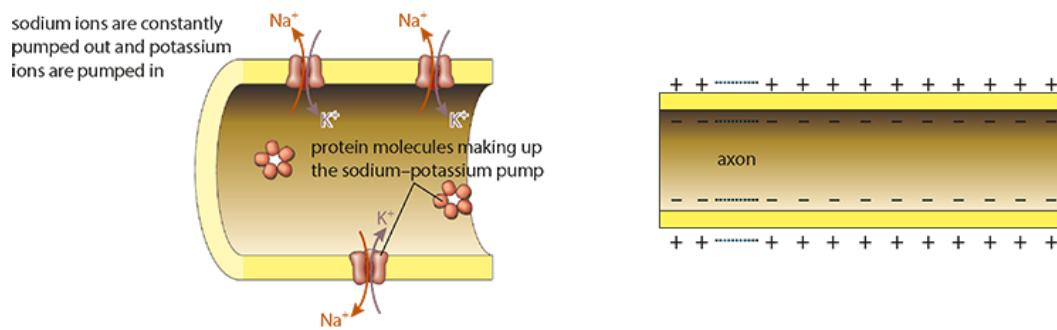


Figure 7.2.5: At rest, sodium ions are pumped out of the neuron and potassium ions are pumped in, to establish and maintain the resting potential. (You can read more about the sodium–potassium pump in [Section 6.2](#).) Inside the neuron is negatively charged because of the presence of chloride and other negative ions.

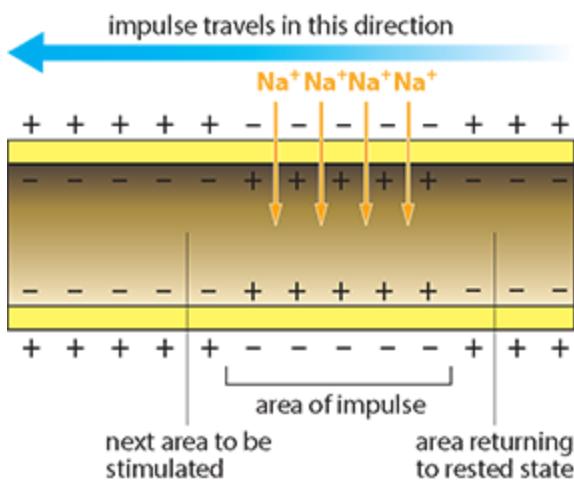


Figure 7.2.6: When an impulse passes along the neuron, sodium ions diffuse via ion channels and the potential is reversed. This process is called an action potential (only a small part of a long neuron is shown).

Figure 7.2.7 shows what is happening at the plasma membrane of the neuron as an action potential is generated. Nerve impulses are action potentials that travel along neurons due to sodium and

potassium ions moving down electrochemical gradients to create local currents.

- 1 When a neuron is stimulated, gated sodium channels in the membrane open and sodium ions (Na^+) from the outside flow in. They follow both the electrical gradient and the concentration gradient, together known as the electrochemical gradient, to move into the cell. The neuron is now said to be depolarised.
- 2 For a very brief period of time, the inside of the axon becomes positively charged with respect to the outside as sodium ions enter. At this point, the sodium channels close.

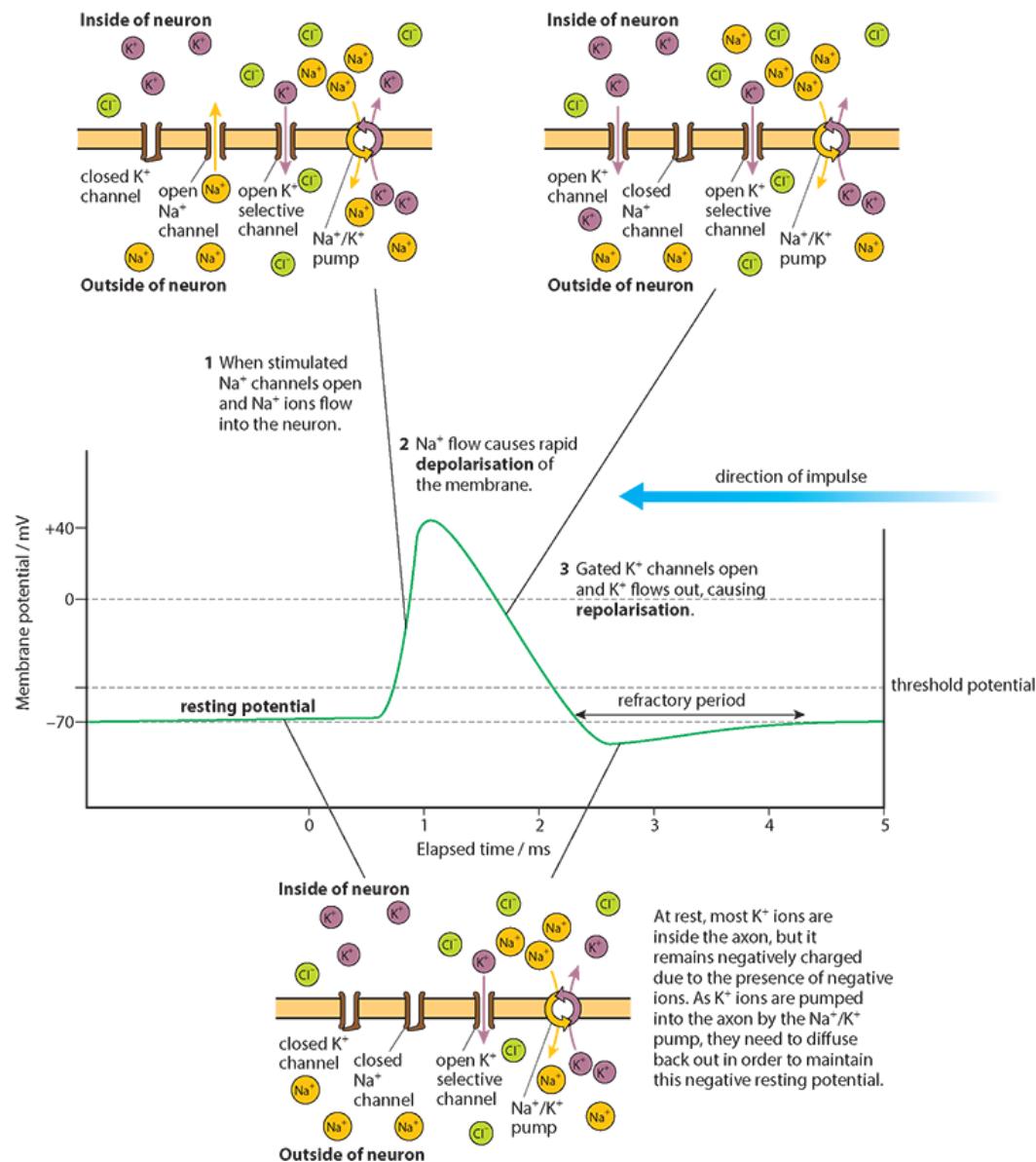


Figure 7.2.7: The action potential.

- 3 Now, gated potassium channels open and potassium ions (K⁺) begin to leave the axon, moving down their electrochemical gradient to re-establish the resting potential, a process known as **repolarisation**.
- 4 Because so many potassium ions start to move, the potential difference falls below the resting potential. At this point,

both sodium and potassium channels close. The resting potential is re-established by the action of sodium–potassium pumps, which move ions back across the membrane.

An action potential in one part of an axon causes the **depolarisation** of the adjacent section of the axon. It occurs because local currents are set up between adjacent regions and these cause ion channels to open, allowing sodium ions in and potassium ions out of the axon. When this happens, each successive part of the axon reaches its threshold potential and becomes depolarised.

KEY POINT

threshold potential the electrical potential across the plasma membrane of a neuron that is required to trigger an action potential.

The action potential travels along the neuron in a cascade, rather like a ‘Mexican wave’. The impulse can only pass in one direction because the region behind it is still in the recovery phase of the action potential and is temporarily unable to generate a new action potential. The recovery phase is known as the **refractory period**.

The speed of conduction along an axon is affected by the diameter of the axon. A larger diameter means faster conduction. Larger axons are myelinated while smaller ones are not. At intervals along myelinated axons are gaps between the myelin covering known as nodes of Ranvier (Figure 7.2.4a). The sheath prevents the flow of ions across the membrane so the current must jump from node to node that speeds up the transmission of the nerve impulse.

Analysing oscilloscope traces

The potential of membranes in neurons can be measured using electrodes on each side of the membrane. The potentials can be shown as a graph or trace on an oscilloscope (a device that displays varying voltages as graphs) as shown in Figure 7.2.8. At rest, the trace shows a potential of -70 mV but as an action potential occurs the trace has a spike. The rising and falling of the line indicates the depolarisation and repolarisation of the membrane. The repolarisation does not return the membrane to its original resting potential immediately: there is a short delay, or refractory period, before it finally returns to -70 mV. Note that the resting potential is not -70 mV for all neurons in all species.

Figure 7.2.8 shows a trace taken from a mouse neuron after it had been stimulated with a small pulse of current.

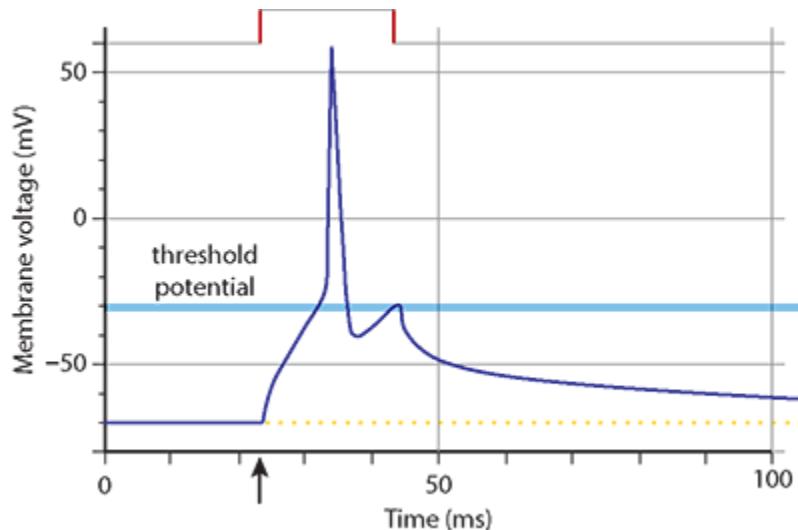


Figure 7.2.8: Action potential of a mouse neuron.

TEST YOUR UNDERSTANDING

- 6 State the resting potential of this neuron.

- 7** Work out the time taken for depolarisation and repolarisation shown on this trace.
- 8** Why does the membrane potential rise for a short time at the end of the repolarisation phase?

7.2.3 Synapses and synaptic transmission

A **synapse** is the place where two neurons meet or where a neuron meets a receptor cell (such as a touch receptor in the skin) or effector cell (such as a muscle cell). Neurons do not touch one another and the tiny gap of about 20 nm between them is known as the **synaptic cleft**. Action potentials must be transmitted across this gap for the impulse to pass on its way. This is achieved by the presence of chemicals known as **neurotransmitters**. Neurotransmitters are held in vesicles in the pre-synaptic cell until an action potential arrives. They are then released into the synaptic cleft, and diffuse across to the post-synaptic membrane. There they can cause another action potential to be produced and a nerve impulse to be initiated, provided the threshold potential is reached.

SCIENCE IN CONTEXT

Multiple sclerosis

Multiple sclerosis (or MS) is a neurological condition that affects the brain and spinal cord. It causes problems with vision, movement and balance. It is an autoimmune condition, which means that the body's own immune system begins to attack a healthy part of the body. In MS, the immune system attacks the myelin covering of neurons. The myelin becomes scarred and damaged so that messages travelling along the neurons are slowed down or disrupted (Figure 7.2.9). MS is usually diagnosed when people are in their 20s and 30s and it is twice as common in females than males. The causes of MS are not fully understood, but are probably a combination of genetic and environmental factors.

