Option A Neurobiology and behaviour

The environment of an organism changes throughout its life and it is an advantage for the organism to be able to detect the changes and respond to them. Most responses improve survival chances and all living things – from the simplest unicellular organisms to insects, birds and mammals – respond to stimuli such as light and chemicals. Animals have a nervous system to detect changes and transmit information around the body. Neurobiology is the study of the structure and functioning of the nervous system.

Behaviour is the pattern of responses of an animal to one or more stimuli and the study of animal behaviour is called ethology. Different behaviours enable animals to develop social patterns and mating rituals.

A1 Neural development

Learning objectives

You should understand that:

- During the embryonic development of chordates, the neural tube forms as ectoderm infolds and elongates.
- Neurons are formed by differentiation of cells in the neural tube.
- Immature neurons migrate to their final positions.
- Chemical stimuli cause an axon to grow from each immature neuron.
- Some axons extend beyond the neural tube to connect with other parts of the body.
- As a neuron develops, if forms many synapses.
- Synapses that are not used are lost – only those that are used remain.
- Unused neurons are removed in a process known as 'neural pruning'.
- The nervous system can change with experience and is said to have plasticity.

Development of the neural tube and nervous system

The development of the human central nervous system begins in the embryo (during the first 12 weeks after conception). A similar pattern of development can be observed in all chordates (vertebrates and other animals that possess a supporting dorsal rod called a **notochord**). In the embryonic **ectoderm**, an area of cells called the **neural plate** develops and becomes a region known as the **neural groove**. It is these cells that eventually become the brain and spinal cord. The cells of the neural plate gradually change and develop into folds, which extend up from it and eventually meet and close over to begin the formation of a tube (Figure **A.1**). In this way, as the growth of the folds continues, the neural groove develops into the **neural tube**. The tube elongates and its outer cells form the foundation of the nervous system – cells at the anterior (front) end become the brain (Subtopic **A.2**) and those in the posterior (back) region become the spinal cord.

The process of neural development (neurulation) has been extensively studied in the clawed toad *Xenopus laevis* (Figure **A.2**).

At the time when the neural plate forms, the embryo consists of three layers of cells:

- **ectoderm**, which will form skin and neural tissues
- **mesoderm**, which will become muscle and bone
- **endoderm**, which forms the inner cells of the digestive and respiratory systems.

Spina bifida

Spina bifida is a congenital disorder caused when the neural tube fails to close properly during embryonic development. Some vertebrae do not form completely and remain unfused and open, so that a portion of the spinal cord may pass through the opening in the bones. This occurs most often in the lower back in the lumbar or sacral vertebrae. Spina bifida can be treated by surgery soon after a baby is born. The surgeon places the spinal cord back into the body and closes up the gap between the vertebrae, but the affected part of the spinal cord will not be able to function normally. Spina bifida is one of the most common birth defects and occurs in approximately 1 in 1000 births worldwide. Folic acid, taken as a dietary supplement during the first three months of pregnancy, has been found to greatly reduce the risk of spina bifida and other neural tube defects.

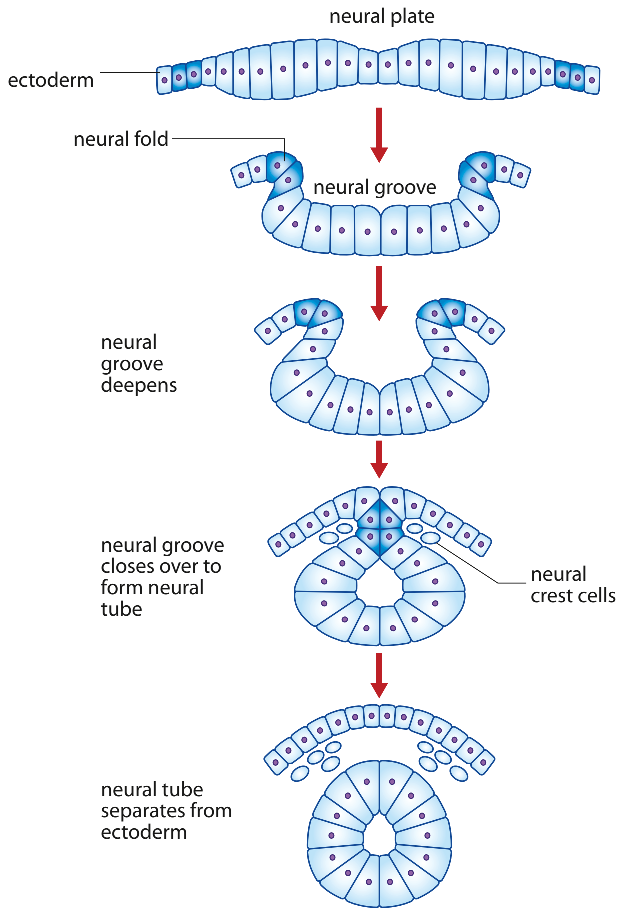


Figure A.1 Neural tube development. Only the ectoderm is shown here – the mesoderm, from which the notochord forms, and the endoderm lie beneath the ectoderm and the neural tube (Figure **A.2**).

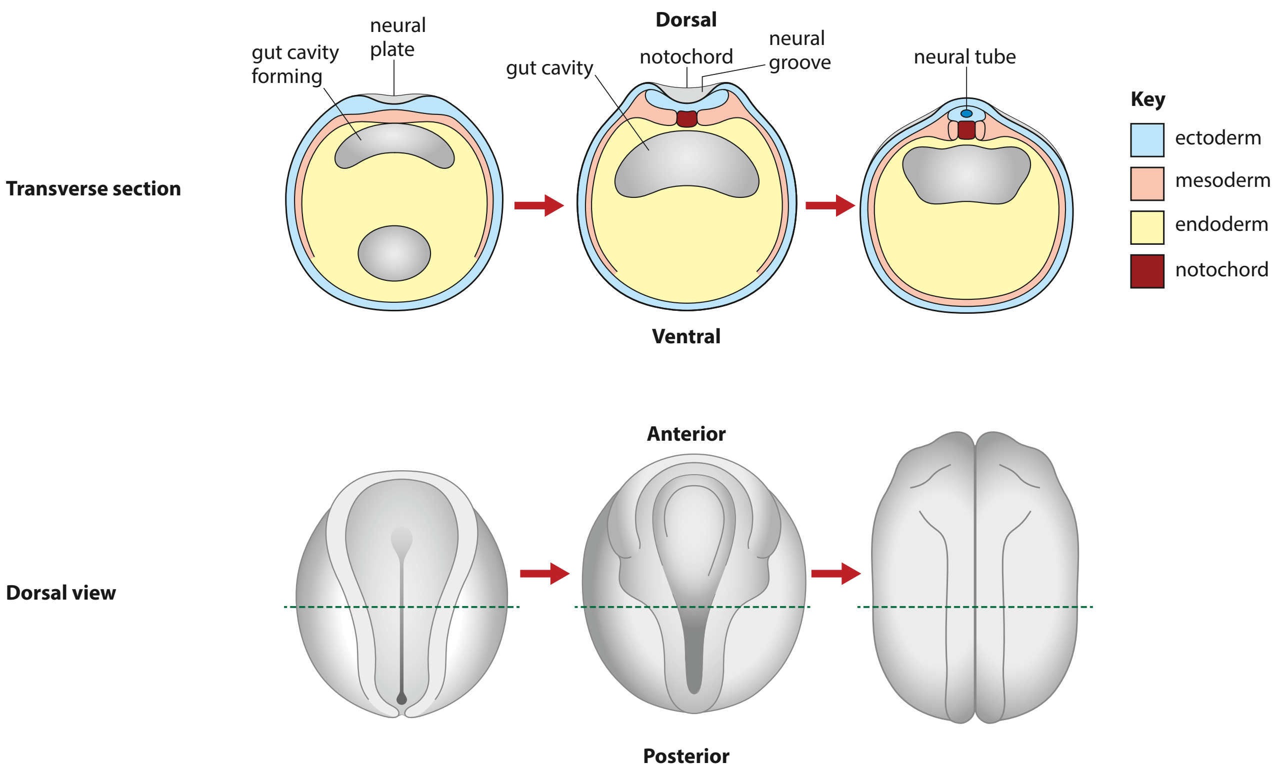


Figure A.2 Formation of the nervous system in the toad *Xenopus*. *Xenopus* is used as a model to study neural development. As an amphibian, it has large eggs with transparent yolk, which enables scientists to study the development of the nervous system as it progresses.

Formation and development of neurons

At the end of the embryonic period of development (12 weeks after fertilisation), the structures that will become the brain and central nervous system (CNS) are established. After this the fetus continues to grow and develop and the fibres of the nervous system extend. Neurons begin to form 42 days (about 6 weeks) after conception and are more or less complete by 18 weeks. Within the developing brain, neurons migrate to different areas and begin to connect with other neurons to make up **neural networks**.

When the neural tube is complete (at about 12 weeks), the cells that will differentiate to become neurons form a single layer lining the tube immediately adjacent to its hollow centre. In the embryo, the hollow centre of the neural tube is cylindrical, like the centre of a straw. But when the brain becomes larger and more complex, the shape of the hollow cavity also changes as the whole embryo changes shape (Figure **A.3**). At this time, a process known as **neural patterning** begins in all parts of the nervous system as neurons take up their positions and start to establish connections. Although this begins in the embryo, the process continues for many years.

Figure A.3 Illustration of a human embryo at five weeks. The embryo is approximately 2 mm across at this stage.

Neuron migration

As the embryo and then the fetus develop, neurons that are produced in the developing brain migrate to different positions. Some move by a method known as **somal migration** in which a neuron moves by extending a long process from its cell body to the outer region of the brain. This region will later become the cortex (Subtopic **A.2**). The long process attaches itself to the outer surface of the brain and the cell nucleus then travels, through its cytoplasm to take up a new position.

Once young neurons have reached their target region, they must become part of a network in order to be able to process information. Neurons need to develop the **axons** and **dendrites** (extensions of their cell bodies) that enable them to communicate with other neurons. Axons send signals away from the neuron cell body, while dendrites receive signals from other neurons. Each cell develops a network of many dendrites close to the cell body and a single axon that can extend for some distance away from the cell (Figure **A.4**). Every axon extends from an area known as a 'growth cone' at the extreme end of the axon. The growth cone responds to and is guided by molecules of certain chemical substances, which direct it to the correct area. Some of these chemical stimuli are attractive while others repel the growing axon. Axons develop within the areas that will become the brain but also extend beyond the neural tube to reach other parts of the body. When an axon has reached its target area, it begins to develop many **synapses** with other cells. Every developing neuron forms multiple synapses and these synapses allow for communication between the cells of the nervous system via **neurotransmitters**.

Exam tip
Check your definitions of key terms such as: neural pruning, plasticity and a model organism.

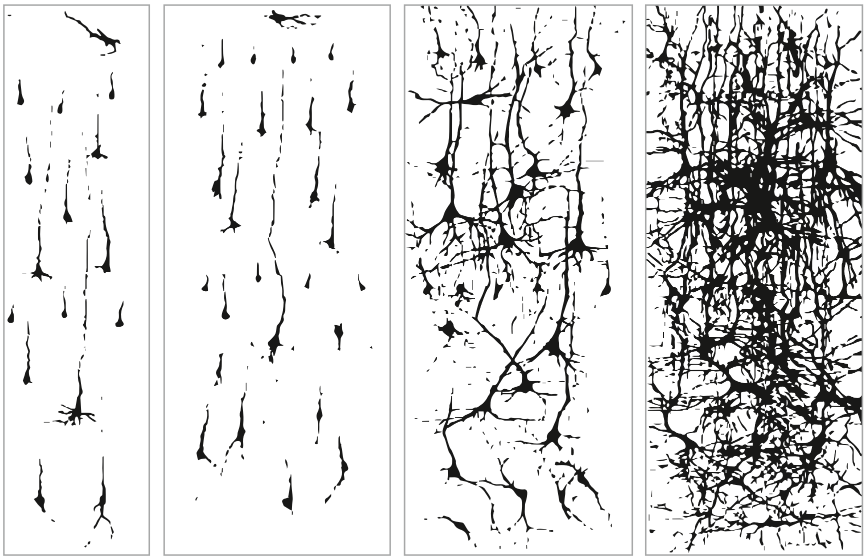


Figure A.4 Connections between nerve cells form during fetal development and become more and more complex in the months and years after birth, establishing intricate neural networks through which information can be passed.

Apoptosis

Apoptosis is cell death that occurs as a result of a regulated sequence of physiological events. A cascade of gene expression results in the breakdown of DNA and histone proteins and eventually the destruction of the cell. All neurons and many other types of cells have this so-called 'suicide' programme. Environmental factors or internal cell events can influence apoptosis. Some factors trigger cell death, while others protect specific cells. Apoptosis occurs in all parts of the developing brain and is particularly high in the cortex, where 70% of cells that form may die as new connections are established or refined.

Cell death in the developing nervous system

During human development there is an enormous amount of cell growth, but the death of neurons is also important. Natural death of cells (**apoptosis**) removes about half of the neurons in certain regions of the brain and, in addition, a second type of cell modification known as 'neural pruning' removes up to half the synapses that have developed between neurons. These two types of cell death are essential to remove unused neurons and thereby help to establish and streamline the complex nerve networks in the brain. The timing of the two types of cell death is different: most cell death (apoptosis) occurs before a baby is born but most neural pruning and synaptic modification occur after birth.

Plasticity of the nervous system

Brain **plasticity** is the ability of the nervous system to change in both structure and function over a person's life, as they react to the changes in their environment.

As a person acquires new knowledge, learns new skills or has new experiences, the brain can establish new neural pathways. Through practice and revision, communication between synapses is enhanced and signals travel more efficiently. Later, if the same neural pathway is used again, the connections between the neurons are re-established and each new attempt means that memory and cognition are made faster. This **synaptic plasticity** is established in a similar way to the way a walker might learn a pathway through a field of corn. If the path is used every day, a clear path will soon become established and the walker will be able to cross the field more quickly and efficiently. Most students can experience synaptic plasticity as they revise for their examinations. On the other hand, if synaptic connections are not used, pathways maybe lost and unused neurons can be removed during neural pruning (see above).

Synaptic plasticity enhances connections between neurons, but a second example of the changes that can occur in the nervous system is **neurogenesis**, the birth and proliferation of new neurons in the brain. For many years it was believed that when neurons died they were never replaced, but stem cells have been found in certain areas of the brain (the hippocampus and the dentate gyrus) that are able to reproduce and migrate to other areas of the brain where they are needed. This may occur after a traumatic event such a stroke, which kills many brain cells. Neurogenesis allows the brain to replace cells that have died and restore functions that have been lost. Alternatively, in some cases, undamaged nerves in different areas of the brain are able to take over the roles of cells that have died and restore some of the functions lost when a person has a stroke.