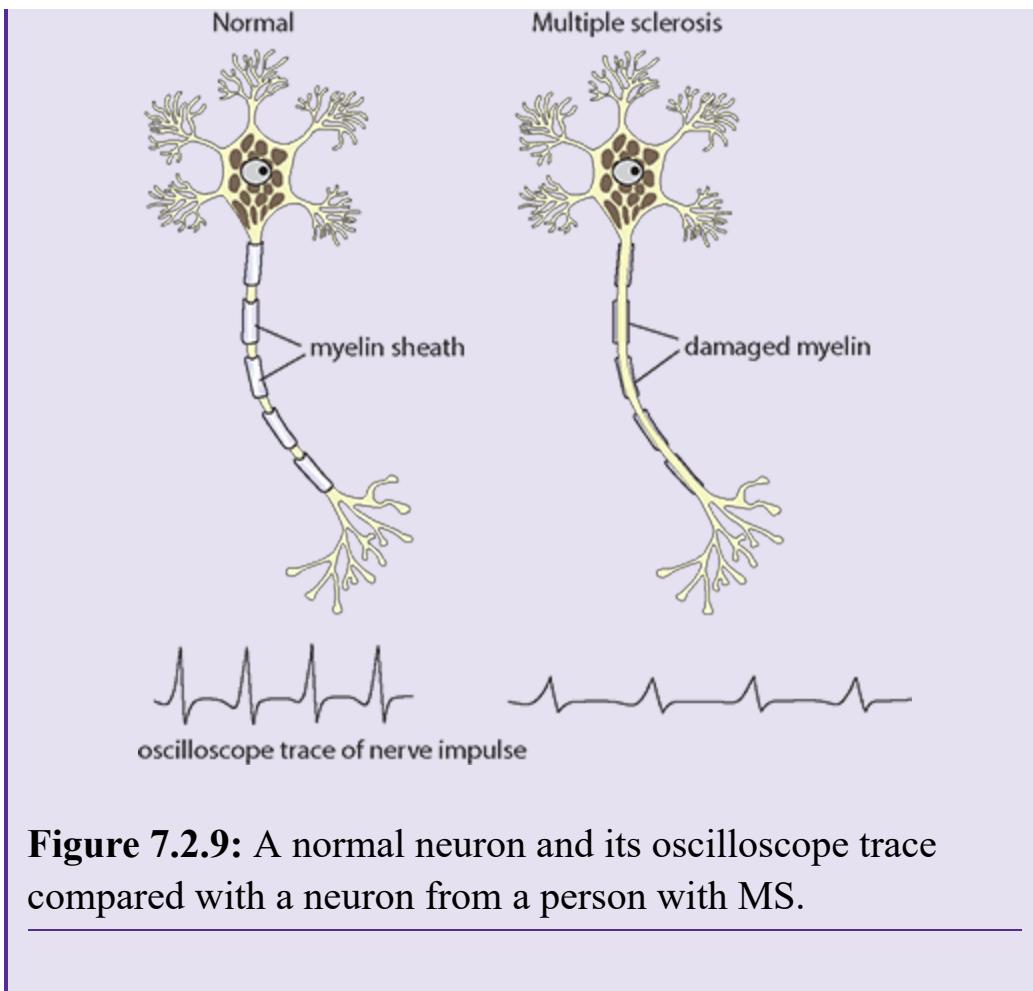


Figure 7.2.9: A normal neuron and its oscilloscope trace compared with a neuron from a person with MS.

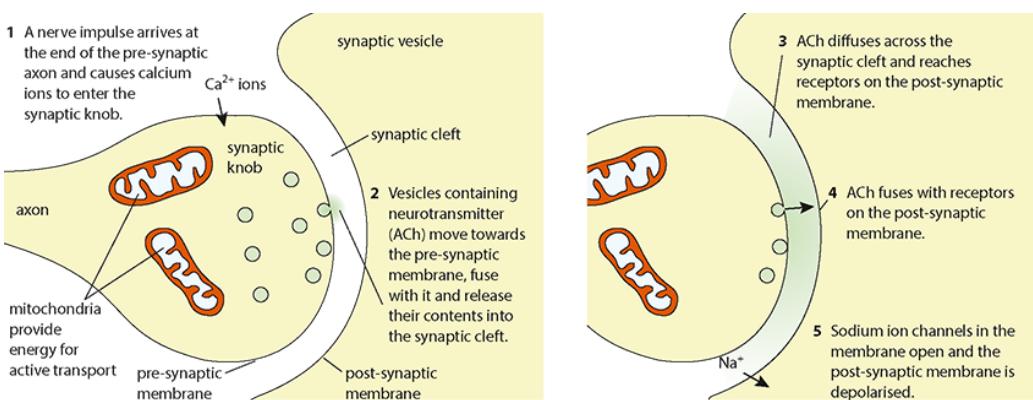


Figure 7.2.10: A cholinergic synapse. The whole sequence of events of transmission at a synapse takes 5–10 ms.

The synapse shown in Figure 7.2.10 uses the neurotransmitter acetylcholine (ACh) and so is known as a cholinergic synapse.

ACh binds to receptors and causes depolarisation of the post-synaptic membrane and the initiation of an action potential. Once an action potential is generated in the post-synaptic membrane, ACh in the synaptic cleft is deactivated by acetylcholinesterase enzymes and the products are reabsorbed by the pre-synaptic membrane to be remade and repackaged in vesicles.

Acetylcholine is the most common neurotransmitter in both invertebrates and vertebrates. It is used at many synapses including those between neurons and muscle fibres. In the human body there are more than 40 different neurotransmitters. Acetylcholine and norepinephrine (also called noradrenaline) are found throughout the nervous system, others (for example, dopamine) are found only in the brain.

Neonicotinoids are chemical pesticides used in insecticides. They are similar in structure to nicotine and block transmission at the synapses of insects by binding to acetylcholine receptors. Neonicotinoid pesticides have been linked to the decline of bee populations throughout the world. In 2013, the European Food Safety Authority declared that these insecticides pose an unacceptably high risk to bees and the European Commission imposed restrictions on their use. In 2018 three main types of the pesticide were banned for all outdoor uses. In the USA the Environmental Protection Agency (US EPA) has also taken steps to reduce the use of neonicotinoids. In 2019 it revoked permissions for the use of several pesticides containing them.

SCIENCE IN CONTEXT

Botox

A neurotoxin produced by the bacterium *Clostridium botulinum* is one of the most toxic substances known.

Nevertheless it has been used in recent years for cosmetic and medical procedures under the trade name Botox. In the early 1980s, it was used to treat muscle spasm, strabismus (squint) and uncontrollable blinking. More recently it has been used to induce temporary muscle paralysis and conceal the appearance of wrinkles.

TEST YOUR UNDERSTANDING

- 9** Explain how sodium and potassium ions establish a resting potential.
- 10** Define the term ‘action potential’.
- 11** Name the substance released by a pre-synaptic membrane.
- 12** List the key events of synaptic transmission.

THEORY OF KNOWLEDGE

How can we test the accuracy of scientific knowledge?

If you wanted to carry out an experiment to verify the information you have been given about neural transmission you could plan to carry out an experiment to gather evidence. It might seem a good idea to observe results first hand for yourself. But this is not easy. You would need special equipment, you would need to take precautions to make sure any experiment was reliable and ethical. You would also need to be completely familiar with concepts such as potential difference and depolarisation.

Gathering knowledge depends on methods that have been used before. Science uses methods to collect information

using observations that limit the number of variables. This allows us to draw conclusions that are as clear as possible based on the abilities we have to see, recognise and understand them.

We can gain, evaluate and produce knowledge for ourselves but we should be aware that other people have the same ‘tools’ for understanding as we do and have used them in the past; so sharing knowledge and understanding is possible and valid. We do not have to repeat every experiment to be sure of its validity.

7.2.4 Myelination of nerve fibres

Speed of transmission of impulses

Action potentials travel along nerve fibres as ions cross the neural membrane. Positive sodium ions enter the neuron and trigger the opening of channels at the start of an axon; this lets in additional positive ions. These positive ions trigger the channels next to them, which let in further positive ions and so on, creating the action potential. The speed of transmission of an impulse is affected by both the diameter of the axon and whether or not it is myelinated.

Axons with a larger diameter can conduct impulses faster than smaller ones because of their lower surface area to volume ratio. Leakage of ions through the membrane is less of a problem in larger axons.

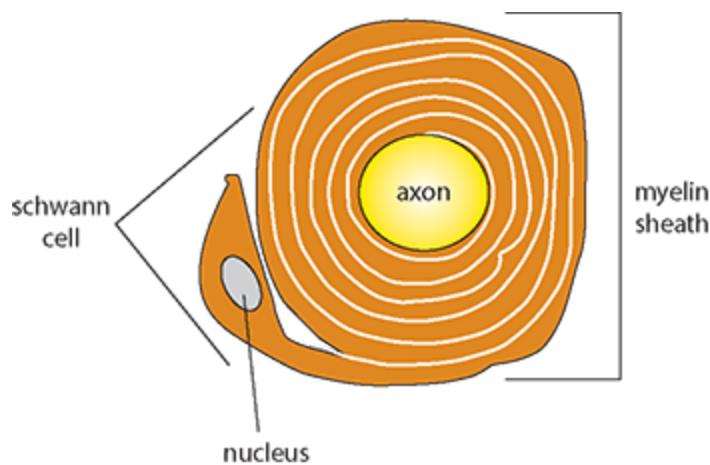


Figure 7.2.11: Schwann cells wrap axons in an insulating layer of myelin.

The rate of transmission of action potentials in an axon is also speeded up if the axon is wrapped in myelin, a fatty material

found in Schwann cell membranes (Figures 7.2.4 and 7.2.11). Schwann cells wrap around axons and create an insulating layer. The presence of myelin prevents ions being lost across cell membranes and maintains the action potential so that the speed of transmission of an impulse is about ten times faster in a myelinated axon than an unmyelinated one.

The reason for the increase in speed is that the process of generating an action potential only takes place at specific points, the nodes of Ranvier (Figure 7.2.4a), where there are gaps in the myelin covering. The gaps between nodes are each about $1\text{ }\mu\text{m}$ long. At each node there is a cluster of voltage-gated sodium ion channels (Figure 7.2.6) as well as non-gated sodium and potassium ion channels. Positive ions gather at the nodes of Ranvier to balance negative ions that maintain the resting potential. At the nodes there is no covering to prevent the ions being close to the neuron membrane. When the action potential arrives at a node sodium ions move into the neuron as sodium channels open (Figures 7.2.7 and 7.2.12). The potential then jumps to the next node. Because it misses out the myelin-covered sections of the neuron, progress of the action potential is very rapid. This type of conduction in a myelinated neuron is called **saltatory conduction**.

In non-myelinated axons, the action potential must propagate continuously along the plasma membrane that makes the process much slower.

KEY POINT

saltatory conduction impulse conduction ‘in jumps’ along myelinated neurons, between nodes of Ranvier.

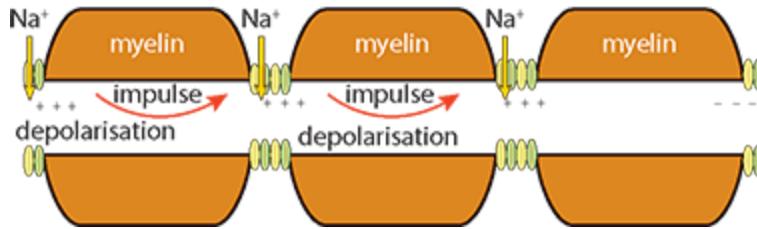


Figure 7.2.12: Saltatory conduction. Depolarisation only occurs at the nodes of Ranvier and the nerve impulse jumps from node to node.

Comparing rates of transmission of action potentials

Myelinated human axons vary in size, but most are between 13 and 20 μm in diameter and in these an action potential can travel at a velocity of 80–120 $\text{m}\cdot\text{s}^{-1}$. Smaller myelinated axons in the range 6–12 μm conduct at 33–75 $\text{m}\cdot\text{s}^{-1}$ (Figure 7.2.13). The velocity of an impulse in an unmyelinated axon is much lower, as the graph shows.

Invertebrate animals have unmyelinated axons that can be very large. The giant squid (*Architeuthis dux*) has giant axons that transmit messages to the muscles in its mantle. When stimulated these muscles can contract instantly to expel water from inside the animal so it can move rapidly away if it needs to escape a predator. Squid axons are unmyelinated and have diameters between 500 and 1000 μm (0.5–1 mm). Despite their size, these axons can only conduct an impulse at a velocity of about 25 $\text{m}\cdot\text{s}^{-1}$.

Temperature is also a factor affect speed of transmission of impulses because it affects diffusion. Sodium and potassium ions diffuse into and out of the axon: cold temperatures slow down the process of diffusion. The speed of transmission of impulses is faster in homeotherms, animals such as mammals and birds that maintain a constant body temperature, than in poikilotherms like

the giant squid, which do not. Velocity of travel of action potentials is directly correlated with increasing temperature.

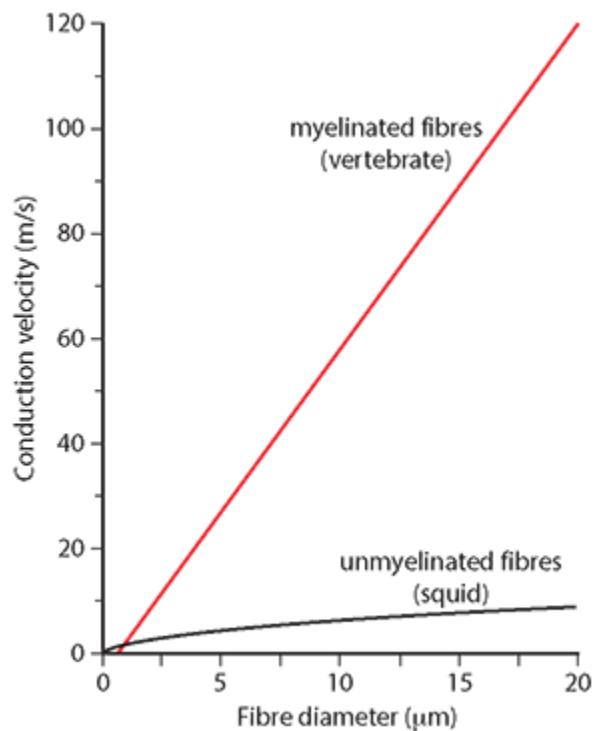


Figure 7.2.13: The conduction of action potentials in myelinated and unmyelinated fibres.

7.2.5 Excitatory and inhibitory neurotransmitters

At synapses, action potentials are passed from one neuron to the next. Some post-synaptic neurons are stimulated by many different pre-synaptic neurons, some of which release excitatory neurotransmitters and others inhibitory neurotransmitters (Figure 7.2.14).

Acetylcholine is an excitatory neurotransmitter. It increases the permeability of the post-synaptic membrane to sodium ions and depolarises the neuron.

KEY POINTS

excitatory neurotransmitter is one that activates receptors on the post-synaptic membrane and increases the likelihood that it will initiate an action potential.

inhibitory neurotransmitter is one that hyperpolarises the post-synaptic membrane and decreases the likelihood that an action potential will be triggered.

summation is the combination of stimuli received by the post-synaptic membrane from excitatory and inhibitory stimuli. If the two types of stimuli cancel each other out there will be no action potential generated.

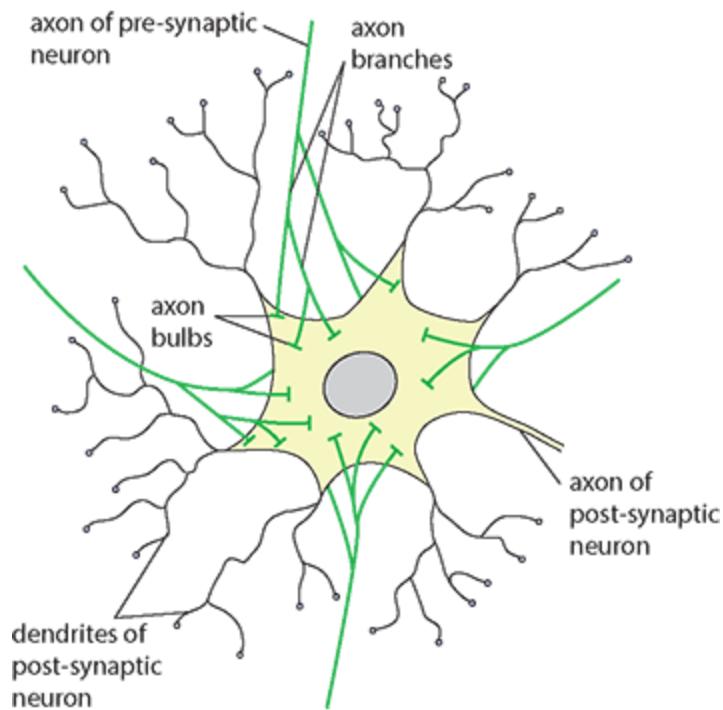


Figure 7.2.14: Some of the neurons that form synapses with the post-synaptic neuron are inhibitory producing inhibitory post-synaptic potentials (IPSPs) and prevent an action potential being stimulated. Others stimulate the propagation of the impulse producing excitatory post-synaptic potentials (EPSPs).

GABA (gamma-aminobutyric acid) is the most important inhibitory neurotransmitter in the brain. It causes the post-synaptic membrane to be **hyperpolarised**, so the inside of the neuron becomes more negative with respect to the outside. This makes it more difficult for an action potential to be generated. Inhibitory neurotransmitters may either cause positively charged potassium ions to move out of the post-synaptic cell or negatively charged chloride ions to move into it.

The balance of stimuli from these many pre-synaptic neurons can either excite or inhibit the post-synaptic neuron, giving a range of possible outcomes. The neuron may receive more stimulatory impulses overall so that it fires an action potential,

or it may receive mainly inhibitory impulses so that it does not. Summation of the excitatory and inhibitory neurotransmitters received from a pre-synaptic neuron will result in an action potential if the excitatory stimuli outnumber the inhibitory ones (Figure 7.2.15). Table 7.2.1 outlines the properties of some important neurotransmitters.

Summation

The effect of a neurotransmitter at a synapse depends on a number of factors, including how much neurotransmitter is released and the action of the neurotransmitter on the post-synaptic neuron. Receptors on the post-synaptic membrane influence ion channels that open when neurotransmitter molecules bind to them, producing a post-synaptic potential. These post-synaptic potentials may be excitatory (EPSPs) or inhibitory (IPSPs), depending on whether they bring the post-synaptic neuron closer to, or further away from, the threshold required to produce an action potential (Figure 7.2.15). A post-synaptic potential is approximately 1–2 mV. When a neuron receives both excitatory and inhibitory inputs together, the response will depend on whether the number of excitatory inputs overall are sufficiently great. If so, it will result in the generation of an action potential in the post-synaptic neuron and the transmission of a nerve impulse.

Neurotransmitter	Effects
acetylcholine	excitatory neurotransmitter that is found throughout the body. It triggers muscle contraction and stimulates the release of certain hormones. It is involved in wakefulness, attentiveness, anger and

	aggression. In some cases it can act as an inhibitory neurotransmitter
GABA (gamma-aminobutyric acid)	inhibitory neurotransmitter found in most inhibitory synapses in almost every part of the brain. many sedative drugs act by enhancing the effects of GABA. GABA contributes to motor control, vision and regulates feelings of anxiety
serotonin	an inhibitory neurotransmitter that is needed to maintain stable moods and to balance stimulatory neurotransmitters in the brain
glutamate	excitatory neurotransmitter found in the brain and spinal cord. It is also used at modifiable synapses that are capable of increasing or decreasing the strength of an impulse and influencing memory
endorphins(opioid peptides)	a group of neurotransmitters found in pain pathways and emotional centres of the brain. They are produced by the pituitary gland and hypothalamus during exercise or excitement or when pain is felt. They are known as ‘natural painkillers’ because some have an analgesic effect

Table 7.2.1: The properties of some important neurotransmitters.

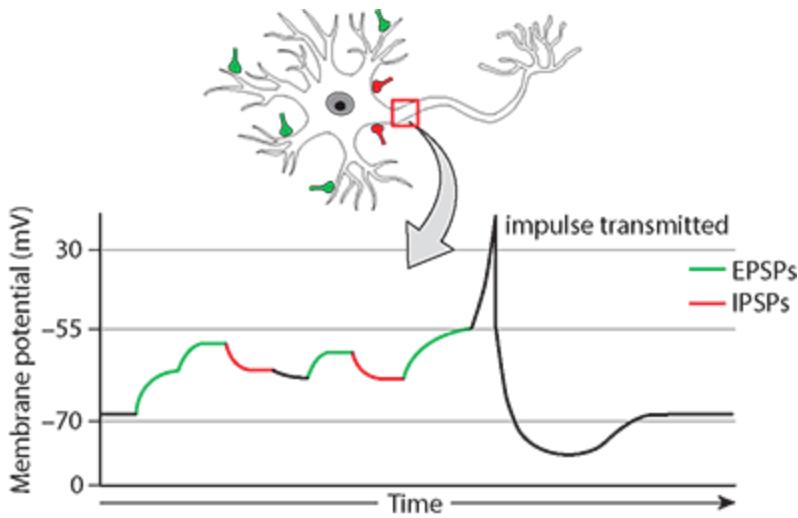


Figure 7.2.15: A neuron both receives EPSPs and IPSPs. The neuron is only able to transmit an impulse when the combination of these incoming impulses reaches the threshold potential of -55 mV .

7.2.6 Effects of chemicals on synaptic transmission

Psychoactive drugs and other chemicals can affect the way that the impulses are transmitted at synapses. They are capable of altering the functioning of the brain and a person's personality.

Chemicals and drugs act in different ways:

- Some have similar structures to neurotransmitters and so either block receptors, preventing a response, or have the same effect as the neurotransmitter, but are not removed, so that the response is prolonged.
- Some prevent neurotransmitters being released.
- Some increase the release of neurotransmitters.
- Some prevent neurotransmitters being broken down and so prolong their effects.

Excitatory substances (stimulants)

Some drugs and chemicals are excitatory, that is, they promote the transmission of impulses at excitatory synapses or inhibit transmission at inhibitory synapses. Examples of excitatory drugs include nicotine, found in tobacco products and cocaine. An example of a chemical with a similar action is neonicotinoid insecticide. Their action and effects are summarised in Table 7.2.2.

Excitatory drug	Mode of action	Effects
nicotine and	acts at synapses that use the	nicotine

neonicotinoid insecticides	neurotransmitter acetylcholine, but is not broken down by acetylcholinesterase, so it remains in the synapse, binding to the same receptors on the post-synaptic membrane as acetylcholine so that synaptic transmission is blocked	produces feelings of pleasure but is strongly addictive
cocaine	stimulates transmission of impulses at brain synapses that use dopamine (a neurotransmitter that is part of the 'reward' pathway) so it leads to a build-up of dopamine in the synapse because the re-uptake of the neurotransmitter is blocked	can produce feelings of excitement and confidence. Raises heart rate and body temperature. Strongly addictive

Table 7.2.2: Action and effects of some excitatory drugs.

Inhibitory drug	Mode of action	Effects
alcohol	increases the binding of GABA to receptors in post-synaptic membranes and causes hyperpolarisation of post-synaptic membranes; decreases the action of the neurotransmitter	in small quantities, affects behaviour by reducing inhibitions in larger quantities, can cause a lack of coordination, slurred speech, loss of balance and, in

	glutamate, which stimulates post-synaptic neurons	some cases, aggressive behaviour
THC (the most important psychoactive substance in cannabis)	affects receptors in cells in the cerebellum and cerebral hemispheres of the brain and causes hyperpolarisation of post-synaptic membranes so that they are more difficult to stimulate	induces feelings of relaxation and affects coordination but causes panic and paranoia in some users; can interfere with short-term memory and learning
benzodiazepines	bind to the same post-synaptic receptors as GABA, the main neurotransmitter at inhibitory synapses cause hyperpolarisation of post-synaptic membranes so that they are more difficult to stimulate	reduce anxiety, cause relaxation and can induce sleep used therapeutically to treat anxiety, insomnia and seizures

Table 7.2.3: Action and effects of some inhibitory drugs.

Inhibitory substances (depressants)

These drugs increase transmission at inhibitory synapses or suppress transmission at excitatory synapses. This class of drugs is also known as sedatives and includes anaesthetics used in medicine. Examples of inhibitory drugs include alcohol, THC and benzodiazepines. Inhibitory substances cause the

postsynaptic membrane to become hyperpolarised. Their effects are summarised in Table 7.2.3.

7.2.7 Perception of pain and consciousness

Pain receptors, also called **free nerve endings** are found in the skin at the base of hair follicles and close to the surface of the skin. Some types of pain receptor respond to pinching or cutting, others respond to extreme heat and other types respond to chemicals such as acids or the chemical capsaicin found in chilli peppers. The receptors respond when a stimulus causes or may cause tissue damage. If cells are damaged or substances synthesised at the site of an injury the receptors have channels for positively charged ions which enter the nerve endings and cause the threshold potential to be reached. This in turn initiates an action potential in the pain nerve fibres. The action potential is transmitted to the spinal cord and onward to the brain where the feeling of pain is perceived.

INTERNATIONAL MINDEDNESS

Human life expectancy is getting longer all over the world and the number of people affected by dementia and reduced brain function is also increasing. Dementia is an age-related neurodegenerative disease. The symptoms include decline in memory, attention span, language and problem-solving abilities. The World Health Organization (WHO) estimates that the number of individuals affected by dementia will triple by 2050 in populations globally. There is no cure for dementia, but treatments for the early stages of the disease include acetylcholinesterase inhibitors and other drugs that prevent the breakdown of acetylcholine and help nerve cells to communicate with each other. Scientists continue to seek ways to prevent the disease. Encouraging new research has

found that *statins*, a common medication given to people who suffer from high blood pressure, may offer potential benefits to prevent dementia in the future.

TEST YOUR UNDERSTANDING

- 13** List three factors that affect the speed of neural transmission.
- 14** Outline the difference between an excitatory and an inhibitory neurotransmitter.
- 15** Where would you expect to find free nerve endings?

Consciousness is loosely defined as the state of being aware of and responsive to one's surroundings, but scientists and philosophers have argued for many years about what being conscious really means. Nevertheless, we can say that interactions between the millions of neurons gives us the ability to speak, think, remember, feel pain and make decisions. Consciousness and these emergent properties are all consequences of the interactions that take place between the individual neurons in the brain.

REFLECTION

After studying this section can you say that you met your goals in understanding methods of cell signalling?

Link

- How is cell signalling important in animal communication?

7.3 Chemical signalling in animals and plants

LEARNING OBJECTIVES

In this section you will:

- learn that hormones include peptides, steroids and other organic molecules that act as chemical messengers
- recall that endocrine glands secrete hormones into the bloodstream that carries them to target organs
- discover that hormones act as first messengers to cause a response in target cells.
- learn how blood sugar level is controlled by insulin and glucagon
- understand that failure to produce enough or failure to respond to insulin can cause diabetes
- recognise that animal hormones or chemicals with similar effects are used in medicine

- learn that steroid hormones enter cells and bind to receptors to form receptor–hormone complexes that promote transcription. Examples include estrogen and testosterone
- learn that peptide hormones bind to receptors on cell surfaces to activate second messengers inside cells

- understand the role of G protein and (cAMP in the action of adrenaline
- understand the mode of action of the hormone insulin involving phosphorylation of tyrosine
- recognise that phototropism is a growth response to the plant growth regulator auxin
- understand that auxin affects gene expression and makes it easier for cell walls to expand so that shoots grow towards a light source
- learn that auxin efflux carriers maintain concentration gradients of phytohormone
- recognise that auxin and cytokinin interact to regulate root and shoot growth
- understand that positive feedback is involved in fruit ripening by ethylene.