Language learning

Young children listen to voices around them and soon learn their home language. Infants develop a preference for the vowel sounds of their own language by the age of about six months. The child begins to 'tune in' to their own language and 'tune out' sounds that are not typical of that language. A parallel process takes place in neural development as pathways related to favoured inputs are retained and develop, while unwanted connections are lost by neural pruning. Developmental modifications to the numbers and locations of synapses are probably essential to language learning, both before and after a child is born.

Nature of science

Using models to study the real world – neural development in *Xenopus*

Model organisms are used to study natural events that are difficult to study directly. Species chosen as models are non-human species, used to provide an insight into the way that the biological processes of humans or other organisms work. Different models are used in the study of genetics, reproduction, embryology and biochemistry. Model organisms are chosen for characteristics such as short life span, DNA content or ease of observation. The clawed toad *Xenopus laevis* has been extensively used to study embryonic development in vertebrates because it produces large numbers of eggs, which can be easily seen. Despite the fact that all vertebrates share a common ancestor, and thus share developmental and metabolic pathways, information gained from studies of model organisms such as *Xenopus* must be carefully applied to other species, as there may be important differences as well as similarities.

Test yourself

1 Define 'neural pruning'.
2 Outline the importance of synaptic plasticity in learning and recall.
3 Describe how the neural tube is formed from embryonic ectoderm.

Treating neural tissue injuries

Until recently, it had been assumed that adult brain and spinal cord neurons do not regenerate after injuries, but new research has led to this being reconsidered. Laboratory studies involving investigations of cell signalling and neuro-immunology have increased understanding about how cells may be regenerated.

Experimenters working with rodents placed stem cells from regions of developing and adult brains into damaged areas of the central nervous system. Stem cells that have been grown *in vitro* can be tagged so that they can be monitored after they are grafted into the brain. Experiments like this have indicated that these stem cells are able to adapt to the region in which they have been grafted and differentiate into the appropriate nerve cells. Other studies have shown that these stem cell grafts can also lead to neurogenesis in model animals.

As this knowledge increases, it may one day be possible to treat people with spinal cord and brain injuries by stem cell grafts or by stimulating neurogenesis.

A2 The human brain

Learning objectives

You should understand that:

- The anterior region of the neural tube enlarges to form the brain.
- Different areas of the brain have specific roles.
- The brain stem controls autonomic functions.
- The cerebral hemispheres form the largest part of the human brain.
- Cerebral hemispheres are folded and have a large surface area.
- Higher-order functions are coordinated in the cerebral hemispheres.
- Each cerebral hemisphere interacts with the opposite half of the body.
- A large energy input is needed for brain metabolism.

Basal metabolic rate the amount of energy used by the body when at rest

Brain development

The anterior part of the embryonic neural tube develops to become the brain, and by the end of the embryonic phase of development, at three months after fertilisation, the basic structure of the complete brain is in place. Thereafter, the fetal brain grows rapidly and fibres of the nervous system form. After birth, the brain continues to enlarge and will be four times bigger by the time the child is six years old. At this time it will have become about 90% of its adult volume.

The brain changes in form throughout childhood and adolescence, with both the structure of the brain and behaviour changing as a result. A young child has far more connections in their brain than an adult but these connections are refined (pruned) (Subtopic **A.1**) as the child learns and has new experiences.

A mature human brain contains about 100 billion neurons. Each one can make connections with more than 1000 other neurons so the adult brain may have as many as 60 trillion connections. The metabolism of the brain requires a great deal of energy to maintain its activity – indeed, it has been calculated that the brain requires larger amounts of energy per unit volume than any other tissue. Up to 25% of the energy needed for a human's **basal metabolic rate** is used by the brain, most of which is used to maintain the membrane potential of neurons (Subtopic **6.5**). The majority of the energy comes from the aerobic respiration of glucose. Active regions of the brain use more energy than non-active regions, and this enables fMRI scanning to identify those regions that are active during different activities (see Figure **A.8**).

The structure and function of the brain

The brain is the most complex organ in the human body. Its billions of neurons and connections are responsible for learning, memory and our individual personalities. A human brain has a characteristic folded appearance (Figure **A.5**), which gives it a large surface area, and it is organised so that each part of the brain has a particular function, some regulating automatic processes, such as heart beat and balance, while others control our physical coordination, speech and ability to reason.

- The **cerebral hemispheres** are the largest part of the brain, and form the coordinating centre for learning, memory, language and reasoning. These regions receive information from the sense organs and coordinate and organise motor functions.
- The **hypothalamus** controls the autonomic nervous system (Figure **A.9**). It coordinates the endocrine and nervous systems by regulating the secretions of the pituitary gland.
- The **cerebellum** coordinates movement, posture and balance.
- The **medulla oblongata** (brain stem) controls automatic and homeostatic activities such as breathing, swallowing, digestion and heart rate.

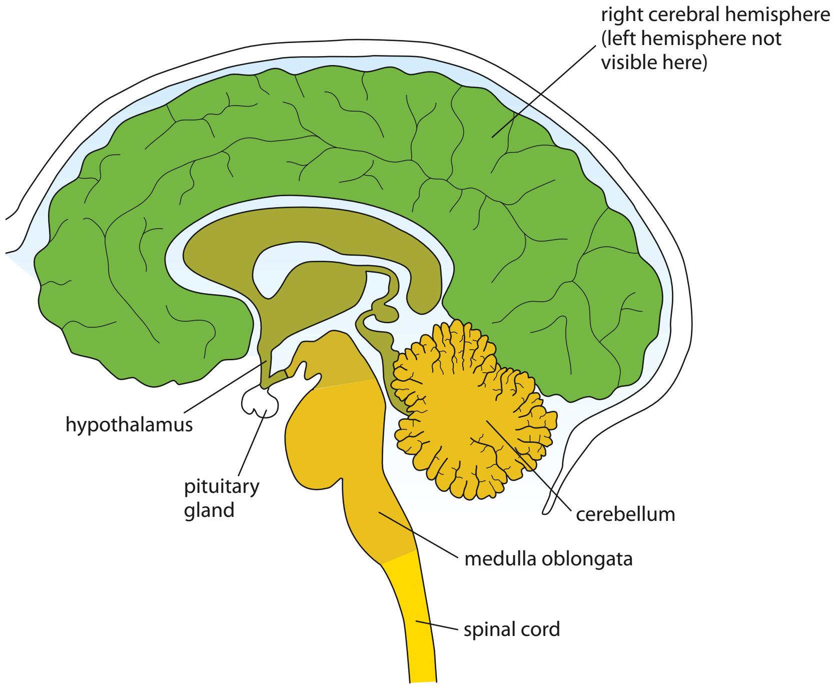


Figure A.5 The human brain.

- The **pituitary gland** has two parts – the posterior lobe stores and releases the hormones oxytocin and ADH from the hypothalamus, while the anterior lobe produces and secretes seven hormones, including FSH and growth hormone, which regulate many of the body's functions (Subtopic **6.6**).

Cerebral hemispheres

The outer, highly folded area of the brain (the **cerebrum**) is made up of two halves, known as the cerebral hemispheres, which are connected by a band of nerve tissue called the **corpus callosum**. The outer layer of each hemisphere is a layer of grey matter called the **cerebral cortex**. The cerebral cortex controls functions such as speech, logic and decision making – the so-called higher-order functions of the human brain.

Although the two cerebral hemispheres look similar, they contain different types of cells and different neurotransmitters. Different areas of the cerebral cortex also have different functions (Figure **A.6**). **Sensory areas** receive impulses from sense organs, **association areas** process the information received and **motor areas** send impulses to effectors in the body.

Information from the left side of the body is received by the right hemisphere and information from the right side of the body is received by the left hemisphere. Likewise, motor signals are sent to each side of the body from the opposite hemisphere. Information is processed by both hemispheres, but there is some division between the functions of each one. For example, association areas of the left hemisphere are important in our use and understanding of language – **Broca's area** is responsible for speaking and writing and **Wernicke's area** is responsible for understanding of language.

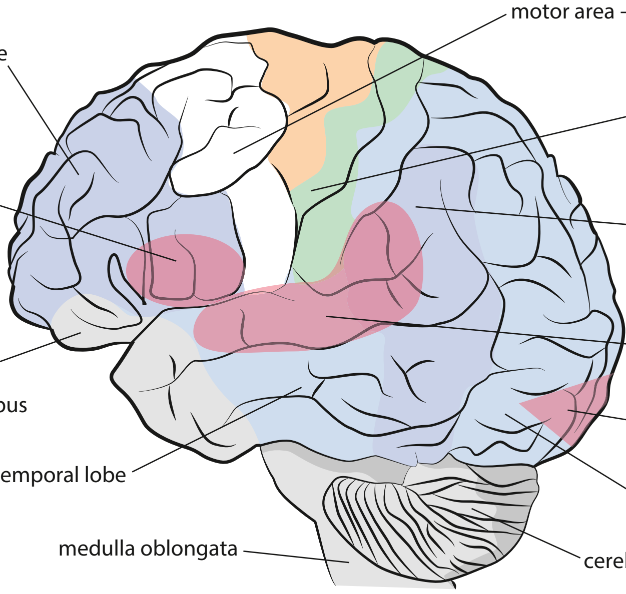


Figure A.6 Approximate locations of important areas of the cerebral hemispheres.

The left side of the brain contains higher levels of the neurotransmitter dopamine while the right has higher levels of norepinephrine. (You may also see norepinephine called noradrenalin in other publications.)

Exam tip
Make sure you do not confuse cerebellum, cerebral cortex and cerebral hemispheres. All are part of the brain but have specific meanings and functions.

Each hemisphere also contains an area known as the **nucleus accumbens**. These regions seem to form part of the brain's 'pleasure centre'. They have been shown to have a role in pleasure, addiction, fear, laughter and reinforcement learning, and research is continuing into their functions.

The **visual cortex** (Figure **A.13**), located at the back of the brain, is the part of the cerebral cortex that is responsible for processing visual information. It receives impulses from the optic nerves and interprets these signals to produce the images we 'see', giving us an understanding of the world around us. Each hemisphere of the brain has a visual cortex. The left visual cortex receives signals from the right visual field and the right visual cortex those from the left visual field.

Brain size and body mass

In general, animals' brain sizes increase with the size of their body so that large animals tend to have larger brains than small animals. But the relationship is not a direct, positive correlation. As the data in Table **A.1** show, mice and humans have a similar brain-size to body-mass ratio, but large animals, including the elephant and hippopotamus, have a relatively small brain for their large body mass even though elephants, in particular, are known to be intelligent animals. For primates, measurements of the size of the whole brain are in fact a better indicator of cognitive abilities than simple brain-size to body-mass ratios, and also remove the need to take account of variations in body mass between underweight and overweight individuals, and differences between adults and young.

Scientists have suggested that a simple size-to-mass ratio is not always helpful in assessing the likely abilities of a species because neurons are very small cells and a large increase in the number of neurons does not cause a huge increase in brain size. A more useful measure than brain-size to body-mass ratios, the encephalisation quotient (EQ), is often used as an alternative. It is calculated from the ratio between actual brain mass and predicted brain mass for an animal of a given size. Scientists propose that this provides a better approximation of the intelligence of the animal and produces a better correlation with the complexity of animal behaviour that we can see.

Species	Brain size : body mass	Encephalisation quotient (EQ)
human	1 : 40	>7
mouse	1 : 40	0.5
elephant	1 : 560	2
dog	1 : 125	1
cat	1 : 100	1
horse	1 : 600	0.9
hippopotamus	1 : 2789	0.9

Table A.1 Brain-to-body-mass ratios and encephalisation quotients for several mammals.

EQ values calculated for mammals, in Table **A.1**, show that carnivores and primates have values greater than 1 while herbivores tend to have lower values. It may be that carnivores with their energy-rich, nutritious diets have greater reserves to support the energy requirements of a large brain but herbivores, which have less energy-rich food, do not. Carnivores may need the greater cognitive ability of a large brain to hunt and kill prey than animals that graze their food.

Investigating brain function

Investigating the brain is a difficult and complex task. Until the arrival of scanning machines, it was difficult to study a living human brain and directly observe its activities.

Animal experiments have yielded valuable information but there are ethical issues involved, particularly when primates, whose brains are most likely to be similar to the human brain, are used. Some procedures involve removing parts of the skull or carrying out experiments on the brain that result in different behaviours. Such experiments may cause distress to the subject animals, which many scientists find objectionable.

Brain lesions – injuries to a specific part of the brain – have provided more direct insights into the functioning of the human brain. Strokes and accidents can damage just one area of the brain and the resulting losses of function give information about what the area controls. One well-documented case of brain injury was that of Phineas Gage in 1848. Gage was a construction worker who survived an accident that sent a large metal pin through his skull and destroyed the left frontal lobe of his brain (Figure **A.7**). Although he physically recovered from the injury and lived for a further 12 years, his personality was completely changed – to the extent that his friends no longer knew him.

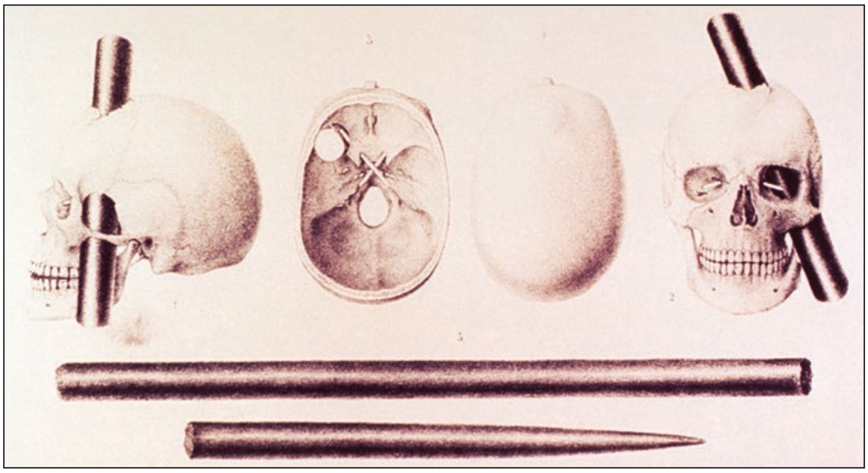


Figure A.7 The skull of Phineas Gage. The fact that his personality changed following the damage to his temporal lobe but he was able to carry on living a fairly normal life, tells us that the temporal lobe is important in coordinating a person's behaviour and reasoning, but not in controlling body functions.

Further information has come from people who have had surgical treatment for epilepsy that involves cutting the corpus callosum, the band of neurons linking the left and right cerebral hemispheres of the brain. Roger Sperry (1913–1994, a psychobiologist who won a Nobel Prize in 1981), and his coworkers carried out 'split-brain' studies on these patients. Sperry discovered that the two sides of the brain can operate almost independently. In a normal brain, the stimulus entering one hemisphere is quickly transferred through the corpus callosum to the other hemisphere so that the brain functions as one. But if the two hemispheres cannot communicate, a person's perception of the outside world is changed. Sperry's work showed that the two halves of the brain have different functions. The left hemisphere of the brain specialises in communication and if a lesion affects this side of the brain, a person may be unable to speak. Damage to the right hemisphere of the brain, which is particularly good at interpreting sensory information and enabling us to understand what we see or hear, may result in a person failing to recognise someone they know well.

Functional magnetic resonance imaging

Since the 1990s, functional magnetic resonance imaging (fMRI) scans have been a key source of new information on brain function. This scanning technique monitors blood flow to different areas of the brain as a subject carries out different tasks. As a region of the brain becomes active, more blood flows to it. Subjects in fMRI experiments are asked to remain still in the scanner as they respond to stimuli or undertake different activities. The scans reveal which areas of the brain are active and help to show how it is working (Figure **A.8**).

Figure A.8 A patient undergoing an fMRI scan.

fMRI scans can reveal Parkinson's disease, tumours and injuries to the brain. But it is important that the images are interpreted carefully. There may be activity in an area of the brain associated with a particular task but correlation does not imply cause. Many brain processes are complex and not confined to one area alone and this explains why, in some cases, different areas of the brain can take over functions of damaged cells following a brain injury or a stroke.

Examination of the brain after death

Brain tissue can also be examined after a person has died and can help our understanding of brain function and disease. Most nucleic acids and proteins are quite stable after death and RNA and protein samples can be used in studies involving RT-PCR (which uses RNA to create DNA profiles), cDNA microarrays (which can identify DNA sequences) and proteomics (the study of proteins and their functions using databases of known sequences). The quantities of nucleic acid and proteins vary from person to person, so it can be difficult to compare different individuals with the same condition or disease, but already researchers have discovered that high levels of certain proteins are associated with brain degeneration and Alzheimer's disease. The rapid development of new techniques available to molecular biologists means that this research is likely to become more and more important in the future.

Sympathetic and parasympathetic control

The **peripheral nervous system (PNS)** consists of all the nerves that do not form the central nervous system (CNS; brain and spinal cord). The PNS comprises the sensory neurons, which carry impulses to the CNS, and the **autonomic nervous system (ANS)**, which is involuntary and regulates internal processes (such as activities of the glands and digestive system, and blood flow) without our awareness (Figure **A.9**).

The autonomic nervous system is subdivided into two parts: the **sympathetic nervous system** and the **parasympathetic nervous system**. Both receive impulses from the medulla oblongata in the brain stem but have opposite effects on the body. The sympathetic system causes responses that are important in an emergency – the so-called 'fight or flight' responses. It is excitatory in its effects. The parasympathetic system controls events in non-urgent, relaxed situations and is inhibitory in its effects. Table **A.2** compares the actions of the two systems on some vital functions.

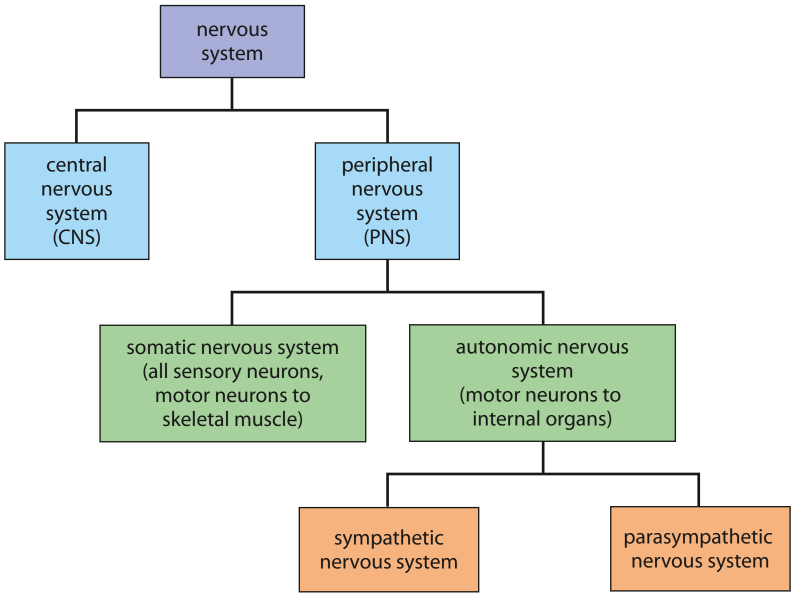


Figure A.9 The components of the human nervous system.

Organ	Effect of parasympathetic system	Effect of sympathetic system
eye	causes contraction of circular muscles of the iris, which constricts the pupil	causes contraction of radial muscles of the iris, dilating the pupil
heart	heart rate is slowed down and stroke volume is reduced as the body is relaxed	heart rate is increased and stroke volume increased so that more blood can be pumped to muscles
digestive system	blood vessels are dilated, increasing blood flow to the digestive system	blood flow to the digestive system is restricted as blood vessels constrict

Table A.2 Comparison of the effects of the parasympathetic and sympathetic nervous systems on three organs.

The pupil reflex

The **pupil reflex** is a constriction of the pupils caused by contraction of the circular muscles in the iris. It occurs when bright light shines into the eye. The rapid, reflex action protects the retina from excess light, which could damage it. Unlike the majority of reflexes, it is controlled by the brain instead of the spinal cord. When light stimulates photoreceptors in the retina, impulses pass along the optic nerve to the medulla oblongata in the brain stem. From here, impulses are sent to the muscles of the iris via parasympathetic nerves. The circular muscles are stimulated and constrict the pupil.

The pupil reflex is used to test the functioning of the brain stem and, along with other tests of reflex actions, is a key indicator of brain death.

Ethics in medicine – the concept of brain death

In medicine, the concept of death is defined in terms of brain functions. Doctors test the activity of the brain stem to determine whether to continue medical treatment. A patient with severe damage to the brain stem (medulla oblongata) is unlikely to recover because this region controls breathing, heart rate and all the automatic, vital functions of life. The legal definition of 'brain death' is based on the activity of the brain stem. If this is permanently damaged, the brain is regarded as having lost neurological function so that consciousness and spontaneous breathing will never be possible.

But life-support machines in modern hospitals can take over the roles of vital organs such as the heart or lungs when a person is seriously ill or injured in an accident. They keep a person's body functioning without the need for impulses from the brain stem and can provide time for an organ to recover. The patient may even be unconscious or in a coma because of damage to the brain, which can recover in time.

Sometimes conflicts can occur when the legal and medical criteria for death do not concur with those of family members.

Questions to consider

- To what extent should the views of family members be given priority in making decisions in medical ethics?
- What are the appropriate criteria to use when making ethical decisions?

Diagnosing death

Bodily death is not clearly definable, and in some cultures diagnosis relies on traditional medical practices. Where loss of brain stem function can be identified, this can be used to diagnose death, based on the understanding that the destruction of the brain permanently removes a person's consciousness so that they cannot interact with others and cannot sustain their own life processes. But sometimes a person with brain damage may enter a 'permanent vegetative state' and this cannot be diagnosed or defined with absolute certainty – there may be a possibility of recovery. At present there is no global consensus on the criteria for brain death and the use of additional tests to confirm death. In an effort to address this, a recent international conference of the European Society of Anaesthesiology in 2013 discussed the criteria used to diagnose death, and the World Health Organization has started work to develop a set of criteria that can be used by doctors all over the world.

Nature of science

Using models to study the real world – sensory and motor homunculi

Sensory and motor homunculi (Figure **A.10**) are models that show the relative space that neurons related to different parts of the body occupy in the sensory cortex and motor cortex of the cerebral hemispheres. Hands, feet, lips and sex organs have more sensory neurons than other parts of the body so, in the model sensory homunculus, these areas are larger. The motor homunculus is similar – again the larger areas are those which have a greater area of the motor cortex is devoted to them. Homunculi are useful for representing the brain to help us visualise the functions of the different areas.

Figure A.10 This model shows a motor homunculus, a similar model can be made to show the relative proportions of sensory neurons.

? Test yourself

4 Outline the role of the brain stem.
5 State what is meant by a 'higher-order function'.
6 Outline the role of Broca's area of the brain.

A3 Perception of stimuli

Human sensory receptors

Sense organs supply our brain with the information it needs to keep us in touch with the world around us. Information about changes in our surroundings is detected by sensory **receptors**, which are able to absorb energy of different types from the environment and transform it into nerve impulses.

We have **thermoreceptors** in our skin that respond to temperature, **photoreceptors** in the retina of each eye that respond to light, and **chemoreceptors** in our blood vessels that detect the pH or carbon dioxide concentration of our blood and help to regulate our breathing.

Chemoreceptors in our noses and on our tongues respond to chemical substances in the environment. Our sense of smell is mediated by olfactory chemoreceptors in the nasal passages. These receptors are activated by the presence of small odour molecules (all with a molecular mass less than 350) and send nerve impulses to the brain. It is estimated that mammals have up to 1000 different receptors, and each receptor can be activated by several similar odour molecules. It is the combination of stimulation of different receptors that builds up our sense of smell, and the number of possible combinations is enormous so we are able to distinguish an almost infinite number of odours.

Mechanoreceptors are another group of receptors, stimulated by pressure or forces. Some respond to changes in blood pressure, others to the movement of fluid in the inner ear. Whenever we move any part of our body (for example, a leg to kick a ball, or an arm and fingers to pick up a pen) we need to know exactly where that part of the body is. We receive this information from mechanoreceptors known as stretch receptors, found in muscles. Stretch receptors respond to stretching of the muscles and allow the brain to work out the positions of all parts of the body.

Variation in sense of smell

Sensitivity to smell varies from person to person and is genetically determined. Some people cannot smell the odour of a skunk and others cannot smell the fragrance of freesias. In general, women have a more acute sense of smell than men and their sensitivity varies through the menstrual cycle, peaking at ovulation when it coincides with a surge in oestrogen. The level of this hormone also increases during pregnancy, and some women report an increase in smell sensitivity during pregnancy.

Many animals have a much more acute sense of smell than humans. Dogs can distinguish non-identical twins by smell, but not identical twins. 'Sniffer' dogs, pigs and even rats have been used to locate explosives and illegal drugs.

Learning objectives

You should understand that:

- Receptors are cells that respond to changes in the environment.
- Rods and cones are photoreceptors in the retina of the eye.
- Rods and cones are sensitive to light of different intensities and wavelengths.
- Impulses from rods and cones are carried by bipolar cells to ganglion cells.
- The optic nerve carries impulses from ganglion cells to the brain.
- Information about the left field of vision, from both eyes, is sent to the right part of the visual cortex, while information about the right field of vision is sent to the left side of the visual cortex.
- Sound waves are transmitted and amplified by structures in the middle ear.
- Sounds are detected in the cochlea by sensory hairs sensitive to specific wavelengths.
- Impulses from the sensory hairs, produced in response to sound waves, are transmitted to the brain via the auditory nerve.
- Movement and orientation of the head are detected by sensory hair cells in the semicircular canals.

The human eye

Photoreceptors in the human eye make it a very efficient light-sensitive organ. Light rays entering the eye are bent by the cornea and lens and focused onto the **retina** (Figure **A.11**).

The two types of photoreceptor cells, arranged in a single layer in the retina, are called rods and cones.

- **Cone cells** are not very sensitive to light but three different types of cone are sensitive to three different wavelengths of light and enable us to see in colour.
- **Rod cells** are much more sensitive to light. They absorb all wavelengths of light and function well at low light intensities. In dim light, only rods cause nerve impulses to be transmitted along the optic nerve so we cannot perceive colour and the world appears in shades of grey.

Table **A.3** summarises the characteristics of rod and cone cells in the retina.

Rods	Cones
highly sensitive to light, work in dim light	less sensitive to light, work in bright light
one type of rod can respond to all wavelengths of light	three different cones respond to red, blue and green light so we can detect colour
groups of rods are connected to a single bipolar cell	each cone is connected to its own bipolar cell
not present in the fovea	not present at the very edge of the retina

Table A.3 Comparison of rods and cones in the human retina.

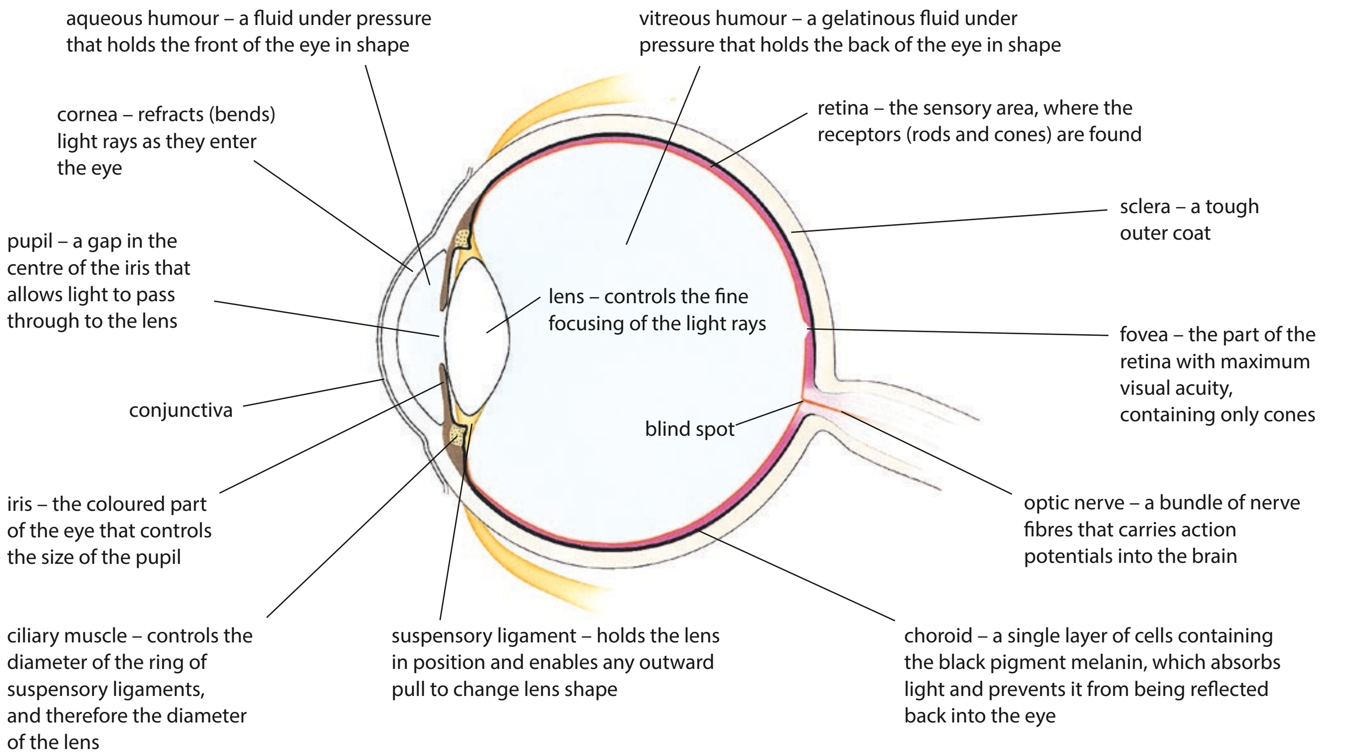


Figure A.11 The structure of the human eye, in transverse section (the eyelids are not shown).