7.3.1 Hormones in animals

The chemical structures of hormones

Hormones are chemical substances that are secreted directly into the bloodstream from **endocrine glands** found throughout the body (Figure 7.3.1). Each endocrine gland secretes a low concentration of hormone that travels in the blood to cells and tissues that are elsewhere in the body. Since hormones circulate in the bloodstream, they come into contact with many cells in the body but only cells that have specific, genetically determined receptors will respond.

These target cells have receptors on their plasma membranes that recognise and bind to the hormone.

Different hormones have different chemical structures and can be divided into three categories, as shown in Table 7.3.1.

KEY POINT

target cell a specific cell in the body that can respond to a particular hormone.

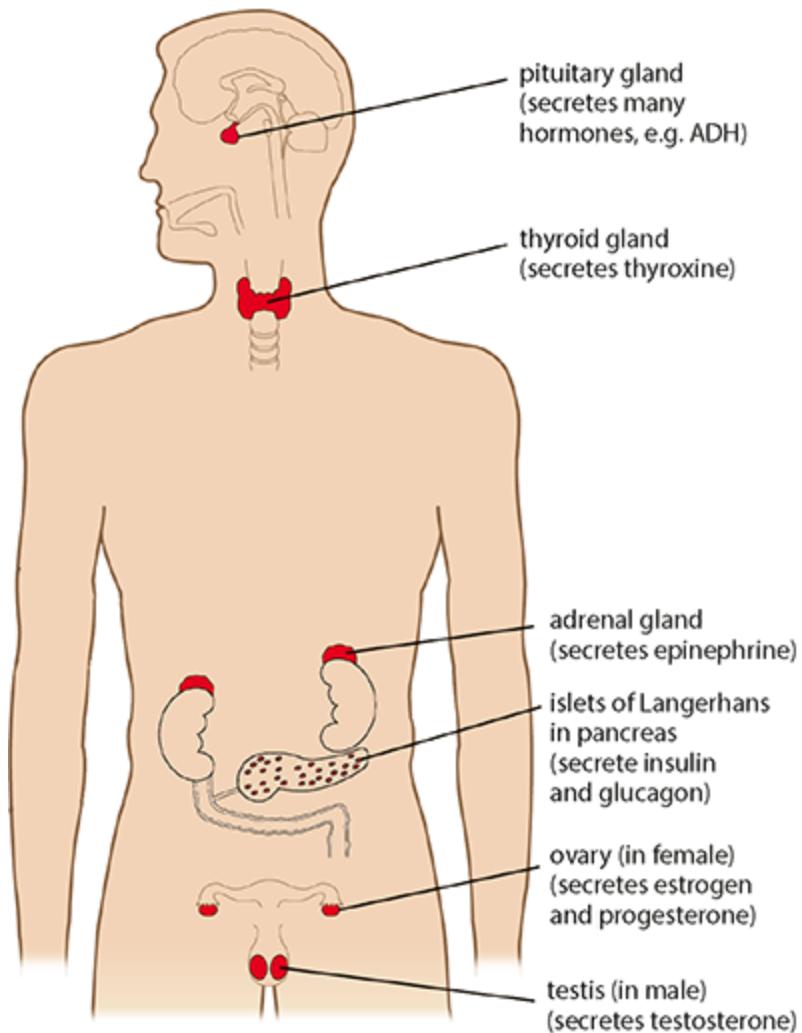


Figure 7.3.1: The location of the endocrine glands and the hormones they produce.

Chemical category of hormone	Examples
steroids derived from cholesterol	testosterone, progesterone
peptides (hormones consisting of chains of amino acids)	follicle-stimulating hormone (FSH), luteinising hormone (LH)

tyrosine derivatives (hormones derived from the amino acid tyrosine)	thyroxine (each thyroxine molecule contains four iodine atoms), epinephrine (adrenaline)
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Table 7.3.1: Hormones are divided into three categories based on their chemical structure.

Hormones act as ‘first messengers’ to cause a response in a target cell. First messengers may or may not cross the plasma membrane but they initiate changes in the cell or tissue that is their target. Steroid hormones enter their target cells, but amino acid-derived hormones are hydrophilic molecules and do not enter the cell. Instead, they only bind to the surface of a target cell.

KEY POINT

first messenger an extracellular factor, often a hormone or neurotransmitter, that initiates changes within a cell even though it may not physically enter the cell.

Feature	Hormonal signalling	Nervous signalling
nature of the signal	chemicals, travelling in the blood	electrical impulses travelling along neurons
speed of action	can be slow, controlling long-term processes	very rapid
duration of response	minutes to days or years; effects may continue after the signal has been removed	milliseconds

area of response	signal affects many organs, more widespread response	response in one area only
example of control	growth, reproduction	movement, reflexes such as blinking

Table 7.3.2: Comparing hormonal and nervous signalling.

Comparing nervous and hormonal cell signalling

Both nerves and hormones send signals to cells, but their effects are quite different. Table 7.3.2 compares their two modes of action.

7.3.2 Insulin and glucagon, and control of blood glucose

Blood glucose level is the concentration of glucose dissolved in blood plasma. It is expressed as millimoles per decimetre cubed ($\text{mmol}\cdot\text{dm}^{-3}$). Normally blood glucose level stays within narrow limits, between $4 \text{ mmol}\cdot\text{dm}^{-3}$ and $8 \text{ mmol}\cdot\text{dm}^{-3}$, so that the osmotic balance (Section 6.3) of the blood remains constant and body cells receive sufficient glucose for respiration. Levels are higher after meals as glucose is absorbed into the blood from the intestine. They are usually lowest in the morning because food has not been eaten overnight.

Glucose levels are monitored by cells in the pancreas. If the level is too high or too low, cells in regions of the pancreas known as the islets of Langerhans produce hormones that turn on control mechanisms to correct it. β cells produce the hormone insulin and α cells in the pancreas produce the hormone glucagon.

Table 7.3.3 summarises these responses.

	Responses to a rise in blood glucose above normal	Responses to a fall in blood glucose below normal
Pancreas	β cells in the pancreas produce the hormone insulin	α cells in the pancreas produce the hormone glucagon
Glucose uptake or release	insulin stimulates cells in the liver and muscles to take in glucose and convert it to glycogen and fat, which can be	glucagon stimulates the hydrolysis of glycogen to glucose in liver cells:

	stored inside the cells: blood glucose levels fall	glucose is released into the blood
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Table 7.3.3: The body's responses to changes in blood glucose.

Diabetes

Diabetes is the inability of the body to control blood glucose level. A person with untreated diabetes will experience wide fluctuations in their blood glucose above and below the normal limits (Figure 7.3.2). There are two types of diabetes: Type I is an autoimmune condition, while Type II is related to lifestyle factors.

In **Type I diabetes**, the β cells in the pancreas do not produce insulin. Without insulin, glucose is not taken up by body cells so blood levels remain high, a condition known as **hyperglycemia** (Figure 7.3.3). Excess glucose is excreted in urine and its presence is used to diagnose diabetes. About 10% of people with diabetes have Type I diabetes. Symptoms usually begin in childhood, which is why Type I diabetes is sometimes known as 'early-onset' diabetes.

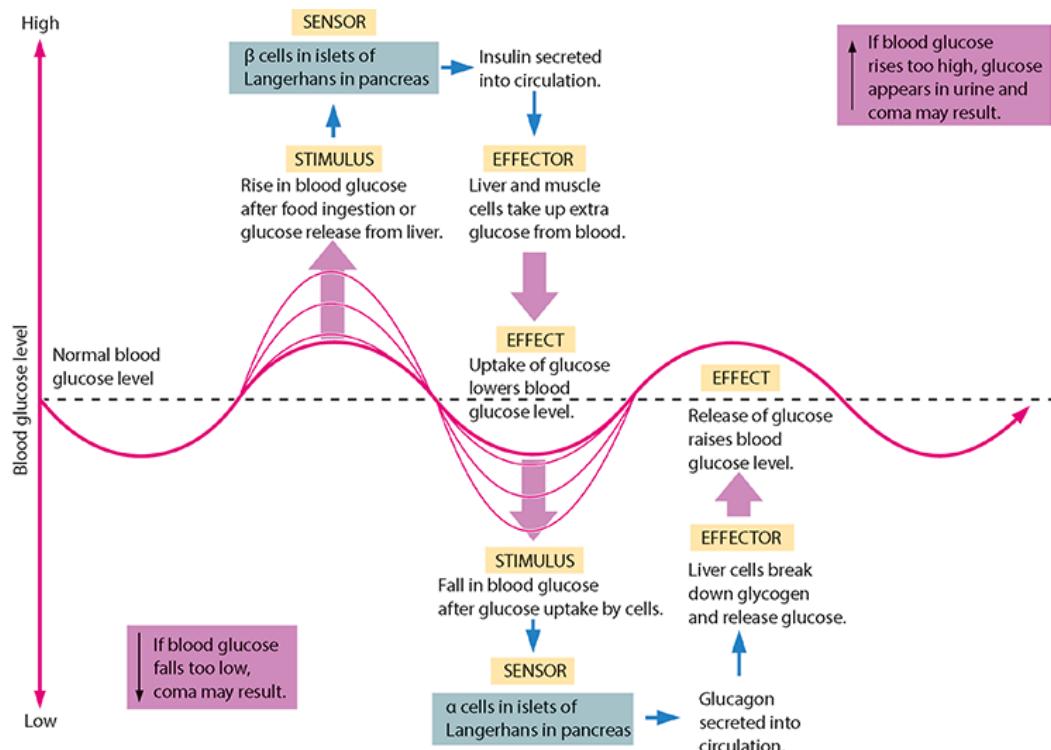


Figure 7.3.2: The control mechanism for blood glucose.

Type II diabetes is the most common form of diabetes, accounting for nine out of ten cases worldwide. The pancreas does produce insulin although levels may fall as the disease progresses. Type II diabetes occurs when body cells fail to respond to the insulin that is produced. Again, the result is that blood glucose levels remain too high. This form of diabetes is also known as late-onset diabetes or non-insulin-dependent diabetes mellitus. Individuals who have the condition develop insulin resistance, which means that the receptor cells that normally respond to insulin fail to be stimulated by it, even though the β cells in the pancreas still produce insulin. This type of diabetes is often associated with obesity, age, lack of exercise and genetic factors.

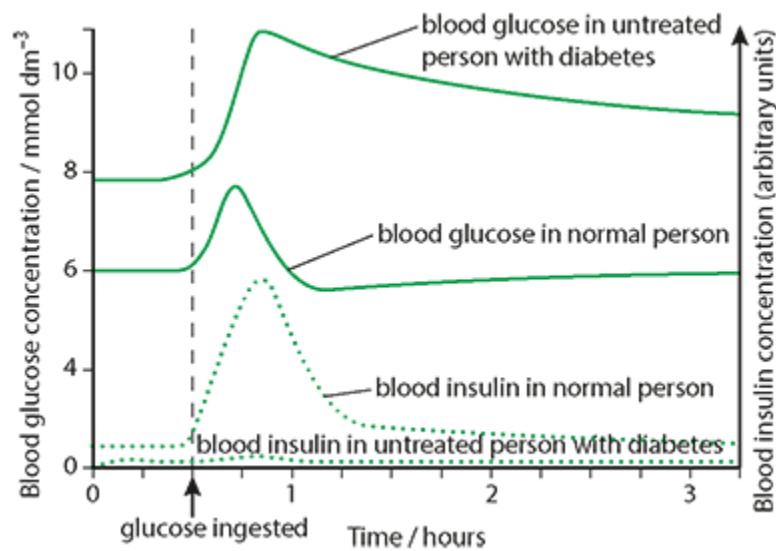


Figure 7.3.3: Blood glucose and insulin levels following intake of glucose in a normal person and in a person with untreated Type I diabetes.