In addition to rods and cones the retina also contains two layers of neurons – **bipolar cells** and **ganglion cells** (Figure **A.12**). These cells conduct the information from rods and cones to the optic nerve.

The **fovea** is an area of the retina directly behind the pupil. It contains the highest concentration of cones in the retina. When you look directly at a small object, its image is focused on the fovea, which is the part of the retina that produces the most visually accurate image.

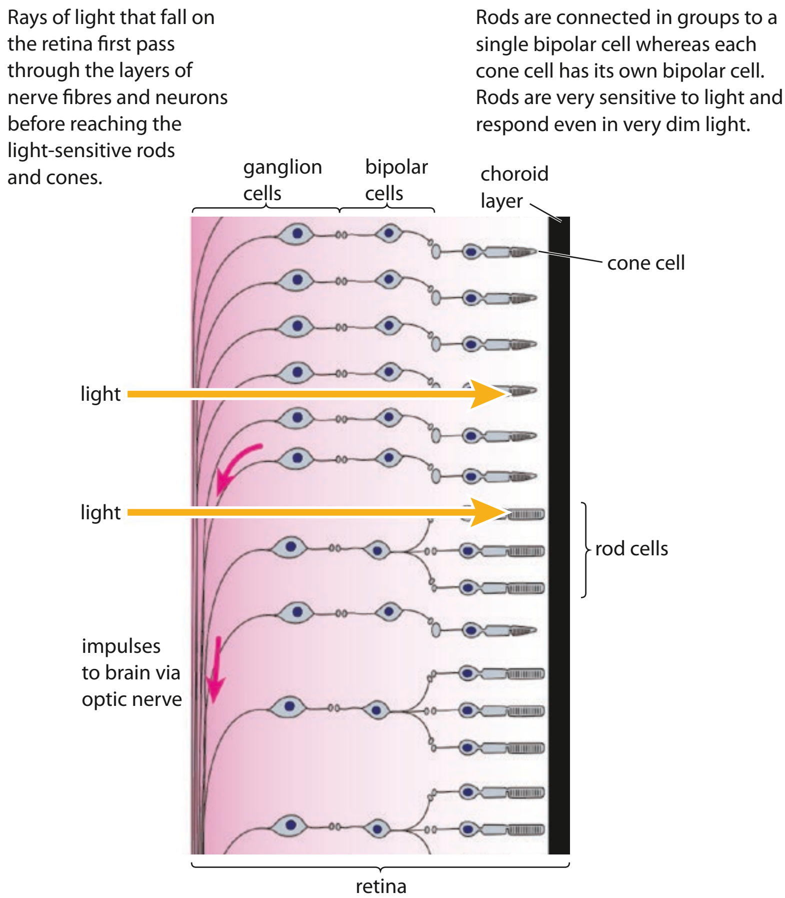
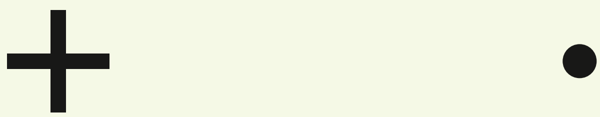


Figure A.12 The retina of the human eye.

> **Exam tip**
> Remember that light passes through the bipolar cells before it hits the rods and cones.

Blind spot

At the point where neurons leave the eye in the optic nerve, they pass through the layer of rods and cones, and this creates the 'blind spot'. We do not perceive an image when rays of light fall on the blind spot, because the light does not fall on any rods or cones here. However, the blind spot is in a slightly different position in each eye, which means each eye is able to 'fill in the gap' for the other, and we are not aware of any blank areas in our visual field.



Position your eyes so you are 60 cm away from the cross and dot. Close your left eye and concentrate on the cross with your right eye. Slowly move close to the image. When the image of the dot falls on your blind spot it will disappear.

What do animals see and can they see in colour?

Humans have three types of cone and can see a range of colours that we call the visible spectrum. No one knows exactly what other animals see or to what extent they see in colour. We can only study the physiology of their eyes and the light-sensitive cells they contain and attempt to deduce what their brains may perceive. Colour vision and perception across the animal kingdom is the subject of ongoing research.

Of the species studied so far, the best colour vision appears to be found in birds, aquatic animals and certain insects, especially butterflies and honeybees. Most mammals have weak colour vision; humans and other primates have the most advanced colour perception. Dogs have two types of cones, suggesting that they may view the world in a similar way to red-green colour-blind humans. Cats have three types of cones, but a much lower proportion of cones to rods than humans. They can distinguish blue and green but probably do not perceive red objects well. Many animals can see things that we cannot. Bees can perceive light in the ultraviolet range but do not see red well. This explains why very few wild flowers are pure red.

Questions to consider

- To what extent can the statement 'beauty is in the eye of the beholder' be related to the physiology of the eye and brain?
- We do not know what animals actually see. Could their understanding of what they see be similar to a human's 'understanding' of an abstract impressionist painting?
- Is it ever likely to be possible to answer these questions?
  - Does a bull really get enraged by a red cape?
  - How do bees know which flowers to visit for nectar?

Visual processing

Light rays entering the eye stimulate photoreceptors (rods and cones), which send impulses to bipolar neurons. These neurons combine impulses from groups of rods or from individual cone cells and generate action potentials in the ganglion cells. From here, nerve impulses travel along the axons of neurons in the optic nerve to the visual cortex at the back of the brain. Impulses pass via the **optic chiasma** and relay areas in the thalamus of the brain as shown in Figure **A.13**. When the impulses reach the visual cortex, they must be interpreted to produce the images we 'see'. For example, because of the way light rays pass through the lens of the eye, the image falling on the retina is both inverted and reversed from left to right. However, the images we 'see' are not inverted or reversed. This is because the brain interprets the impulses it receives, so that we perceive the world 'the right way up'. This is **visual processing**.

Contralateral processing

The brain must also coordinate the information it receives from both eyes. As we view an object, each eye receives a slightly different view of the visual field, which is detected by different regions of the retina in each eye. Axons from the region of the retina closest to the nose in each eye cross over in the optic chiasma to go to the opposite side of the brain. This means that all the information from the left visual field goes to the right visual cortex and all the information from the right visual field goes to the left visual cortex (Figure **A.13**). This is called **contralateral processing**. The visual cortex assembles all the information it receives and gives us an understanding of what we are looking at.

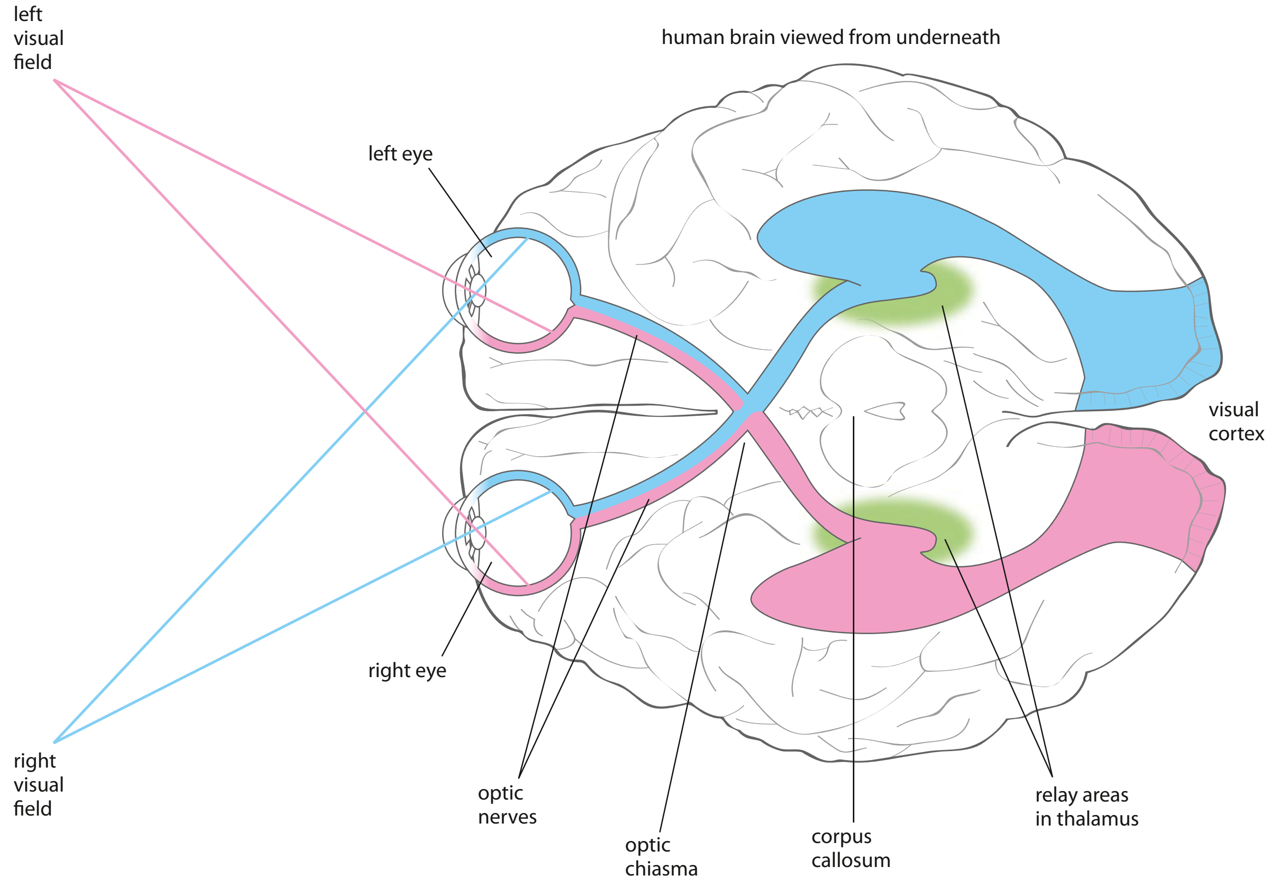


Figure A.13 Both sides of the brain work together to enable us to recognise objects. Contralateral processing allows us to work out the size of an object and its distance from us.

Red-green colour blindness

Red-green colour blindness is a sex-linked condition caused by a faulty gene on the X chromosome. For men to be affected, the recessive 'colour blindness' allele need only be present on their single X chromosome, whereas for women the alleles on both X chromosomes must be recessive (Subtopic **3.4**). This explains why red-green colour blindness is far more common in men than in women. About 8 in 100 men and 1 in 100 women are affected.

Anomalous trichromatism is the medical term for the mildest and most common form of colour blindness. All three types of cone cells are present in the retina but there is a fault in either the red or green cones, giving reduced sensitivity to certain colours. For example, if the red cone is faulty, colours containing red cannot be distinguished clearly. People who are colour blind vary in their ability to distinguish between different colours – some are more affected than others. A very small number of people are unable to see any colour at all and are truly colour blind.

Stereoscopic vision

Each eye captures its own slightly different view of an object and so two separate images are passed to the brain for processing. When the images arrive, they are combined into just one 'picture'. The brain unites the two images by matching up the similarities and adding in the small differences to produce stereoscopic vision. With stereoscopic vision, we can perceive where objects are in relation to us quite accurately. This is especially true when things are moving towards or away from us. We can even perceive and measure 'empty' space with our eyes and brains.

The human ear

Figure **A.14** shows a diagram of a section through the human ear. It is divided into three regions – outer, middle and inner ear.

The outer ear and middle ear are separated by the **ear drum**, and the middle ear is separated from the inner ear by the oval and round windows. The **pinna** is a sound-collecting device and in many animals it can be rotated by muscles to pick up sounds from all directions. Most humans have lost the ability to use these muscles.

The **Eustachian tube** connects the middle ear to the back of the throat via a valve and maintains an equal pressure of air on each side of the ear drum. In the inner ear, the **cochlea** detects sound and the **semicircular canals** detect motion.

Exam tip
Check that you can label a diagram of the eye and ear – this is often part of an exam question.

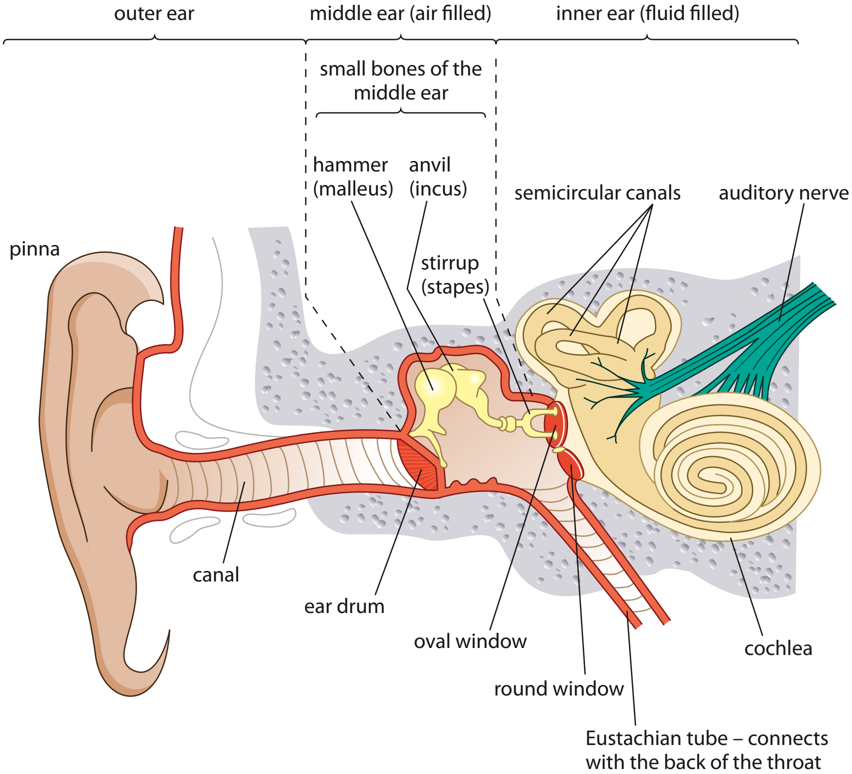


Figure A.14 Section through the human ear. Note that the pinna is not drawn to scale with the internal structures of the ear.

How sound is perceived

Sound is created by differences in air pressure, which produce vibrations called sound waves. Sound waves enter the outer ear canal and cause the ear drum to vibrate back and forth (Figure **A.15**, top). These movements are transmitted to the three tiny bones in the middle ear. The ear drum is in contact with the first bone and the third bone touches the oval window. Each bone vibrates in turn so that vibrations pass via the bones to the oval window. By the time the vibrations reach the inner ear they have been amplified up to 20 times because the bones act as levers, increasing the force of the waves, and also because the oval window is much smaller than the ear drum.

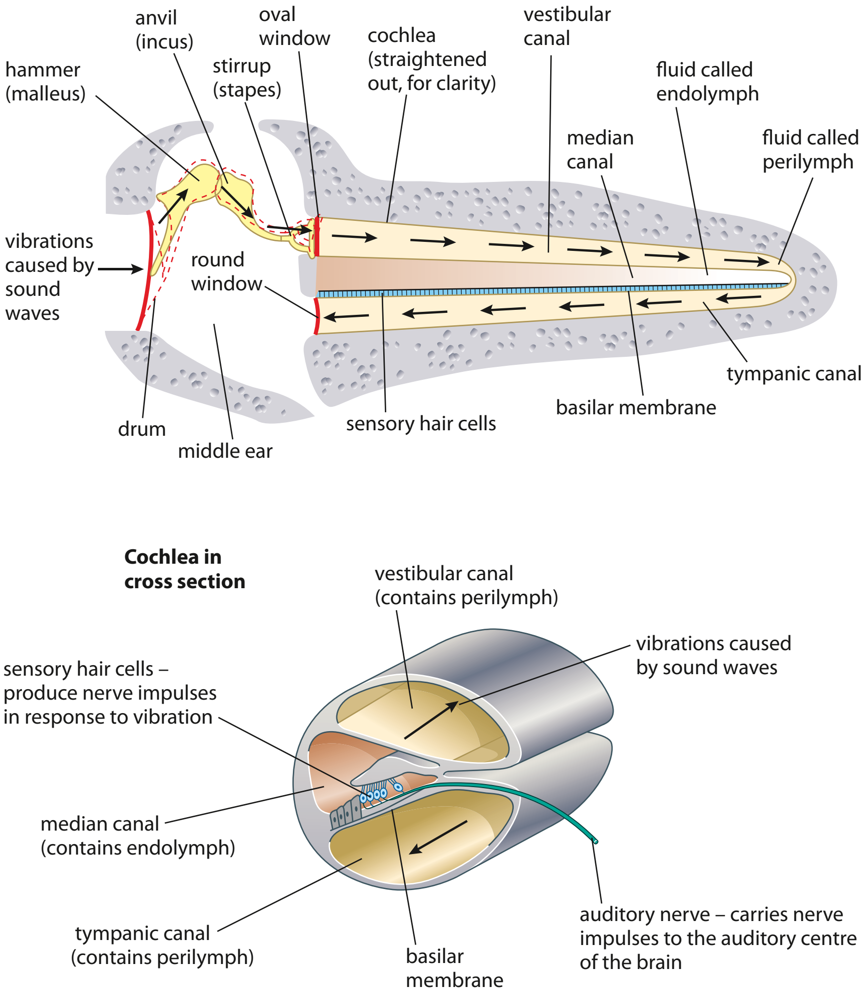


Figure A.15 The structure of the cochlea.

Vibrations of the oval window are passed on to the fluid contained in the cochlea. The fluid cannot be compressed and can only move because the round window at the end of the coiled cochlea absorbs the pressure of the waves of fluid as they arrive.

Inside the cochlea are sensory hair cells attached to membranes, as shown in Figure **A.15**. As the fluid moves, it moves groups of hair cells, which initiate nerve impulses that are passed via the auditory nerve to the auditory centre of the brain. Different regions of the cochlea respond to different frequencies of sound. High frequencies (short wavelengths) are detected nearest to the oval window and the lowest frequencies (longest wavelengths) are picked up further away. Hair cells in any one region vary in their sensitivity and this allows differences in loudness to be detected. A quiet sound stimulates only a few hair cells in a particular region so few nerve impulses are sent to the brain. If the sound is louder, more hair cells are stimulated and more nerve impulses pass to the brain.

Hearing range

A young person can detect sounds of wavelengths between 40 and 20 000 Hz but as we age we lose the ability to detect higher frequencies. Loss of hearing is also common among rock musicians and people who work in very noisy environments without ear protection because excessive noise damages the hair cells in the cochlea. Many species can hear a different range of sounds from humans. Dogs can hear up to 40 000 Hz and bats up to 100 000 Hz.

The semicircular canals

The semicircular canals are organs that give us a sense of position and balance, by enabling us to detect movements of the head. The three fluid-filled canals are arranged so that each one is aligned in a different plane, at right angles to the others (Figure **A.16**). At the end of each canal is a cavity containing receptors, called the **ampulla**, and the canals

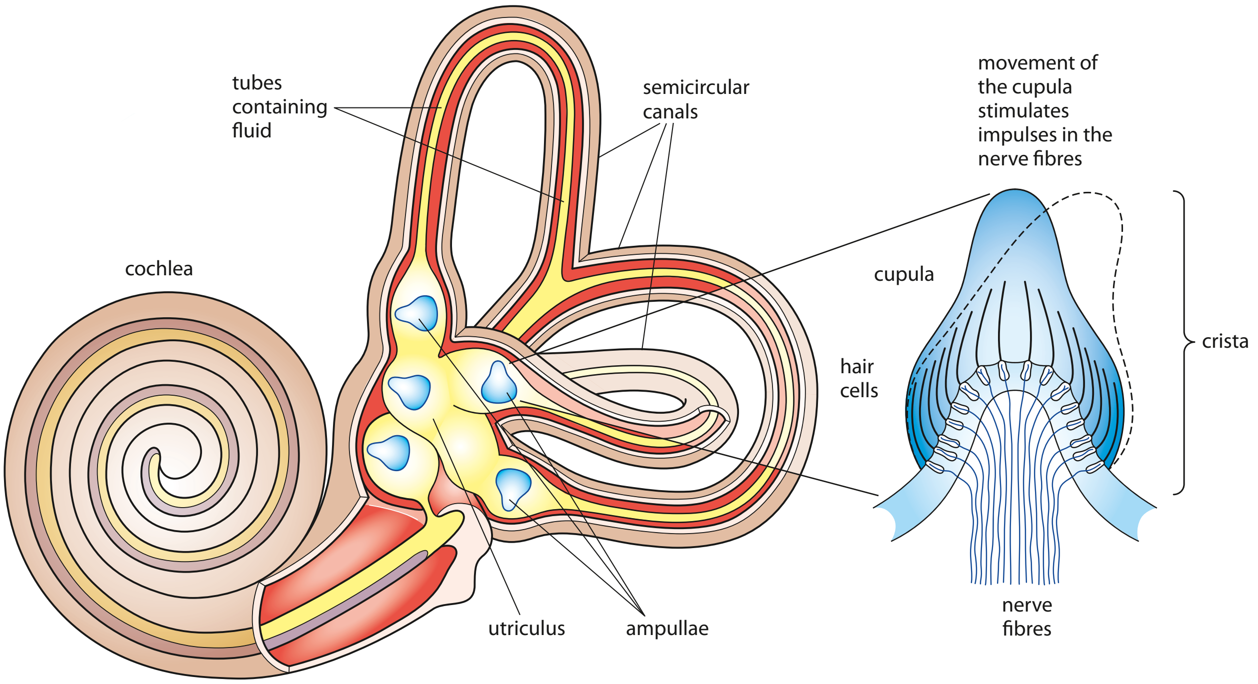


Figure A.16 The semicircular canals and utriculus.

are attached to a central structure known as the **utriculus**, which also contains receptors. The semicircular canals are stimulated by rotation of the head, while the utriculus responds to changes in position. Within each ampulla, sensory hairs are embedded in a jelly-like cap, which is deflected by movements. The inertia of the fluid inside each canal means that the cap is deflected in the opposite direction to the movement of the head. This in turn pulls on the hair cells, which send impulses to the brain.

Nature of science

Scientific understanding drives technical advance – cochlear implants

Understanding the functioning of the ear and how sounds are perceived has led to the development of cochlear implants. A cochlear implant is an electronic device that is surgically placed to provide hearing for people who have damage to the hair cells in the cochlea. Many thousands of people worldwide have benefitted from this technology. Damage to the ear may be caused by diseases such as meningitis, genetic factors or exposure to excessive noise for long periods of time. The cochlear implant bypasses the hair cells in the cochlea and stimulates the cochlear nerves directly using electrical impulses. The brain is able to interpret the frequency of sound as it would if the hair cells were functioning properly. Implants are placed under the skin behind the ear and consist of a microphone that collects sounds, a speech processor that filters and selects important sounds and a transmitter that sends impulses to the internal part of the device. A receiver and stimulator are implanted in bone beneath the skin and these send impulses to electrodes that are woven into the cochlea. The electrodes send impulses to the brain via the auditory nerve.

Test yourself

7 The retina is made up of three layers of cells – photoreceptors, bipolar cells and ganglion cells. State which cell layer light strikes first on entering the eye.
8 Explain the function of bipolar cells.
9 List **three** differences between rods and cones.
10 Outline what is meant by 'contralateral processing'.
11 State the name of the region of the brain where neurons from the left eye and the right eye cross over.

A4 Innate and learned behaviour (HL)

The study of behaviour attempts to understand many aspects of an organism's life, from its instinctive responses to more complex feeding and breeding habits. In a natural environment, two types of animal behaviour can be recognised: innate, instinctive behaviours and learned behaviours that develop as a result of experience.

Learning objectives

You should understand that:

- Innate behaviour is genetically determined and develops independently of the environment.
- Autonomic and involuntary responses are known as reflex actions.
- A reflex arc is a neural pathway that enables a reflex action to occur.
- Reflex conditioning involves forming new associations between neurons.
- Learned behaviour develops as a result of experience.
- Imprinting is a type of learned behaviour that occurs at a particular stage of life and is not affected by the consequences of the behaviour.
- Operant conditioning is a form of learning that involves trial and error.
- Learning is defined as the acquisition of skills or knowledge.
- Memory is the process of encoding, storing and accessing information.

Innate behaviour

Innate behaviour is very often called 'instinct'. This behaviour is common to all members of a species and is genetically controlled. Innate behaviour occurs independently of the environment and is crucial to survival, helping in activities such as finding food, building a nest or escaping from danger. Short-lived species do not have time to acquire learned behaviours or skills and a high proportion of the behaviour of most invertebrates, which are relatively short lived, is innate. Examples of innate behaviour include the movements of dragonfly nymphs as they prepare to pupate (Figure **A.17**), movements of woodlice towards damp areas to avoid drying out, the dances performed by honeybees to communicate the direction of a food source and the mating behaviour of many bird species. Another example of innate behaviour is seen in the mating behaviour of lions (Subtopic **A.6**).

Experimental study of innate behaviour

Innate behaviour of invertebrates includes the movements they make towards or way from stimuli such as food or light. Two examples of this kind of orientation behaviour that can be investigated are taxis and kinesis.

A **taxis** is when an organism moves towards or away from a directional stimulus. A choice chamber is a simple piece of apparatus that can be used to investigate taxis in small invertebrates (Figure **A.18**). It consists of a circular clear plastic box with four sections in the base, over which a piece of gauze can be stretched as a platform for small invertebrates to walk on.

The innate behaviour of woodlice can be observed and recorded using a choice chamber. The conditions under the gauze can be varied to change the humidity in each section of the chamber and the lid covered to provide different light intensities. To investigate the animals' response to light and dark, one half of the chamber can be covered with black cloth,

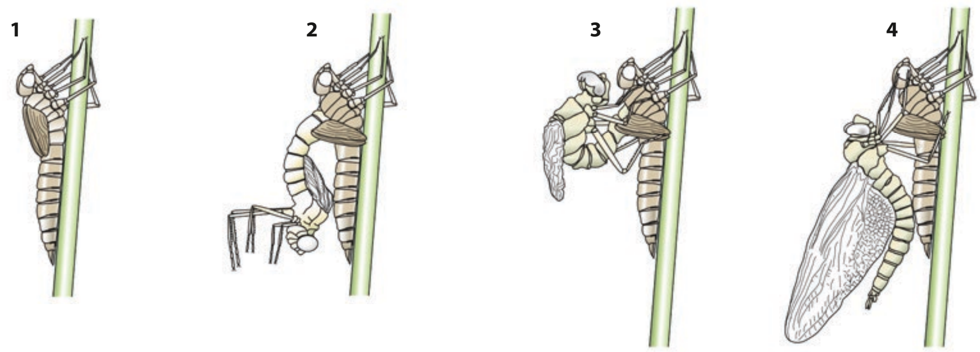


Figure A.17 A dragonfly nymph demonstrates innate behaviour.

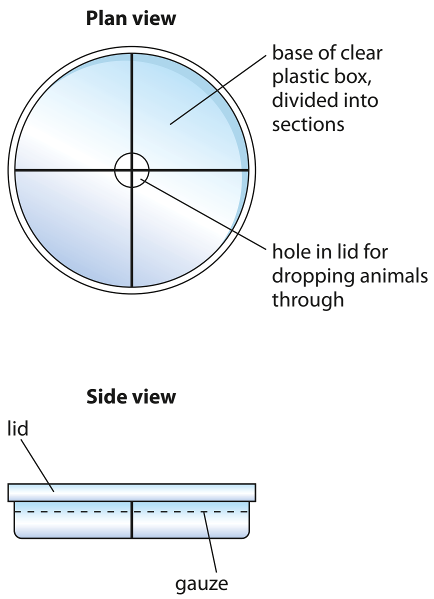


Figure A.18 Plan view and side view of a choice chamber.

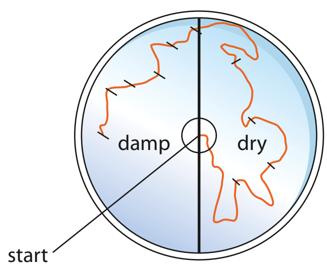


Figure A.19 The distance moved by the woodlouse in 10 seconds is greater in the dry half than in the damp half. The animal also changes direction more frequently.

while the other is left open. When investigating any one environmental factor, all other variables must remain unchanged.

Woodlice can be introduced to the chamber through a hole in the lid and their movements observed. In an investigation into their response to light, the woodlice begin to move from the light area into the dark side after a few minutes. The numbers of animals in each half can be counted after a fixed period of time to provide quantitative data, and the experiment repeated to obtain more accurate results. Directional movement away from light is known as **negative phototaxis**. It helps woodlice to avoid bright sunny places that are likely to be dry and also ensures that they move to shelter under stones and logs away from predatory birds.

A **kinesis** is a response to a non-directional stimulus. It can be recognised as a change in the level of response to a stimulus.

To investigate the response of woodlice to humidity, a choice chamber can again be used, this time with half the chamber providing damp condition and the other half providing very dry conditions. This can be achieved using a drying agent under the gauze in one side of the choice chamber and damp paper in the other. A single woodlouse put into the chamber moves about on the gauze and behaves differently in the different conditions. Its movements can be recorded as shown in Figure **A.19** by tracing its path on an overlay of clear acetate film. The trace can be marked at 10-second intervals, as shown, so that the speed of the woodlouse can be calculated.

The animal moves further and turns more frequently in the dry conditions. This type of behaviour is a kinesis: the rate of movement and turning depends on the level of the humidity stimulus. Woodlice live in damp environments with a high humidity. In dry conditions, they will keep moving and turn more, searching for a more humid environment.

Both of these investigations show how the innate behaviour of woodlice increases their chances of survival. The longer an animal survives, the greater the likelihood of it being able to reproduce. Since these innate behaviour patterns are genetically controlled and inherited, responses that increase survival are more likely to be passed on to offspring.