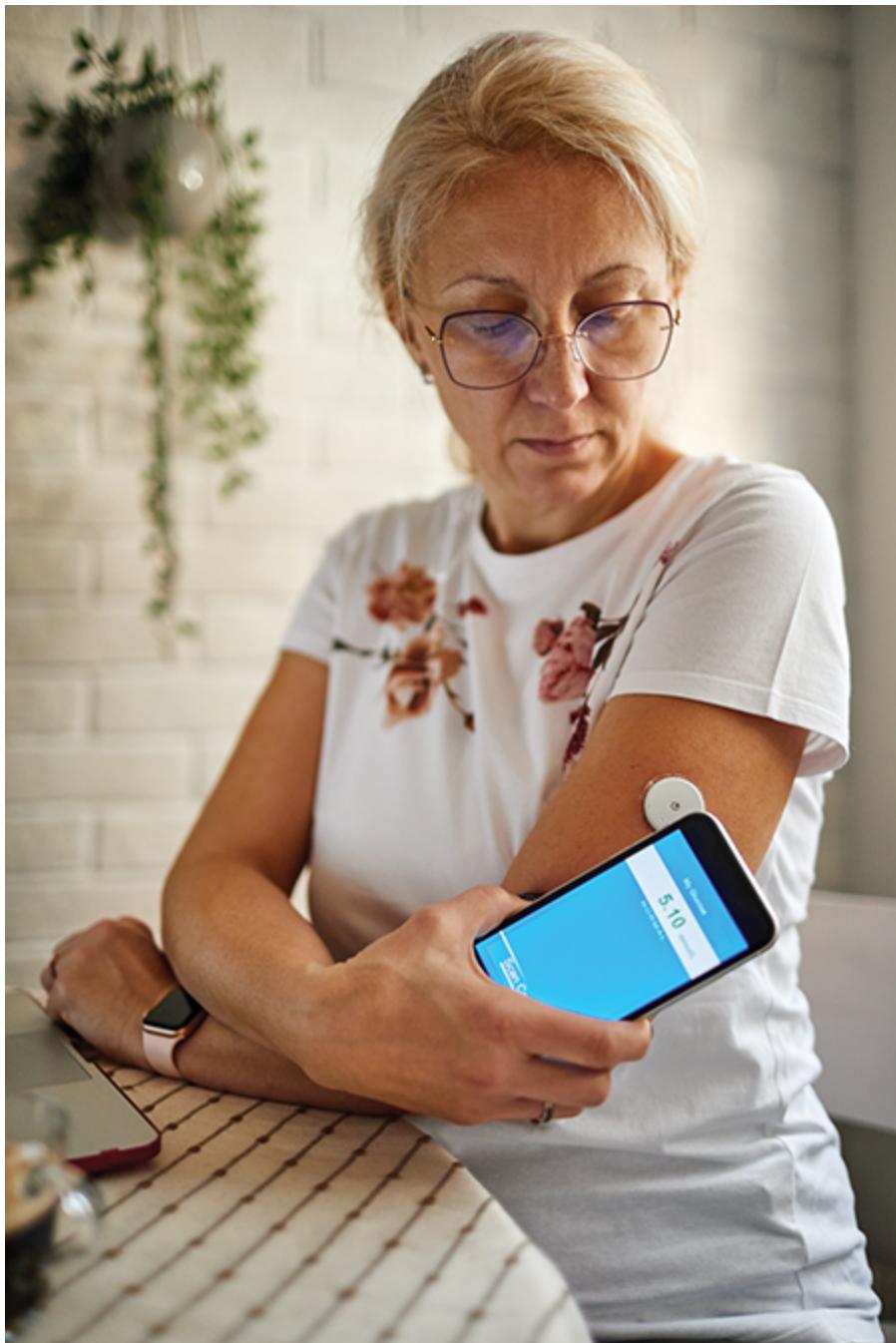


Figure 7.3.4: This woman has diabetes. She is wearing a glucose sensor on her arm and checking her blood sugar level using a smartphone app.

People with diabetes must monitor their blood glucose level carefully so that they can control it, as the body's internal control

mechanism is not working properly. This may involve taking tiny blood samples throughout the day and checking the amount of glucose that is present. Or, the person may be able to wear a glucose monitor that can be read using a smartphone app (Figure 7.3.4).

Causes and symptoms of diabetes

Type I diabetes is caused when the β cells in the pancreas do not produce insulin. This can be a result of autoimmune disease in which the body's immune system destroys its own β cells.

The causes of Type II diabetes are not fully understood but the risk of developing the disease has a strong correlation with weight and diet. High levels of fatty acids in the blood may be a factor causing the condition. People whose diets are high in fat but low in fibre seem to be most at risk. Obesity, associated with a lack of exercise or a genetic makeup that influences fat metabolism, is a key risk factor. The condition is more common in older people but there are an increasing number of cases in overweight children.

Studies of ethnic groups worldwide have shown that some are more likely to develop Type II diabetes, and this provides evidence for a genetic predisposition to the condition. The indigenous Aborigine population in Australia, people of Asian and Afro-Caribbean origin, the indigenous United States population and Polynesian Maori peoples all have a higher incidence of diabetes than would occur by chance.

The symptoms of diabetes include:

- high glucose levels in the blood
- glucose in the urine

- frequent need to urinate, which leads to dehydration and increased thirst
- tiredness and fatigue
- some loss of weight.

In Type II diabetes, these symptoms tend to develop slowly.

Treatment of diabetes

Type I diabetes must be controlled by regular insulin injections, but many people who have Type II diabetes are advised to control their blood sugar levels by following a healthy diet, taking exercise and losing weight. They are advised to eat foods that are low in saturated fat and salt but high in fibre and complex (slowly absorbed) carbohydrates, such as wholegrain cereals, pulses, beans and lentils. These foods, especially if they are taken at regular intervals during the day, help to keep blood sugar levels steady. Foods that should be avoided include sugary snack foods and drinks, and food with a high level of saturated fat. These foods cause a rapid rise in blood sugar level that the person with diabetes is unable to deal with.

If left untreated, Type II diabetes can lead to long-term health problems such as kidney disease, retinal damage, high blood pressure, stroke and heart attack.

7.3.3 Using hormones in medical treatments

Animal hormones or their artificially produced equivalents can be used to correct medical problems in many cases. The hormone insulin is needed to treat millions of people with diabetes all over the world. Doctors prescribe the hormone to protect their patients from harm caused by excessive blood sugar. Insulin is produced in recombinant bacteria or yeast by biotechnology companies. It is delivered to the patient with insulin pens or pumps that deliver it directly to the bloodstream.

Human growth hormone is produced by the pituitary gland and regulates growth in children and adolescents. Growth hormone deficiency is the most common cause of short stature in children, with about 1 in 5000 children being affected. Synthetic human growth hormone, first produced in 1985, is used to treat children with genetically inherited growth hormone deficiency or conditions such as Turner's syndrome, a genetic disorder that affects girls' development, and Prader–Willi syndrome. Growth of such children is increased so that they reach a more average height.

Two other widely used synthetic hormones are estrogen and progesterone, which are two female sex hormones that are used in oral contraceptive pills and in hormone replacement therapy treatments.

NATURE OF SCIENCE

Cause and correlation

A correlation between two variables does not guarantee a causal relationship, where one factor causes another. It is often difficult to work out whether one factor causes another or whether the two are simply correlated. In hormone research, many scientists have noticed an association between a person's testosterone levels and the risk of some diseases, including Type II diabetes. It was not clear whether testosterone level caused the risk of disease or was simply correlated with it.

In 2020 a new study involving nearly half a million European males and females analysed data from the UK Biobank and was able to show that many genetic variations influence testosterone levels and also that levels of testosterone are causally related to the risk of several diseases. The study showed that testosterone levels in males and females are inherited and influenced by many genetic variants and genes. Research continues to establish how testosterone influences diabetes and also how it is different between females and males.

SCIENCE IN CONTEXT

Human growth hormone in athletics

Human growth hormone (HGH) has been used by some athletes to promote muscle growth in an attempt to improve performance, particularly in power sports such as bodybuilding, swimming and weight lifting. The Olympic Committee declared the hormone a banned substance in 1989, but there is evidence that it is still used illegally (a practice called 'doping'). In the USA, HGH is available with a doctor's prescription. Scientific evidence about the effect of HGH on muscles is mixed. The hormone seems to reduce

body fat and increase lean body mass, but does not increase the strength of muscles.

It builds up connective tissue in muscles, making them appear larger, and it helps muscles resist injury and repair themselves. But these effects do not make the muscle stronger.

In 2010 researchers funded by the World Anti-Doping Agency in Sydney, Australia, reported that there was no evidence that HGH gave an increase in power, strength or endurance.

Despite the results of studies like this, and HGH's side effects, which include muscle and joint pain and swelling, some athletes still use the hormone illegally. Part of its attraction may be that, because it is a naturally occurring substance, it is hard to detect in anti-doping tests.

TEST YOUR UNDERSTANDING

- 16** Define the term hormone.
- 17** Name three types of chemical molecules that act as hormones.
- 18** State the effect of insulin on blood sugar levels.
- 19** Where is glucagon produced?
- 20** Summarise the difference between Type I and Type II diabetes.

7.3.4 Mode of action of steroid and amino acid-derived hormones (ligands)

Amino acid-derived hormones and steroid hormones control their target cells in different ways (Figure 7.3.5).

Steroid hormones, such as estrogen and testosterone, enter target cells because they are lipophilic and can easily diffuse through the plasma membrane. They bind to specific receptor proteins in the cytoplasm, forming a receptor–hormone complex, which is transported through a nuclear pore into the nucleus. Here, the hormone regulates the process of transcription of one or more specific genes (Figure 7.3.6).

Peptide hormones bind to a surface receptor, very often a glycoprotein, but do not enter the cell. Instead, the binding process triggers the release of a second messenger, a chemical that cascades from the cytoplasmic side of the plasma membrane and this messenger controls the activity of the cell. The second messenger may regulate the activity of a specific enzyme in the cell, either activating it or inhibiting it or trigger changes such as cell division, differentiation and apoptosis.

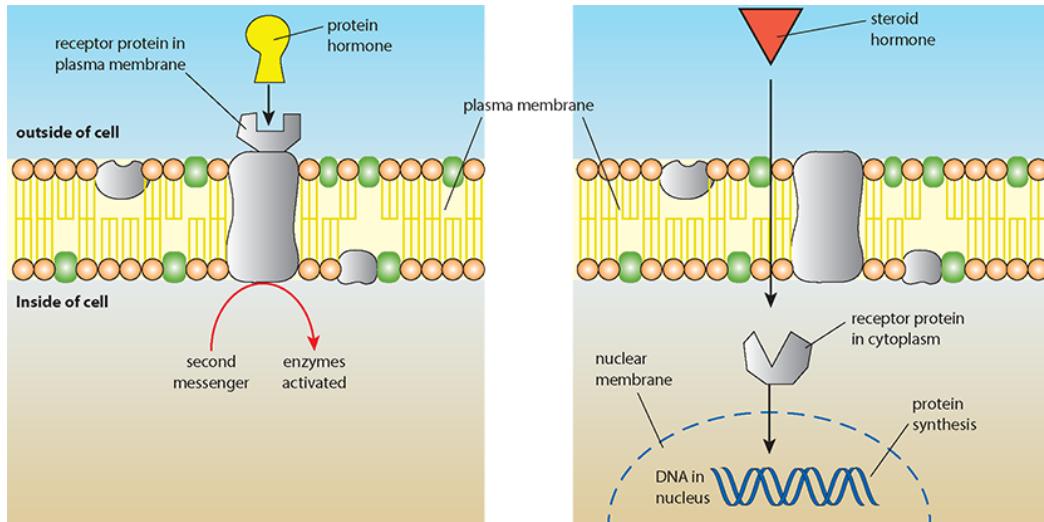


Figure 7.3.5: Ligands which are protein hormones do not enter cells but bind to receptors in the membrane. Steroid hormones enter cells and bind to receptors inside.

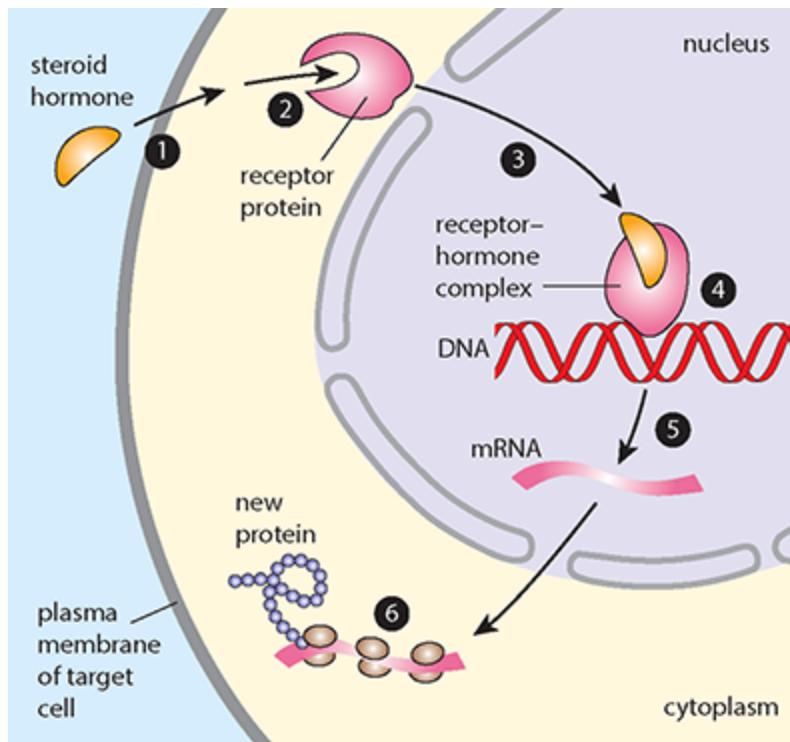


Figure 7.3.6: Mode of action of steroid hormones such as estrogen.

NATURE OF SCIENCE

Understanding key terms

International naming conventions are used in science so that all scientists and students can benefit and discuss their work. Adrenaline and epinephrine are two terms used for the same hormone. Both are based on the fact that the hormone is produced by the adrenal glands situated just above the kidneys. Adrenaline comes from Latin Ad = at and ren = kidney, while epinephrine is derived from Greek. Epi= above and nephros = kidney. Both these names are used interchangeably in different parts of the world.

Estrogen is a category of sex hormones that control the development and regulation of the female reproductive system and secondary sex characteristics. There are three major types of estrogen: estrone, estradiol, and estriol. Estradiol is present in women of reproductive age, estrone is predominant in women after menopause and estriol is at the highest level in the blood during pregnancy. You will probably see the term estrogen used most of the time although medical professionals are more likely to distinguish between the three types of estrogen.