Intuition in science

It seems intuitive to surmise that the innate behaviour of woodlice in seeking out darker and more humid conditions would increase their chances of survival.

Questions to consider

- Is such intuition sufficient basis upon which to base conclusions?
- In this case, how could this intuition be tested, and would such tests be ethically acceptable?

Test yourself

12 In each of the following, state the type of orientation behaviour that has occurred and suggest why the behaviour helps the animals to survive.

a A sample of 50 *Euglena,* a single-celled photosynthesising organism, was placed in a small, oblong dish and observed under even illumination under a microscope. The distribution of the *Euglena* was seen to be evenly spread over the dish. The illumination was changed so that half of the dish was illuminated and the other half was shaded. After 5 minutes, 48 *Euglena* were in the illuminated side and two remained in the shaded side.

b Newly hatched female silkmoths, *Bombyx mori,* release a pheromone (scented sex hormone) called bombykol, which causes male moths to turn and fly towards them.

c Ten garden snails were placed at the foot of a vertical wall. After 15 minutes the snails had re-orientated themselves and climbed vertically up the wall.

d Three human body lice were placed in a circular chamber that was divided into two parts. One half was kept at a temperature of 35 °C and the other at 30 °C. At the cooler temperature, the insects made few turns but at the warmer temperature, the insects made many random turns and travelled a greater distance in the same period of time.

e *Planaria* are small flatworms that live in lakes and ponds. They have simple light-sensitive eyespots and chemoreceptors at the front of their bodies. Experiments with ten *Planaria* in a choice chamber showed that the animals all moved away from a source of light into a darker area. If a small piece of fish (the natural food of *Planaria*) was introduced into the light section of the choice chamber, five individuals moved towards it.

How should this experiment be modified to include a control?

Reflex actions

Autonomic and involuntary responses (Subtopic **A.2**) are together known as **reflex** actions. A reflex is a specific reaction that is always produced in response to a particular stimulus, and which does not require prior learning. The reflex also forms the basis of Pavlovian conditioning. Sometimes a rapid response to a stimulus is vital for an animal's survival and reflex actions all take place quickly and automatically. Human reflexes include the pupil reflex, which reduces the diameter of the pupil in very bright light to prevent damage to the retina, and the coughing reflex, which occurs when a piece of food enters the trachea.

The **pain withdrawal reflex** takes place if you touch something that causes pain. For example, if you touch a very hot object or are stung by a bee, you pull your hand away quickly, without thinking about it at all. The pain withdrawal reflex is an example of a **reflex action**, mediated by a rapid and simple neural pathway called a **reflex arc** (Figure **A.20**).

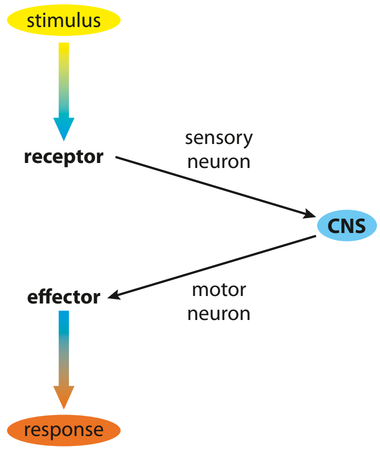


Figure A.20 The basic parts of a reflex pathway.

The pain withdrawal reflex arc involves the receptor cell in your finger, a sensory neuron that carries an impulse to the CNS, a relay neuron in your spinal cord, and a motor neuron that carries an impulse from the spinal cord to the effector – the muscles of your arm that cause you to draw your hand away (Figure **A.21**).

The pathway of a reflex arc is genetically determined so that appropriate responses to different stimuli occur. There are a number of different reflexes that are controlled by the spinal cord, such as the pain withdrawal reflex and the knee jerk reflex. The brain also controls some reflex actions such as the blinking reflex, which happens if something touches the conjunctiva of the eye.

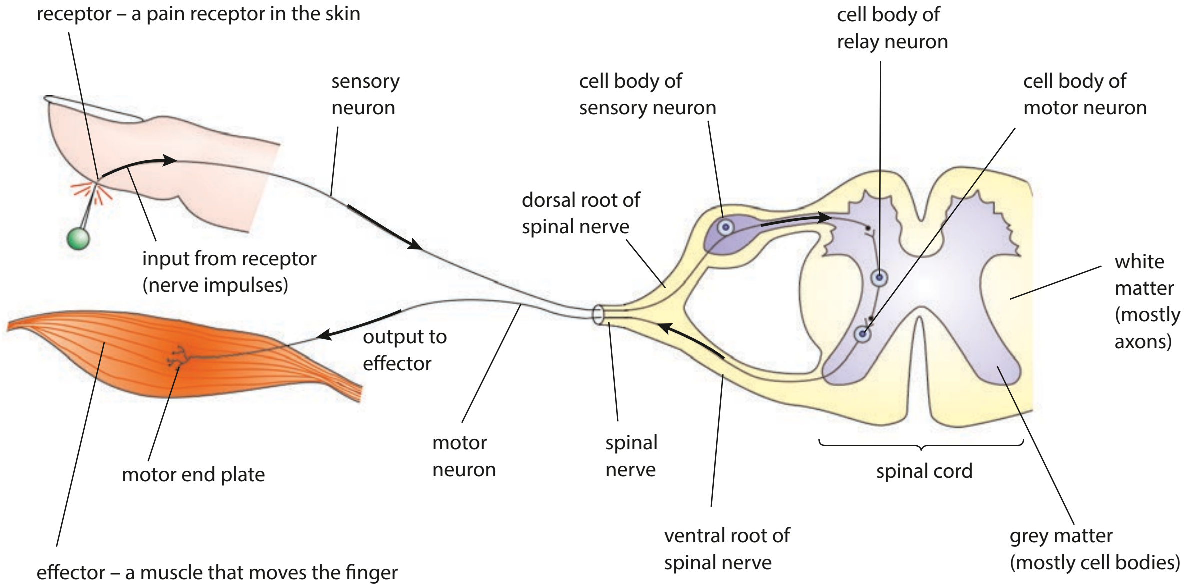


Figure A.21 The spinal reflex arc for the pain withdrawal reflex.

Stimulus a change in the environment (either internal or external) that is detected by a receptor and elicits a response

Response a reaction or change in an organism as a result of a stimulus

Reflex a rapid, unconscious response

Important parts of a reflex arc

Receptors detect a **stimulus** and initiate a nerve impulse. There are many types – e.g. pain, temperature and pressure receptors in the skin.

Effectors are muscles or glands that carry out a **response** to a stimulus.

Reflex arc pathways usually involve the **CNS** – either brain, spinal cord, or both.

Sensory neurons carry impulses from receptors to the CNS.

Motor neurons carry impulses from the CNS to the effector.

Relay neurons inside the CNS connect the sensory and motor neurons via synapses. Relay neurons also connect to neurons going up and down the spinal cord, carrying information to and from the brain. So if you touch something painful, not only do you withdraw your hand rapidly, but information is also sent to the brain so you learn not to do it again.

Learned behaviour and survival

Learned behaviour, unlike innate behaviour and reflex actions, develops as a result of experiences. It is much more adaptable and produces a greater range of behavioural patterns than innate behaviour. Learning is defined as the acquisition of new skills or knowledge, or the modification of existing abilities, which an animal encodes and stores in its **memory**, and can later access as required. Longer-lived organisms with more developed nervous systems are likely to show a higher proportion of behaviour that is learned. Many animals learn from their parents or from older members of their species. Primates, big cats, wolves and many other mammals spend a long time with their parents learning social and hunting skills from them. The matriarch of an elephant herd remembers where water supplies can be found during the dry season and the routes are learned by younger members of the herd.

Primates, in particular, show the ability to acquire new skills that help them to survive. Many monkeys and apes can remember where a particular tree will be fruiting at a certain time of the year and pass on this knowledge to their young. The wild chimpanzees in the Bossou Reserve in Guinea have learned behaviours such as fishing for ants and termites in logs using sticks (Figure **A.22**), and cracking nuts open with a stone hammer and anvil. The young chimps watch other members of the troop and then try to copy them. These behaviours provide a wider range of food sources for the animals that are able to develop the necessary skills.

Many animals learn from experience or by trial and error. Caterpillars of the monarch butterfly in North America feed on a poisonous plant called milkweed. Poison is stored in the caterpillars' bodies and after pupation it is also found in the adult butterflies. If a young toad or bird catches a monarch butterfly, it quickly spits it out and avoids similar prey afterwards. Learning in this way prevents unpleasant and potentially toxic food being taken again.

Raccoons are mammals common throughout North America. Their normal habitat is forest but they have learned that human habitations are excellent sources of food, which they find in pet bowls, garbage cans and even kitchen cupboards. All these new food sources – along with good dens that can be found under houses, in attics and garden sheds – have improved survival rates so much that the animal has become a serious pest in some places.

Figure A.22 These chimpanzees are fishing for termites using tools that they have made.

Imprinting

Imprinting is a type of learning that takes place at a particular stage of life and is independent of the outcome of the behaviour. The best-known work on imprinting was carried out in the 1930s by Konrad Lorenz (1903–1989) who investigated learning in graylag geese. He discovered that in a natural situation newly hatched goslings follow their mother, but that if eggs are removed from a nest and hatched in an incubator, the chicks will 'imprint' on the first moving object they see. When he remained with the eggs as they hatched, and the mother was not present, he found that the newly hatched goslings would follow him (or his boots) instead of the mother bird. He also noticed that this effect only occurred if the exposure was within 13 to 16 hours after hatching – a time he named the **critical period**.

More recently, imprinting has been used to help re-introduce captive-bred birds to the wild. These birds have no adult birds to teach them how to hunt or how to follow the migratory routes of their species. In a novel study in Russia, an Italian hang glider pilot called Angelo D'Arrigo (1961–2006) allowed chicks to hatch under his hang glider so that they imprinted on it. He later encouraged the young birds to follow him into the air so he was able to teach them to fly and hunt. Because the flight path of a hang glider follows air currents and thermals in a similar way to birds, he used his hang glider and knowledge of imprinting behaviour to teach endangered captive-bred Siberian cranes their migration routes from Siberia to the Caspian Sea.

Critical periods for learning

The idea that learning occurs during a critical period is not limited to imprinting in geese. Songbirds have a critical period for song learning and humans also seem to have some critical learning periods. Children below the age of 4 years, for example, seem to learn a language with little effort, without lessons or instructions, while older learners often have much more difficulty and adults seldom learn to speak a new language as well as native speakers.

Operant conditioning

Operant conditioning is behaviour that develops as a result of the association of reinforcement with a particular response. It is a type of trial-and-error learning. The apparatus used to investigate operant conditioning is known as a Skinner box (developed by the behavioural scientist, B. F. Skinner). The box contains a bar or lever that an animal, such as a pigeon or rat, can press or manipulate in order to obtain a reward of food or water (Figure **A.23**). Using these boxes, researchers can study behaviour of animals in a controlled environment. At first, a hungry animal learns by trial and error that pressing the lever causes food to be released. The animal learns to associate the lever with the food reward. The reward is known as **reinforcement**. Experimenters can then condition or train an animal to press the lever in response to specific stimuli such as a sound or pulse of light. If the animal performs the task correctly it receives the food reward. Skinner discovered that operant conditioning develops more quickly if the reward is given sooner after the animal responds, but unexpectedly he found that the response develops more strongly if the reward is not *always* given after the response – the animal presses the lever over and over again, in anticipation of the missing reward. This behaviour could be compared to that of a person in an unmoving elevator who repeatedly presses buttons on the control panel until the expected reward – the movement of the elevator – finally occurs.

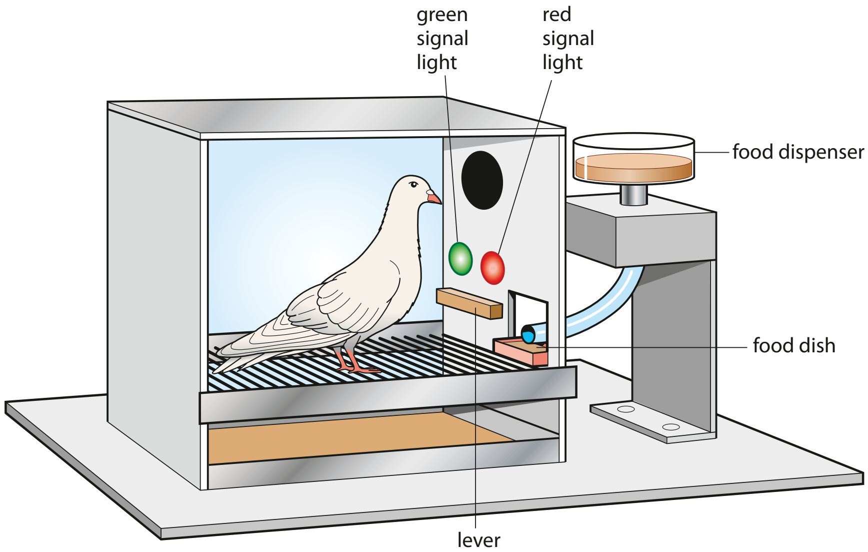


Figure A.23 A pigeon receives a reward of food (reinforcement) for pressing a lever in a Skinner box. Birds can be conditioned to press the lever in response to a signal from a coloured light.

Pavlov's dogs and classical (reflex) conditioning

Ivan Pavlov was a Russian physiologist, psychologist and physician. In the 1890s, he studied the gastric function of dogs and tried to relate the quantity of saliva produced by the dogs' salivary glands to the stimulus of food. Salivation is a reflex response to the presence of food in the mouth but Pavlov noticed that his experimental dogs began to release saliva before they started to eat and he decided to investigate this 'psychic secretion' (Figure **A.24**).

Just before giving the dogs food, and before they could see or smell it, he rang a bell. After repeating his experiments several times he noticed that the dogs salivated as soon as he rang the bell. They had come to associate the sound of the bell with the arrival of food. Even when Pavlov used different sound stimuli, the results were always the same. He called this modification of the dogs' behaviour **classical conditioning** and he used a number of specific terms to explain his results.

- Before training, the normal behaviour involved an **unconditioned stimulus** (the food) producing an **unconditioned response** (the release of saliva).
- After training, the dogs responded to the **conditioned stimulus** (the sound of a bell) and produced the **conditioned response** (the release of saliva without the appearance of food).

Imprinting vs. conditioning

Imprinting and conditioning are two very different modes of learning.

Imprinting usually carries a selective advantage – for example, it causes young birds to stay almost literally 'under the wing' of their parent, where they are likely to benefit from its protection and guidance. But imprinting itself happens 'automatically', regardless of any reward or advantage it brings – so that young birds will imprint on almost anything, however unhelpful.

This type of learning is very different from operant conditioning, for example, which depends on direct rewards. When he carried out his investigations, B. F. Skinner proposed that all behaviour is a reaction to environmental stimuli. Rewards and punishments influence operant conditioning and act as inducements to learning. This fact has many practical advantages in nature and is also used to good effect by teachers in schools and colleges.

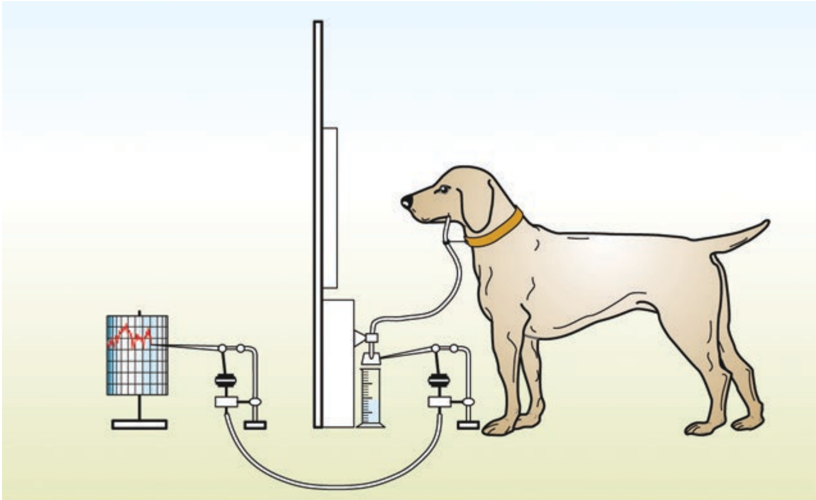


Figure A.24 One of Pavlov's experiments into classical conditioning. A tube in the dog's cheek collected saliva, and the volume collected was recorded on the kymograph drum. Pavlov used this apparatus to investigate the response of the dog's salivary glands to different types and strengths of stimuli.

Behavioural responses involving classical conditioning

Many instances of simple classical conditioning can be observed in animals, including humans.

Questions to consider

Consider the examples below and decide if the behaviour involves Pavlovian classical conditioning or not.

- If you have bells in your school to mark the end of each lesson, watch what the other students do as soon as the bell rings at the end of a class. It is likely that they start to pack up their books and pens, even if the teacher is still talking.
- As you walk past a house, a dog in the garden starts to bark at you.
- A homeowner puts out food for the birds first thing every morning. Early in the morning birds start to gather in the trees near the bird table.
- A sheepdog runs in particular directions or lies down when his owner makes specific whistles.
- A chicken kept in a battery farm cage for a year will start to scratch and peck at the ground when released into a farmyard.

Inheritance and learning in the development of birdsong

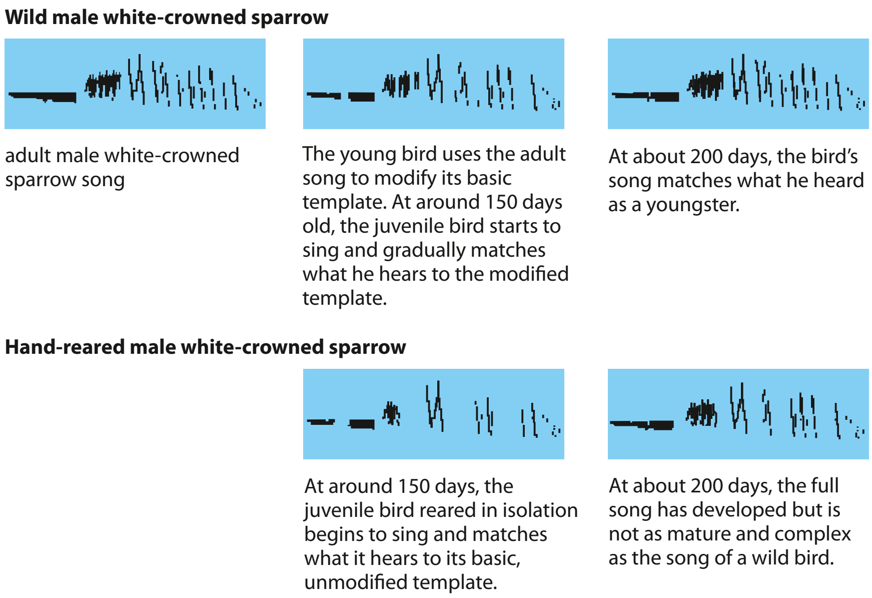
Birds sing to defend their territories and to attract mates in courtship rituals. It is usually male birds that sing so a male bird's song is crucial to both its survival and reproductive success. A bird's song is a long and complex series of notes, which can be analysed using acoustic spectroscopy. Different species have quite different songs, but within a species it appears that, although the basic song is the same for all members of the species, variations do develop. Young birds are born with an innate, *inherited* ability to sing a basic song but *learn* details of their species' song from their fathers. Variations in the song gradually appear and over generations these variations can build up to form local 'dialects'.

One bird that has been extensively studied is the North American white-crowned sparrow (Figure **A.25**). An immature male bird inherits the ability to sing a basic song called a 'template'. However, even before it is able to sing, a young bird listens to its father singing close to the nest and it uses what it hears to upgrade its own basic template. When the young bird starts to sing its own song, it matches what it hears to this upgraded template. A hand-reared bird that never hears adult birds sing is deprived of this learning process and is unable to produce a proper song when it matures. The sonograms of wild and hand-reared birds are shown in Figure **A.26**. A male who does not sing properly will be unable to find a mate.

Figure A.25 A male North American white-crowned sparrow in song.

Memory

Memory is defined as the process of encoding, storing and accessing information. The memory associated with learning a song or learning to respond to the sound of a ringing bell involves changes in an animal's neurons and neural pathways and can be influenced by neurotransmitters (Subtopic **A.5**).



Data from Peter Marler, Animal Communication Laboratory, Section of Neurobiology, Physiology and Behavior, University of California, Davis, CA 95616, USA

Figure A.26 Sonograms of North American white-crowned sparrows.

Nature of science

Looking for trends and discrepancies – laboratory experiments and field investigations

In the study of animal behaviour, both laboratory experiments and field studies have been vital in developing our understanding of different types of behaviour. Skinner and Pavlov both used laboratory studies and apparatus they built themselves to develop theories of operant and reflex conditioning, but other behavioural scientists such as Lorenz have made their observations in the field. Austrian Nobel laureate Karl von Frisch was a contemporary of Lorenz who studied bees and spent long hours tracking the insects and noting the flowers they visited many miles away. Eventually he was able to decode the bees' waggle dance, which they use to communicate the location of flowers to other members of the hive.

In each case, many hours of painstaking observations are needed to collect sufficient data to draw conclusion about the patterns and trends in different animal behaviours.

Test yourself

13 Describe **two** examples of ways in which learning might improve an organism's chances of survival.

14 State **one** example of a taxis and **one** example of a kinesis.

15 Explain how innate behaviour is different from learned behaviour.

A5 Neuropharmacology (HL)

Inhibitory and excitatory synapses

The structure of synapses was discussed in Topic **6**. The most important parts of any synapse are the pre-synaptic membrane, the neurotransmitter it releases and the receptors on the post-synaptic membrane that are stimulated by it (Figure **A.27**).

The synapses discussed in Topic **6** are **excitatory synapses**. When a neurotransmitter is released from the pre-synaptic membrane, the post-synaptic membrane is depolarised as positive ions enter the cell and stimulate an action potential.

But there are many different types of synapses in the body and many different neurotransmitters. Some pre-synaptic neurons release neurotransmitters that inhibit the post-synaptic neuron by increasing the polarisation of its membrane (hyperpolarisation), therefore making it harder to depolarise the membrane and trigger an action potential. Post-synaptic transmission is therefore inhibited at these **inhibitory synapses**.

Neurotransmitters

Neurotransmitters are the chemical substances that are released from the pre-synaptic neuron at a synapse, diffuse across the synaptic cleft, and activate receptors on the post-synaptic membrane. It is these receptors that determine whether the neurotransmitter will cause depolarisation of the post-synaptic membrane or not – that is, whether the stimulus is excitatory or inhibitory. For some neurotransmitters, such as glutamate, the most important receptors all have excitatory effects and increase the probability of an action potential occurring in the post-synaptic cell. For other neurotransmitters, such as GABA, the important receptors all have inhibitory effects. And some neurotransmitters, such as acetylcholine (ACh), are received by both excitatory and inhibitory receptors. Nerve impulses are initiated or inhibited in the post-synaptic cell as a result of the **summation** of all excitatory and inhibitory stimuli they receive from pre-synaptic neurones.

Learning objectives

You should understand that:

- Some neurotransmitters excite post-synaptic membranes but others inhibit them.
- The summation of excitatory and inhibitory effects of neurotransmitters secreted by pre-synaptic membranes results in the initiation or inhibition of nerve impulses in post-synaptic membranes.
- Fast synaptic transmission in the brain is regulated by many different slow-acting neurotransmitters.
- Learning and memory involve changes in neurones caused by slow-acting neurotransmitters.
- Psychoactive drugs work by either increasing or decreasing post-synaptic transmission in the brain.
- Anesthetic drugs interfere with neural transmission between areas of sensory perception and the central nervous system.
- Stimulant drugs mimic the stimulatory effects of the sympathetic nervous system.
- Addiction to drugs can be influenced by genetic predisposition, social environment and dopamine secretion.

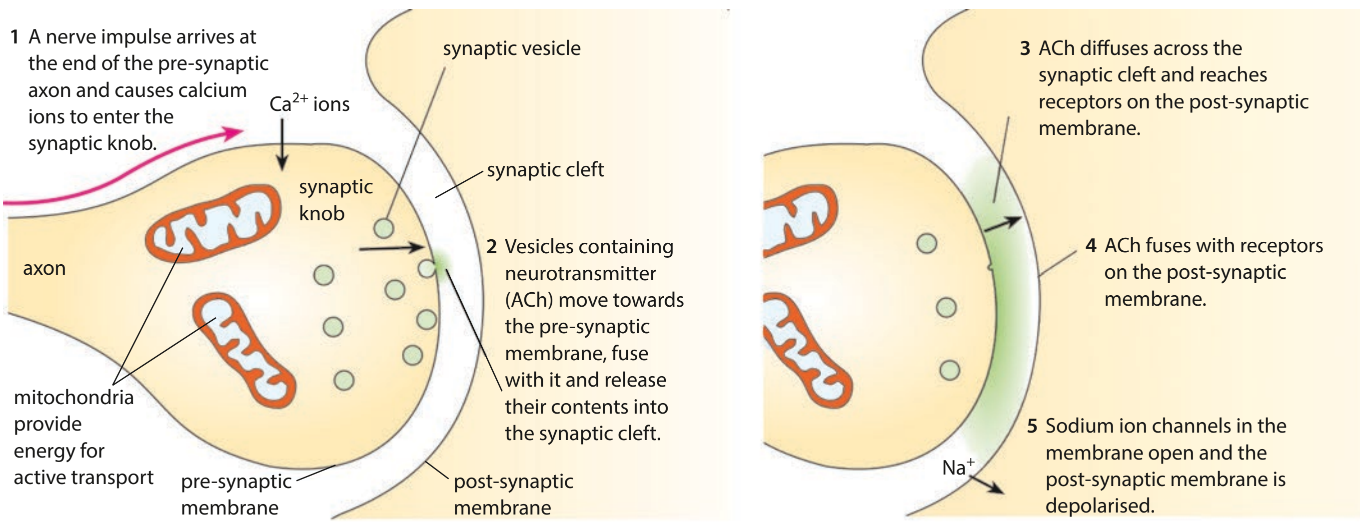


Figure A.27 Synaptic transmission involving ACh (acetylcholine).

Decision making in the CNS

Synapses are the places where action potentials are passed from one neuron to the next. Some post-synaptic neurons are stimulated by many different pre-synaptic neurons, some excitatory and some inhibitory (Figure **A.28**). 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. The balance of the impulses provides an arrangement that allows us to make decisions about the actions we take.

Many different neurotransmitters are found in the brain. Some of these are listed in Table **A.4**. Memory and learning involve changes in neurons caused by a number of these neurotransmitters. For example, patients suffering memory loss due to Alzheimer's disease have a lower level and concentration of acetylcholine and acetylcholinesterase (the enzyme that removes neurotransmitter from the synapse) as well as a loss of cholinergic neurons. Glutamate, one of a group of amino acids that act as excitatory neurotransmitters, is also thought to play an important role in learning and memory. Glutamate has a key role in synaptic plasticity (the ability of synapses to change their **strength** – that is, the ease with which a pre-synaptic depolarisation can cause an action potential to be stimulated in the post-synaptic membrane). The form of plasticity associated with glutamate is known as long-term potentiation (LTP) and occurs at synapses in several parts of the brain. LTP is a long-lasting enhancement in signal transmission between two neurons and is thought to be an important process in learning and memory. Memories are probably encoded by modifications of synaptic strength. In abnormal conditions, glutamate can also act as a neurotoxin and cause damage to the brain, especially in older people.

Synaptic strength

Synaptic strength is defined as the change in membrane potential in a post-synaptic membrane (measured in millivolts, mV) following a pre-synaptic action potential. This change in the post-synaptic membrane may result from activity either at a single synapse or at a number of connections between pre-synaptic neurons and the post-synaptic neuron, and can also depend on the sizes of these connections.

Synaptic strength can vary as a result of previous activity in the neurons, and can be short-term, lasting a few seconds or minutes, or long term, lasting hours (long-term potentiation, LTP). Learning and memory are thought to result from long-term changes in synaptic strength, which result from this synaptic plasticity.

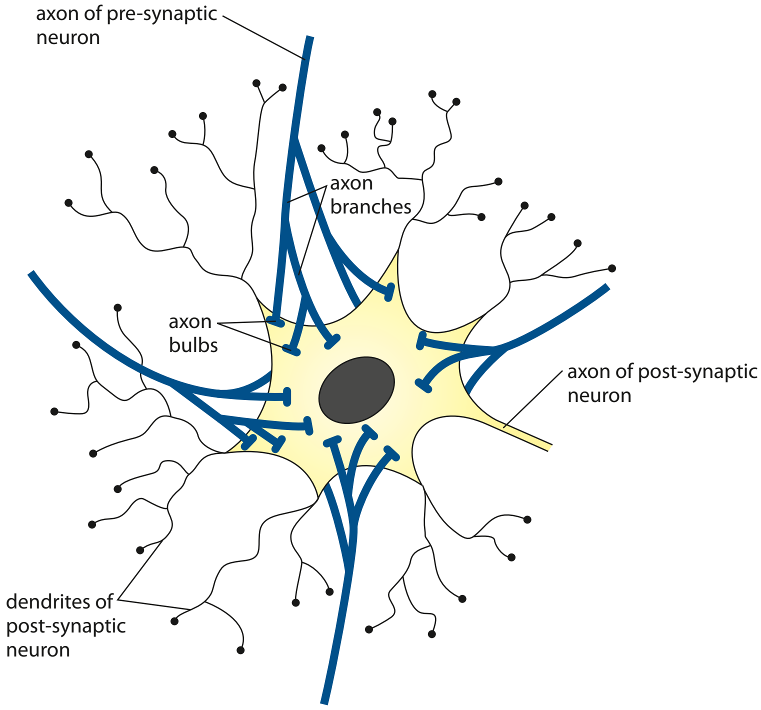


Figure A.28 Some of the neurons that form synapses with the post-synaptic neuron are inhibitory and prevent an action potential being stimulated. Others stimulate the propagation of the impulse.