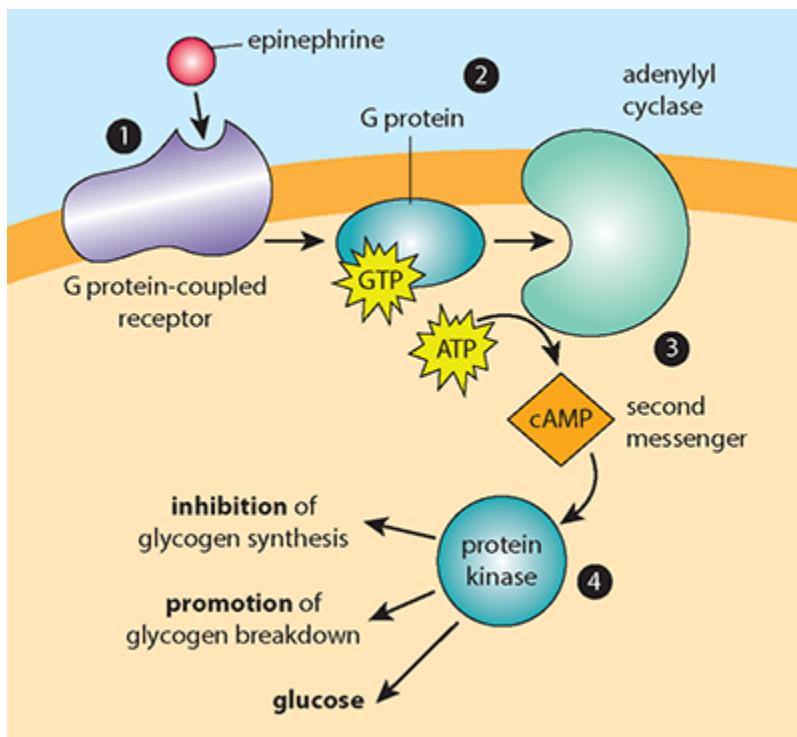


Figure 7.3.7: Mode of action of the amino acid derived hormone epinephrine. 1 Epinephrine binds to a G-protein-coupled receptor. 2 When stimulated, this receptor activates a G protein. 3 This initiates production of cAMP. 4 Cell signalling pathway acts to break down glycogen to glucose in the liver.

Insulin works in this way. Insulin binds directly to a receptor in the plasma membrane and causes the phosphorylation of tyrosine inside a cell. Insulin receptors are present on all cells, but their density is greatest on liver and adipose (fat) cells. A sequence of events follows:

- 1 Insulin binds to the receptor in the plasma membrane
- 2 Tyrosine inside the cell is phosphorylated
- 3 A cascade of phosphorylation causes vesicles containing glucose transporters to move to the plasma membrane

- Glucose can now enter through the membrane and be metabolised or stored.

Epinephrine (adrenaline) is an example of a hormone derived from amino acids. It is involved in the ‘fight or flight’ response that occurs when a person feels under threat. Epinephrine is released by the adrenal glands and travels to its target cells in the blood. Epinephrine and glucagon together stimulate the release of glycogen stores in the liver to release energy for action. Epinephrine binds to alpha-1 adrenergic receptors on the outside of cells, causing them to change their shape and starting a cascade of reactions inside the cell. As a result of the change in shape of the receptors, a G protein is activated and this enables adenylyl cyclase and ATP to become active as well. Adenylyl cyclase breaks down ATP into a second messenger molecule called cyclic AMP, usually called cAMP. This second messenger causes protein kinase to inhibit glycogen synthesis and promote the breakdown of glycogen so that glucose can be released. (Figure 7.3.7).

7.3.5 Effects of phytohormones (plant growth regulators)

Plants produce signalling chemicals called phytohormones which control their growth, development and response to stimuli.

Charles Darwin noted the existence of these growth substances in 1880 in a report of his experiments on plant shoots. He observed that oat seedlings grew towards light because of some ‘influence’, which he thought was transmitted from the shoot tip to the area immediately below. We now know that the substance that causes shoots to bend towards the light is **auxin** and the response it causes is called **phototropism**. Auxin is found in the embryos of seeds and in apical meristems, where it controls several growth responses, or tropisms. Positive phototropism is a directional growth response of shoots towards a source of light.

Phototropism involves auxin and **phototropins**, which are photoreceptor proteins that respond to the blue wavelengths of visible light. These proteins are found in shoot cell plasma membranes and throughout a plant. Auxin which controls the growth of stems and roots can diffuse freely into plant cells but not out of them. It is moved from cell to cell, and its flow through the plant is redirected continuously as a plant is developing. Auxin is pumped out of cells by proteins in the cell membrane called **auxin efflux carriers**.

Phototropins become phosphorylated and activated on the side of a shoot that receives more light. Auxin is then redistributed to the side of a shoot tip that is away from a light source. The uneven distribution of auxin allows cell elongation on the

shaded side of a shoot, which in turn causes bending towards light (Figure 7.3.8).

In an evenly lit shoot, auxin promotes the elongation of cells at the shoot apex so that the shoot grows straight upward.

When auxin is present, a high concentration of hydrogen ions in the cell walls builds up due to the transport of ions through the plasma membrane. This reduces the pH and enables enzymes to break the cross links between cellulose molecules in the cell wall. As bonds are loosened between cellulose fibres, their structure becomes more flexible so that cells can expand. Auxins also interact with other plant hormones such as cytokinins to influence the general pattern of development. They influence and coordinate the development of plants by influencing the expression of genes. Auxin may activate certain genes, leading to a rapid response, or it may inhibit other sets of genes. Auxin affects both cell division and cell enlargement.

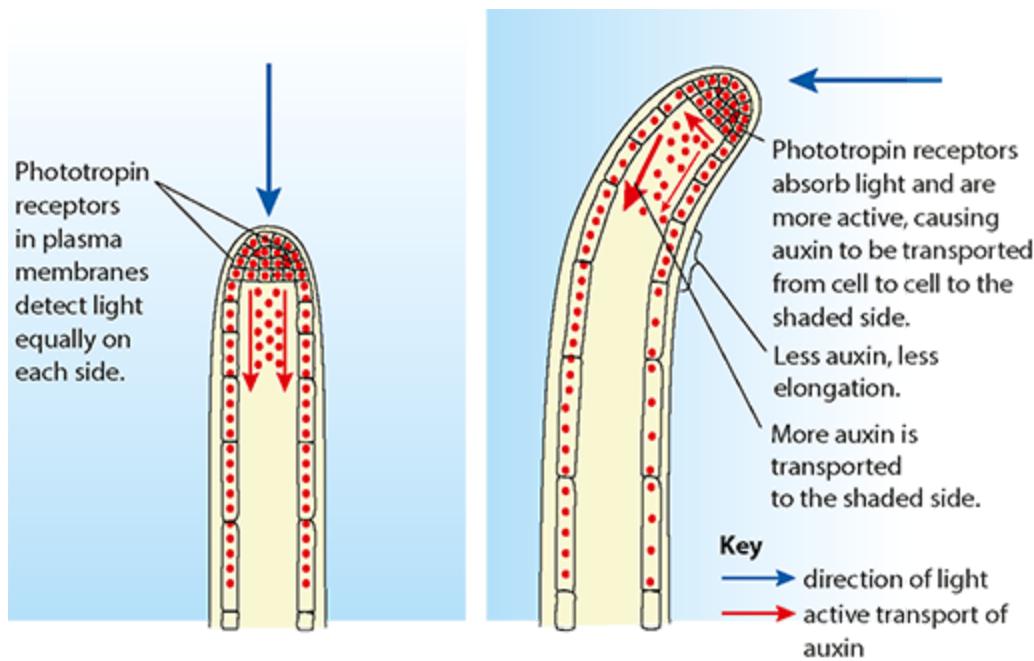


Figure 7.3.8: Some proteins (phototropins) in the plasma membranes of certain cells in plant shoots are sensitive to light. When light falls on them, they cause auxin to be transported to the shaded side of the shoot, which in turn causes the shoot to bend towards the light.

EXAM TIP

You should be able to make observations and measurement of tropic responses from experiments using seedlings.

You should also be able to annotate diagrams such as the one shown in Figure 7.3.8 to show the reactions of seedling you have grown.

There are five types of **phytohormone** with very different chemical structures: they are auxin, gibberellins, cytokinins, abscisic acid and the gas ethylene. Based on the effects they have, they can be divided into two main groups:

- 1 Growth promoters that promote cell division, cell enlargement, flowering, formation of fruits and seeds.
Examples are auxins, gibberellins and cytokinins.
- 2 Growth inhibitors that inhibit growth and promote **dormancy** and abscission (leaf fall). An example is abscisic acid that regulates seed dormancy, and helps the plant respond to environmental stress.

Animal hormones	Phytohormones (plant growth regulators (PGRs))
produced in special endocrine glands	produced by most plant cells

target cells may be a long way from the site of hormone production	target cells are usually cells close to the cells that produce PGRs
two main types of hormone are peptides and steroids, which are complex organic molecules	five different types of growth substances are small simple organic molecules
hormones are secreted into the blood and are carried to target cells in the bloodstream	PGRs diffuse to nearby cells but may travel in the phloem
influence body growth and development	control all aspects of plant growth and development

Table 7.3.4: Comparison of animal hormones and plant growth regulators.

Ethylene is usually a growth inhibitor although in some circumstances it can become a promoter.

In most cases plant growth substances influence cells that are close to the cells that produce them. They are said to have a local effect. They travel to the target cells by diffusion. One example is auxin, which is produced in the stem, buds and root tips of plants and influences stem elongation and inhibits the growth of lateral (side) buds. Unlike animals, plants have no special organs to produce or store hormones and their growth regulators usually diffuse only short distances, although sometimes they can be carried in the phloem to target cells further away. Auxin and cytokinin work together to regulate root and shoot growth. Root tips produce cytokinin which is transported to shoots, while shoot tips produce auxin which is transported to roots. Interactions between these two growth substances helps to

ensure that root and shoot growth proceed at the correct rates. Table 7.3.4 shows some differences between plant and animal hormones.

SCIENCE IN CONTEXT

Ethylene and ripe bananas!

Bananas produce the plant growth regulator, ethylene (C_2H_4). Ethylene is a gas that influences the ripening of bananas and other fruits including apples, pears, peaches and melons, which all produce ethylene. Commercial fruit companies use ethylene to speed up the ripening process. Ethylene works using positive feedback. It stimulates the start of the ripening process and ripening also stimulates increased production of ethylene. Positive feedback ensures that fruits ripen rapidly and that ripening is synchronised. Tropical fruits such as bananas are picked when they are green and unripe. They may have to travel long distances to consumers and ripe fruits would be past their best after a long journey. At their destination bananas are ripened artificially by exposing them to ethylene in special ‘ripening rooms’ before they are sent to the shops. The rooms are kept at a high level of humidity so that the fruit does not crack or dry out and this has the added advantage that it extends the shelf life of the fruit.

TEST YOUR UNDERSTANDING

- 21** Summarise how steroid hormones promote the transcription of specific genes.
- 22** Outline how amino acid-derived hormones activate a second messenger inside a cell.

23 Name an example of a plant growth regulator.

24 What is a positive phototropism?

REFLECTION

After studying this section can I say that I met my goals in understanding methods of cell signalling?

Links

- How do hormonal and nervous communication vary between different classes of organisms? ([Chapter 9](#))
- How do the structures of cell membranes help cell signalling? ([Chapter 6.1](#))
- How are hormones involved in homeostasis? ([Chapter 8.5](#))

SELF-ASSESSMENT CHECKLIST

Think about the topics covered in this chapter. Which parts are you most confident with? Which topics require some extra practice?

I can...	Subsection	Needs more work	Nearly there	Confident to move on
describe the importance of cell signalling to unicellular and multicellular organisms	7.1.1, 7.1.2			
outline how emergent properties can develop as a result of cell signalling	7.1.3			
state that ions, neurotransmitters and hormones act as signals to cells	7.1.3			
summarise the differences between animal hormones and	7.1.3			

plant growth regulators				
summarise the effects of ligands on receptors in the plasma membrane and intracellular receptors	7.1.3			
recognise the differences in receptors and signal transduction involved in signals from adrenaline, acetylcholine, insulin and steroid hormones	7.1.3			
describe the structure of a typical neuron	7.2.1			
explain the importance of sodium and potassium ions in generating a nerve impulse	7.2.2			
define the terms resting potential,	7.2.2			

threshold potential, action potential, depolarisation and repolarisation and interpret traces of action potentials				
describe the events that occur at a synapse as an action potential arrives	7.2.3			
state that the brain processes information from the nerves while the spinal cord processes unconscious actions	7.2.3			
summarise the importance of myelin sheaths and saltatory conduction in speeding up transmission of impulses	7.2.4			
describe the events of saltatory conduction	7.2.4			

<p>including gated and non-gated sodium and potassium channels at the nodes of Ranvier</p>				
<p>explain the difference between excitatory and inhibitory neurotransmitters and the importance of summation at a post-synaptic neuron</p>	7.2.5			
<p>outline the effects of chemicals such as nicotine and alcohol on the brain and their addictive nature</p>	7.2.6			
<p>recall that free nerve endings in the skin send pain messages to the brain</p>	7.2.7			
<p>state that consciousness is a consequence of</p>	7.2.7			

nerve interactions in the brain				
identify three types of hormone molecule that act in cell signalling	7.3.1			
explain that hormones are produced by endocrine glands that secrete directly into the bloodstream	7.3.1			
state that hormones act as first messengers	7.3.1			
recall that insulin and glucagon are produced by α and β cells in the pancreas and control blood sugar levels	7.3.2			
explain how failure to produce or respond to insulin can lead to diabetes	7.3.2			
animal hormones can be produced	7.3.3			

artificially and used to treat medical problems				
recall that steroid and amino acid hormones work in different ways	7.3.4			
understand that steroid hormones enter cells and form receptor–hormone complexes that affect transcription	7.3.4			
understand that amino acid-derived hormones (insulin and adrenaline) do not enter cells but they stimulate release of second messenger molecules	7.3.4			
explain that positive phototropism is a directional growth response in plants controlled by the	7.3.5			

phytohormone auxin				
describe how movement of auxin controls cell elongation	7.3.5			
describe how auxin and cytokinin regulate root and shoot growth	7.3.5			
explain positive feedback in fruit ripening by ethylene.	7.3.5			

EXAM-STYLE QUESTIONS

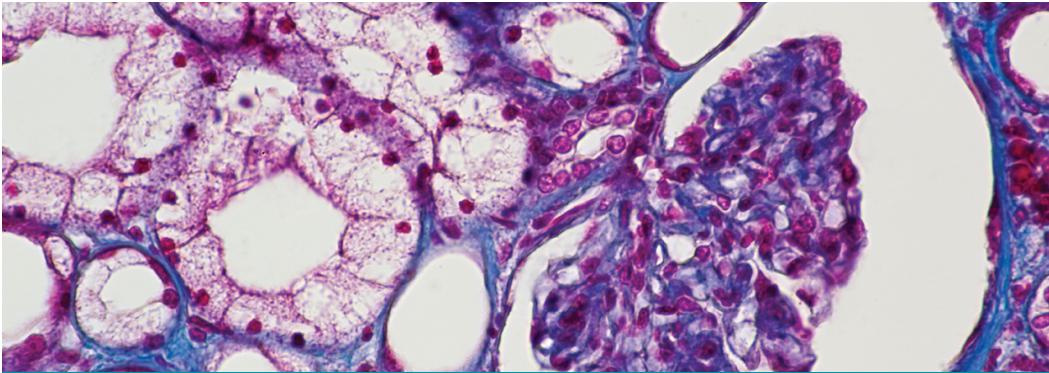
You can find questions in the style of IB exams in the digital coursebook.

> Unit 3

Organ systems and integration

INTRODUCTION

In multicellular organisms, cells are organised into tissues and organs that have their own jobs to do in the body. In complex organisms, processes such as transport of materials and gas exchange are carried out by specialised organ systems. For example, the heart and the blood system are responsible for transporting substances to and from cells. Plants exchange gases through their leaves and absorb nutrients through their roots. Animals exchange oxygen and carbon dioxide at surfaces such as the alveoli of the lungs. The tissues in a multicellular organism communicate with each other via nerves, hormones and cell signalling. Homeostasis monitors and keeps the levels of different substances constant so that the organism can always function at its optimum level. Animals also develop immune systems to protect their bodies from disease.



› Chapter 8

Physiology

B3.1, B.3.2, D3.1, D3.2

INTRODUCTION

Multicellular organisms have cells that work together and are organised into tissues and organs that must function in harmony to carry out the functions of life. Physiology is the study of the organs and organ systems of the body and how they interact to keep complex organisms alive. Physiologists examine both the physical structure of organs and investigate the biochemical processes that operate to keep them working efficiently. Hormonal and nervous signalling systems integrate the actions of organs while transport systems carry materials between them.

8.1 Physiology - organ systems and integration

LEARNING OBJECTIVES

In this section you will:

- learn that multicellular systems show cell adhesion, communication and interdependence
- discover that multicellular organisms have emergent properties and differentiation of cells involves the expression of specific genes
- understand that complex multicellular organisms have cells organised in tissues
- recognise that differentiation involves programmed cell death and cell division
- recall that stem cells retain the ability to differentiate into many other cells
- recognise the location of stem cells in adult humans
- understand the differences between totipotent, pluripotent and multipotent stem cells
- recall that different tissues work together to become organs and that organs are organised to form organ systems
- discover that multicellularity has problems and advantages for organisms

- recognise that stem cells persist in animal bodies to replace cells.

GUIDING QUESTIONS

- How are multicellular organisms organised?
- What are the advantages of multicellularity?
- How do cells specialise in a multicellular organism?

8.1.1 Multicellular organisms

Multicellular organisms are composed of more than one cell. All multicellular organisms, even the simplest, such as *Hydra* (Figure 8.1.1), have cells that are held together by cell adhesions that form connections between adjacent cells. Cells are linked together either by special proteins that are part of the cytoskeleton ([Section 5.2](#)) or through tight junctions or desmosomes, both of which are formed by proteins embedded in the plasma membranes of adjacent cells. The connections made by cell adhesion are important in enabling cells to communicate and regulate cell activities, as well as in the development and maintenance of tissues. Cell communication in a multicellular organism means that cells are interdependent and enables different cells to carry out different specialised tasks.

Hydra is a small pond-dwelling organism that has different cells that form a two-layered body cavity, tentacles, stinging cells (called nematocysts) and a nerve net.

Cells in a multicellular organism form a system that carries out all the functions that are needed for life: metabolism, reproduction, response to the environment, nutrition, homeostasis, excretion and growth ([Section 5.1](#)).

KEY POINT

cell adhesion the process by which cells form connections with each other.

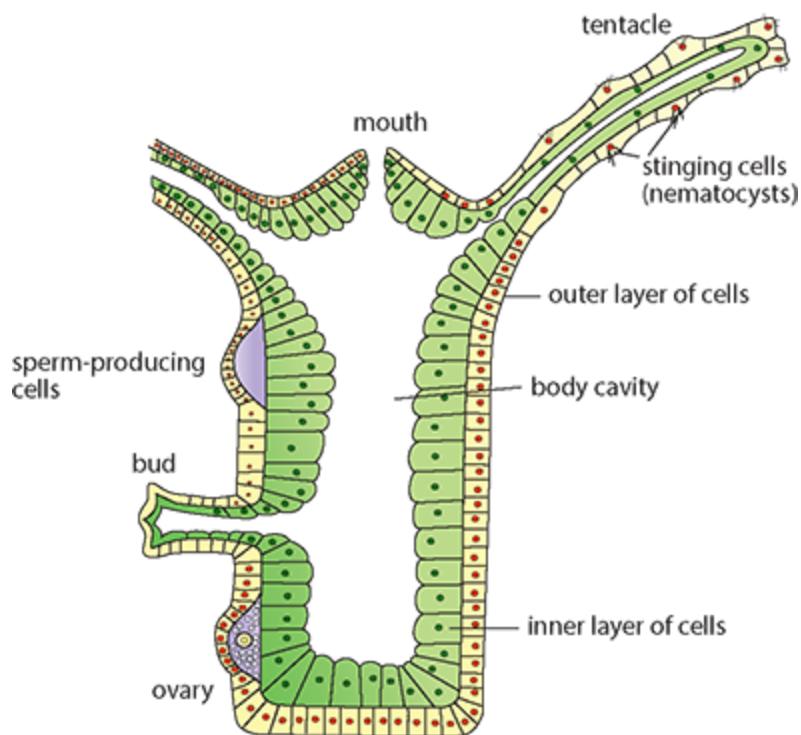


Figure 8.1.1: *Hydra* is a small aquatic multicellular animal.

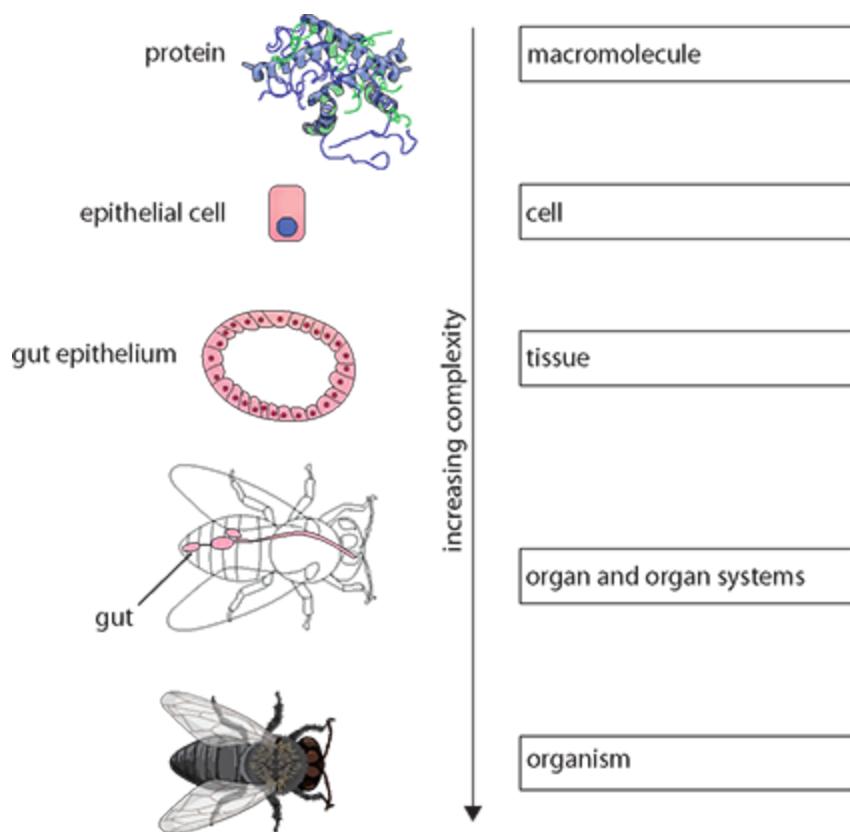


Figure 8.1.2: Multicellular organisms have properties that emerge from the interaction of their components.

Multicellular organisms like hydra and more complex plants and animals have emergent properties that arise from the interaction of their cells. But we cannot predict what these new properties will be from studying the individual component parts of the organism. Even though we can separate the parts of a living cell into the macromolecules that build it, and we have information about macromolecules, we could not have predicted the characteristics that emerge in a cell when the macromolecules are combined.

The cells built of macromolecules are organised into **tissues**, which are groups of similar cells with the same function that work together. Tissues form **organs**, which work with other organs to form organ systems, such as the heart and circulatory systems. A complex multicellular organism will contain many organ systems with different jobs to do in the body (Figure 8.1.2).

8.1.2 Differentiation

How do cells in the same organism behave in different ways when they all arose from the same parent cell and so have the same genome? In our own bodies, nerve cells and muscle cells all have the same sets of genes but look and behave very differently. The logical answer is that in some cells some genes are expressed that are not expressed in other cells, and that each type of cell expresses a slightly different set of genes. For example, a human pancreatic cell will express genes for the production of digestive enzymes or insulin, but a skin cell will not. **Differentiation** of cells into different types involves the expression of some genes from the organism's genome in a cell, while others are not expressed.

KEY POINT

programmed cell death (apoptosis) removal of cells during development to eliminate unwanted cells.

As well as gene expression, programmed cell death (apoptosis) plays an important role in forming organs and structures during embryo development. Apoptosis refers to changes that occur inside cells when they are no longer needed. These changes cause them to die or cause their own death. Apoptosis is called programmed cell death because it occurs at a specific time in the growth or development of an organism. One example of the role of apoptosis can be seen in the formation of the human hands as a baby grows during fetal development. Cells, which are present between individual fingers in the early stages of development, are removed through apoptosis so that the structure of the hand can be formed. Another example can be seen in frogs and toads

that develop from tadpoles. Cells in the tail of a tadpole are removed by apoptosis as the tadpole becomes an adult. See Figure 8.1.3.

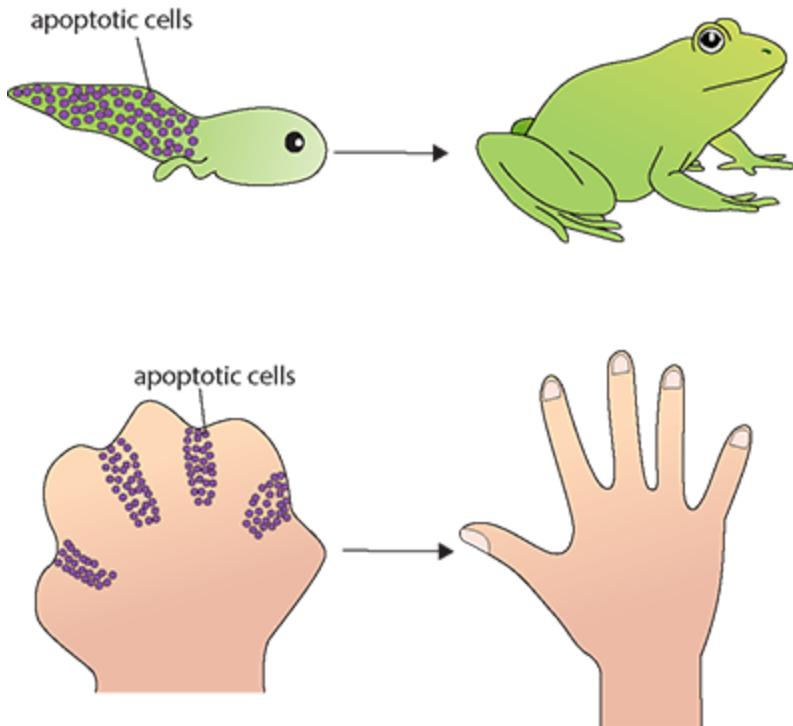


Figure 8.1.3: Apoptosis contributes to development in multicellular organisms as specific cells are programmed to die.

8.1.3 Stem cells

A stem cell is defined as any cell type that has two important properties. Firstly, it can divide and renew itself endlessly to make more cells with the same properties and, secondly, it can differentiate to make other cell types, with other biological functions.

Stem cells differ from most other cells in the following ways:

- They are unspecialised.
- They can divide repeatedly to make large numbers of new cells.
- They can differentiate into several types of cell.
- They have a large nucleus relative to the volume of the cytoplasm.

But not all stem cells have the same **potency**; that is the ability to give rise to similar cell types. Stem cells may be totipotent, pluripotent or multipotent. Stem cells found in bone marrow are an example of **multipotent** cells. They can produce many kinds of cells, but only types of blood cell. (Figure 8.1.4) In contrast, **pluripotent** stem cells can make multiple types of cell from all three layers of an embryo (known as embryonic germ layers and shown in Fig 8.1.5) but not form extra-embryonic tissue that becomes the amnion. Finally, **totipotent** stem cells can make all three embryonic germ layers and the extra-embryonic tissue. The only truly totipotent cell is the zygote (fertilised ovum).

KEY POINTS

stem cells retain the ability to develop into specialised cells to replace cells that are damaged or diseased.

totipotent cells have the potential to divide until an entire organism is formed

pluripotent cells can divide into most cell types in an organism but cannot form an entire organism

multipotent cells are able to self-renew by dividing and develop into several specialised cell types in a specific tissue or organ. Most adult stem cells are multipotent stem cells

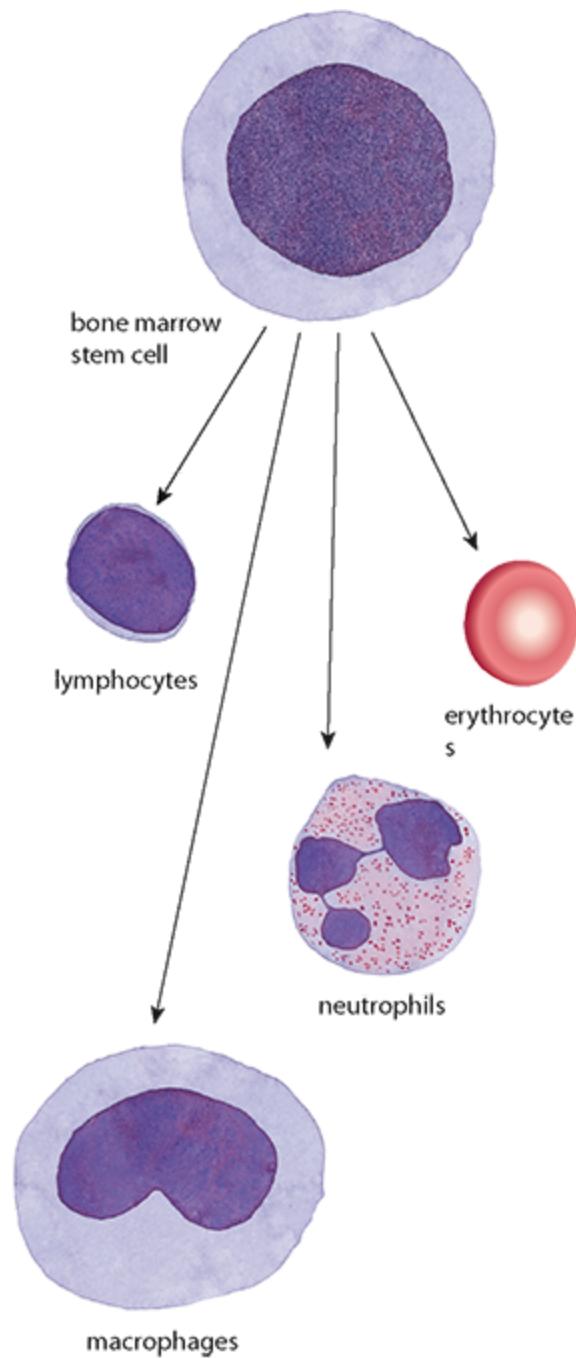


Figure 8.1.4: Bone marrow cells differentiate into the different types of blood cell.

Stem cells are found in embryos but also persist in adults. Examples of adult stem cells are found in the bone marrow and hair follicles, both are multipotent. Bone marrow stem cells only

produce cells which will become part of the immune system and red blood cells while hair follicle stem cells have the capacity and ability to generate various tissues. They are found in an area called a niche close to the base of a hair follicle sebaceous gland. They generate all cell types of the skin, including keratinocytes, that make up the structure of the skin and hair.

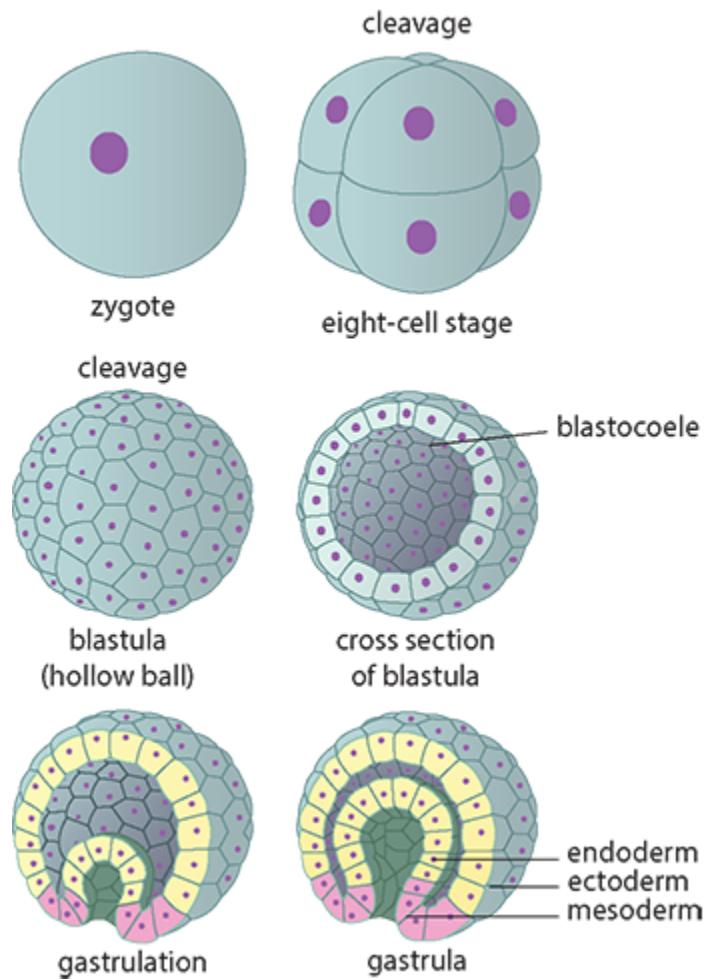


Figure 8.1.5: Development of the three layers in an embryo.

Early cell specialisation

The fertilised egg of any organism contains all the information needed to enable that single cell to develop into a complex organism consisting of many different types of cell. The genes

inherited from the maternal and paternal DNA carry this information. A fertilised egg which is totipotent divides rapidly and produces a ball of cells called a blastocyst in which all the cells are alike (Figure 8.1.5). Gradually the cells in the blastocyst differentiate and begin to develop to form specialised tissues such as muscle or liver. The process of differentiation produces cells for specific purposes: muscle cells for contraction, liver cells for metabolism of toxins, and so on. Once differentiation has happened, it cannot be reversed. Cells in the blastocyst have the potential to turn into a great many different cell types: they are said to be **pluripotent** and are known as embryonic stem cells. Pluripotent stem cells can divide into most, or all, cell types but cannot develop into an entire organism on their own.

In human development, the first eight weeks after fertilisation of an egg are when stem cells in the blastocyst grow and differentiate. During week three, the process of gastrulation occurs, which folds layers of cells until there are three distinct cell layers: the mesoderm, endoderm, and ectoderm. These layers are known as the primary germ cell layers from which organs are formed. The position of a cell will determine which genes are expressed and what each cell will become.

- The endoderm forms organs of the intestine and respiratory systems, as well as the thymus, parathyroid, bladder, and urethra.
- The ectoderm forms the skin, the nervous system, and parts of sensory organs.
- The mesoderm forms the circulatory system and blood, lymphatic system, bone, cartilage, muscles, and many internal organs such as the kidneys.

After eight weeks of development, organ systems have developed and by week nine, the embryo becomes known as a fetus. Growth and differentiation continue until birth.

As the embryo continues to develop, individual cells continue to differentiate from what were pluripotent **embryonic stem cells**. Cells are guided towards particular developmental pathways, creating different cell types. This is possible because the cells can control which genes are expressed and translated into proteins. Different signals cause embryonic cells to select specific parts of their DNA that are used to synthesise the proteins needed to form different cell types. This differentiation is brought about by factors inside the cells as well as factors that act on the cell from the outside. The exact molecular interactions that control cellular differentiation in the developing embryo are still not fully understood.

You can read more about the development of the human embryo and fetus in [Section 8.4](#).

Plants also contain stem cells. These are found in the meristems just behind the tips of growing roots and stems. These cells can only differentiate to become various tissues of the root and stem.

TEST YOUR UNDERSTANDING

- 1 Define the terms tissue and organ.
- 2 Outline the special properties of stem cells.
- 3 Describe how cells differentiate to carry out different functions.
- 4 What is the function of stem cells in the human body?

SCIENCE IN CONTEXT

Therapeutic use of stem cells

Another source of stem cells, which has been successfully used in medical treatments, is the blood in the umbilical cord of a newborn baby (Figure 8.1.6). These stem cells can divide and become any type of blood cell. Cord blood can be used to treat certain types of leukemia, a cancer that causes overproduction of white blood cells in the bone marrow. Cells from the cord blood are collected and their tissue type is determined. After chemotherapy to destroy the patient's own bone marrow cells, stem cells that are the correct match to the patient's tissue, are given by transfusion. If the treatment is successful, the stem cells become established in the person's bone marrow and start producing blood cells as normal.

This treatment can work well in young children, but there are not enough cells in a single cord to meet the needs of an adult patient. Scientists have been looking for ways to either combine the cells from more than one baby, or to use laboratory techniques to increase the number of cells.

Allowing the stem cells to divide in the laboratory produces many blood cells, but not more stem cells. In 2010, scientists in Seattle, USA, managed to alter a signalling pathway in the stem cells so that the cells could increase in number without losing their stem cell properties. As a result of this process, known as therapeutic cloning, umbilical cord blood may prove to be an even more valuable source of stem cells in the future.



Figure 8.1.6: This technician is collecting blood from an umbilical cord. This blood is a rich source of stem cells.

Transplantation of stem cells is a new technology. So far it has also been successfully used in the treatment of Type I diabetes, and research is continuing into therapies to treat a range of conditions involving neurological damage, such as multiple sclerosis and Alzheimer's disease.

NATURE OF SCIENCE

Ethics and new medical treatments

Although scientists from many countries have cooperated on stem cell research, the laws governing research vary from place to place. In the European Union, research using human embryos is permitted in some countries but is illegal in others such as Germany, Ireland, Italy, Portugal and Austria. In the USA some states fund the research, while others ban it. Australia permits research and New Zealand restricts it. Laws also differ in their application to embryonic stem cell research and in stem cells taken from adult tissues. Because laws depend on political and religious viewpoints, they may change as new information and research develops.

REFLECTION

Could I teach this topic to someone else? Which are the most difficult concepts to communicate?

Links

- Why are prokaryotic cells in a biofilm not considered to be multicellular? ([Chapter 7](#))
- How does epigenetics contribute to differentiation? ([Chapter 4](#))
- How can cells in a multicellular organism specialise when they all contain the same genes? ([Chapter 4.2](#))

8.2 Transport in animals and plants

LEARNING OBJECTIVES

In this section you will:

- learn that circulatory systems are mass flow systems for transport, communication and defence
- learn that the heart, arteries, veins and capillaries make up a circulatory system
- understand that the circulatory system adapts to the changing needs of the body by alterations in blood pressure and heart rate
- compare the structures of arteries, veins and capillaries and relate the differences to their functions
- recall that materials are exchanged between cells and blood in capillaries
- understand that water is transported from roots to leaves during transpiration
- recognise the adaptations of the xylem
- draw a diagram of a section of a plant stem



Describe and explain stages of the cardiac cycle including interpretation of graphs

- compare the single circulatory system of fish with the double circulation of mammals
- understand the function of the lymphatic system
- understand that blood flow to different parts of the body varies with its needs and activity levels
- understand how root pressure causes water movement
- recognise the adaptation of phloem for the transport of substances up a stem.

GUIDING QUESTIONS

- How are organs adapted to their functions?
- How do the different organs in an organ system work together?

Multicellular organisms need to co-ordinate the different parts of their bodies so that they work together and enable the organs to perform their functions. Cells work with other cells to produce tissues and organs and organs are integrated to form effective body systems.

In complex organisms the nervous system and endocrine system send nerve and hormonal messages to ensure effective co-ordination ([Chapter 7](#)). In our own bodies, the blood system transports materials and chemical messages between vital organs while in plants the xylem and phloem perform similar integrating functions.