Neurotransmitter	Effects
acetylcholine	Widely distributed excitatory neurotransmitter that triggers muscle contraction and stimulates the release of certain hormones. It is involved in wakefulness, attentiveness, anger and aggression. Alzheimer's disease is associated with a lack of acetylcholine in certain regions of the brain.
dopamine	Involved in controlling motor actions such as movement and posture. In the brain it modulates mood and pleasure related to motivation. It has a role in positive reinforcement and dependency. If it is lost from certain parts of the brain it can cause muscle rigidity and Parkinson's disease.
GABA (gamma-amino butyric acid)	Found widely distributed in the neurons of the cortex and the majority of fast 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 many other functions, and regulates feelings of anxiety.
glutamate	A major excitatory neurotransmitter that is associated with learning and memory.
norepinephrine (noradrenalin)	Important for attentiveness, emotions, sleeping, dreaming, and learning. It is also released as a hormone into the blood, where it causes blood vessels to contract and heart rate to increase. It plays a role in mood disorders such as manic depression.
serotonin	Contributes to functions such as regulating body temperature, sleep, mood, appetite and pain. Depression, suicide, impulsive behaviour and aggressiveness all appear to involve certain imbalances in serotonin.
substance P	Responsible for transmission of pain from certain sensory neurons to the central nervous system. It is a neurokinin (small peptide) and is released when stressful stimuli are received.
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, excitement or when pain is felt. They are known as 'natural painkillers' because some have an analgesic effect and can cause feelings of pleasure or well-being.

Table A.4 Neurotransmitters and their effects.

Cholinergic and adrenergic synapses

Two of the most important neurotransmitters in the nervous system are acetylcholine and norepinephrine (noradrenalin). Synapses are divided into two types, defined by which of the two neurotransmitters they use.

Cholinergic synapses use acetylcholine and are found in the parasympathetic nervous system. Nicotine increases transmission at these synapses and has a calming effect on mood.

Adrenergic synapses use the neurotransmitter norepinephrine and are found in the sympathetic nervous system. Norepinephrine is crucial to the 'fight or flight' response. Amphetamines stimulate these synapses and produce feelings of alertness and euphoria.

Psychoactive drugs

Psychoactive drugs are chemical substances that affect the way the brain transmits impulses at synapses. They are capable of altering the functioning of the brain and a person's personality.

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.

Exam tip

Do not forget that psychoactive drugs can either increase or decrease postsynaptic transmission.

Excitatory drugs (stimulants)

Some psychoactive drugs are excitatory – that is, they promote the transmission of impulses at excitatory synapses or inhibit transmission at inhibitory synapses. Excitatory, or stimulant, drugs mimic the stimulation provided by the sympathetic nervous system. Examples of excitatory drugs include:

- cocaine
- amphetamines
- nicotine.

The effects of these substances are summarised in Table **A.5**.

Excitatory drug	Mode of action	Effects
nicotine	• acts at synapses that use the neurotransmitter acetylcholine • is not broken down by the enzyme acetylcholinesterase, which breaks down acetylcholine • remains in the synapse, binding to the same receptors on the post-synaptic membrane as acetylcholine • increases levels of dopamine in the brain, which stimulates synapses in 'reward' pathways, giving feelings of pleasure and well-being	• produces feelings of pleasure, in the same way as cocaine and amphetamines, although to a lesser degree • strongly addictive because effects wear off quickly, so users must dose themselves frequently to maintain pleasurable sensations and prevent withdrawal symptoms • has a calming effect, despite being an excitatory drug, possibly because it reduces agitation caused by cravings and withdrawal symptoms
cocaine	• stimulates transmission at brain synapses that use dopamine • leads to a build-up of dopamine in the synapse by blocking its return to pre-synaptic neurons • causes continuous transmission of impulses in 'reward' pathways, giving feelings of pleasure and well-being	• produces feelings of increased energy, confidence and euphoria often mixed with restlessness and anxiety • highly addictive, with users seeking to maintain feelings and 'highs' induced by dopamine • as it wears off, feelings of euphoria turn into depression, and the user may 'crash', losing all energy and sometimes sleeping for long periods • prolonged use can cause long-lasting mental health problems such as depression, anxiety, paranoia and delusions
amphetamines	• stimulate transmission at synapses that use norepinephrine (noradrenalin) • have similar effects to cocaine but are longer lasting • cause the release of neurotransmitter into the synapse and prevent it being broken down • increase the concentration of dopamine present	• produce feelings of euphoria and high levels of energy and alertness • may cause hyperactivity and aggression in some people

Table A.5 Effects of excitatory drugs.

Ecstasy (MDMA)

Ecstasy or MDMA (methylenedioxymethamphetamine) causes neurons to release serotonin, a neurotransmitter that controls emotions, mood, pain perception and sleep. The drug also alters the sensitivity of the brain to serotonin. Some of the behavioural effects of the drug are due to a massive release followed by depletion of serotonin. Depletion of serotonin can cause depression and memory loss. One serious effect of ingestion of MDMA by humans is hyperthermia (raised body temperature) which can induce other clinical problems and occasionally death. MDMA has also been shown to induce dose-dependent hyperthermia in experimental animals.

Consider the data shown in question **11** at the end of the topic, which shows effects of MDMA given to experimental animals.

Inhibitory drugs (sedatives)

These drugs increase transmission at inhibitory synapses or suppress transmission at excitatory synapses. This class of drugs is also known as sedatives and includes anesthetics used in medicine. Examples of inhibitory drugs include:

- benzodiazepines
- alcohol
- THC.

Their effects are summarised in Table **A.6**.

The effect of anesthetics on the nervous system

An **anesthetic** is defined as a drug that that causes a reversible loss of sensation. **Local anesthetics**, such as novocaine used by dentists, are used to block the transmission of nerve impulses to pain centres in the central nervous system during minor surgical procedures. They work by binding to and inhibiting sodium channels in the cell membranes of neurons. This prevents nerve impulses passing messages to the central nervous system from the region near the site of injection, but the patient will still be awake and will not have any change in perception in other parts of the body.

General anesthetics cause a reversible loss of consciousness. They induce a state of general insensibility to pain. During medical procedures an anesthetised patient loses consciousness but their vital functions, such as breathing and heart beat, continue. Many different substances have been used as general anesthetics for more than 150 years (Figure **A.29**). They are known to cause a reduction in nerve transmission at synapses but even today their exact mechanism of action is not fully understood.

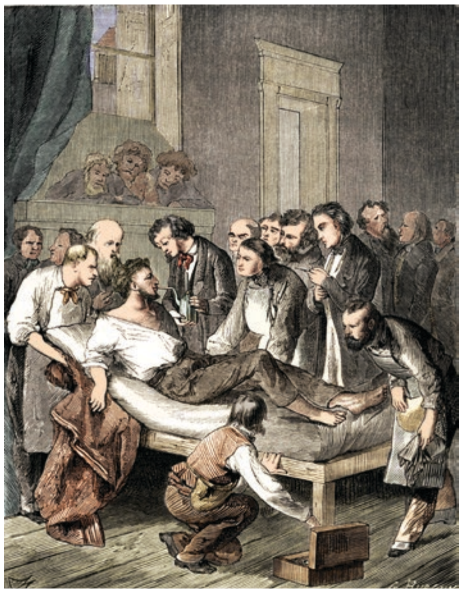


Figure A.29 William Thomas Green Morton (1819–1868), an American dentist from Boston, administering ether to a patient during the public demonstration of an operation by the surgeon John Collins Warren, on 16 October, 1846. This was the first documented successful major surgical intervention under a general anesthetic.

Inhibitory drug	Mode of action	Effects
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
THC (tetrahydrocannabinol – the most important psychoactive substance in cannabis)	• affects receptors in cells in the cerebellum and cerebral hemispheres that use the neurotransmitter anandamide • similar in structure to anandamide and binds to the same receptors, known as cannabinoid receptors • causes hyperpolarisation of post-synaptic membranes so that they are more difficult to stimulate	• induces feelings of relaxation and affects coordination • causes panic and paranoia in some users • can interfere with short-term memory and learning, as many cannabinoid receptors are found in areas of the brain concerned with memory
alcohol	• increases the binding of GABA to receptors in post-synaptic membranes • causes hyperpolarisation of post-synaptic membranes so that they are more difficult to stimulate • decreases the action of the neurotransmitter glutamate, which stimulates post-synaptic neurons	• in small quantities, affects behaviour by reducing inhibitions • in larger quantities, can cause a lack of coordination, slurred speech, loss of balance and, in some cases, aggressive behaviour

Table A.6 Effects of inhibitory drugs.

Another way in which patients may be prepared for medical procedures is sedation. During sedation small amounts of anesthetic or similar drugs are used to produce a 'sleep-like' state. Under sedation the patient is physically and mentally relaxed so that procedures such as endoscopy, which may be unpleasant or painful, can be carried out. The patient may have little memory of events and may not recall what has happened to them.

Barbiturates and benzodiazepines are drugs that are used to produce either sedation or anesthesia (loss of sensation, such as touch, for example) but themselves have no pain-relieving properties. **Analgesics** such as aspirin and ibuprofen are painkillers that relieve pain but do not eliminate sensation, such as touch. Combinations of anesthetics and analgesics are sometimes used to produce additive therapeutic effects.

What causes addiction?

Addiction is a chemical dependence on a psychoactive drug. Many different factors are involved in addiction as the body becomes **tolerant** of a drug, needing more and more of it to produce the same effects.

Three factors seem to be common to all addictions, whether drugs have been taken for therapeutic reasons or recreation.

Social factors

Peer pressure can influence young people to experiment and drug-taking behaviour can be associated with a need to belong to a group. Culture also affects whether drug use is acceptable. In some cultures, cigarette smoking is freely accepted, but in others it is only acceptable for men to smoke in public; in some cultures, alcohol is used to celebrate at social events, while in others it is prohibited entirely. The use of opium, for example, has a long history. In Homer's *Odyssey*, written around 800 BCE, opium is referred to as a '*drug that had the power of robbing grief and anger of their sting*' and in the 1850s Chinese immigrants who helped build the railways in the USA smoked opium as an integral part of their culture to relieve stress and exhaustion. Today, drug addiction is often linked to factors such as poverty or poor family circumstances, which can increase the chances of an individual starting to use drugs. However, certain drugs (such as cocaine) may be used by more affluent members of society.

Dopamine secretion

Most drugs that cause addiction are those involving 'reward' pathways and the release of the neurotransmitter dopamine. Users of addictive drugs find it hard to give them up because of the feelings of well-being that are induced by dopamine. As dopamine receptors are repeatedly stimulated, they become desensitised so that more and more of the drug is required to produce the same feelings. In this way, the user develops a **tolerance** to the drug.

Genetic predisposition

Relatively few people become addicted to drugs although many are exposed to them. The tendency to become addicted has been shown to be more common in some families and groups than others. Research on identical twins also supports this view. This evidence seems to indicate that some individuals are more likely to carry genes that predispose them to addiction than others.

Nature of science

Assessing risk in science – approving new drugs

The National Institute for Health Care and Excellence (NICE) is an organisation that gathers the available evidence on new medicines in the UK. Similar organisations exist in many other countries. Such organisations are responsible for considering and summarising evidence on new drugs that are developed for use with patients. Before any new medication is used it must be thoroughly tested so that patients are not put at unnecessary risk. But sometimes patients or their families may press for drug approval processes to be speeded up if they feel it may be of benefit to them. This encourages a greater tolerance of risk and may lead to reckless use of new medicines.

Neuro-adaptation

Excessive use of a psychoactive drug can cause the brain to attempt to counteract the effect of the drug in a process known as **neuro-adaptation**. If the brain is frequently exposed to a drug it adapts to compensate for its presence and if the drug is withdrawn, the brain overcompensates and becomes imbalanced in different way. Neuro-adaptation is the basis of addiction and drug tolerance.

? Test yourself

16 Describe how THC affects synapses in the brain.
17 List **three** causes of addiction to psychoactive drugs.
18 Outline the effect of inhibitory drugs at a synapse.

A6 Ethology (HL)

Behaviour is the pattern of responses of an animal to one or more stimuli, and the study of animal behaviour in natural conditions is called **ethology**. Some examples of different behaviours, such as patterns of social interaction and mating rituals, are considered in this subtopic.

Learning objectives

You should understand that:

- Ethology is the study of the way animals behave in natural conditions.
- Natural selection can influence animal behaviour.
- Behaviour that increases survival and reproductive chances will tend to become more prevalent in a population.
- Learned behaviour can spread through or be lost from a population more rapidly than innate behaviour.

Natural selection and animal responses

Natural selection acts on the behavioural responses of animals in just the same way as it does on other characteristics. Behaviour that increases the chances of survival and reproduction will tend to become more prevalent in a population. One well-documented example is the migratory behaviour of a small European songbird called the blackcap (*Sylvia atricapilla*).

Blackcaps breed in summer, in Germany and other areas of northern and eastern Europe, and then migrate south about 1600 km to winter feeding grounds in Mediterranean regions of Spain (Figure **A.30**). Since the 1960s, biologists in the UK have recorded increasing numbers of birds travelling northwest from Germany to overwinter in the UK, a distance of only 900 km. At the end of winter, these birds leave the UK up to 10 days earlier than other migrants left Spain.

Modification of their migration pattern has meant that the birds travelling from the UK can quickly return to their summer breeding grounds and occupy the best nest sites. Observations of the birds have shown that they have different-shaped beaks, more suited to the food available in the UK, and also more rounded wings, which are less suitable for long migration. The 'modified migrants' also tend not to interbreed with the birds that migrate back from Spain.

Figure A.30 Changes in migration patterns of the blackcap. Blackcaps tended to breed in Germany in the summer and migrate in winter to feed in Spain. In recent decades, increasing numbers have instead travelled northwest from Germany, to overwinter in the UK.

Figure A.31 There is a selective advantage for great tits in laying eggs early, if the parents can get enough food for egg production, because when the chicks hatch they will be first to take advantage of the springtime abundance.

To study the behaviour of these birds in more detail, eggs were removed from the nests of both types of migrants and the hatchlings hand-reared. In autumn when the young birds migrated, the direction in which each bird flew was carefully observed. It was found that birds reared from eggs of south-migrating parents headed south, and those birds reared from northwest-migrating parents headed northwest. The birds had had no previous migration experience and their behaviour had not been learned from their parents. The migration patterns must be genetically determined, indicating that natural selection is operating on the behaviour of the blackcap.

A second example of how natural selection affects animals' responses can be seen in the breeding behaviour of the great tit (*Parus major*, Figure **A.31**). This European bird lays eggs at a time that is influenced by day length, and the behaviour is genetically determined. In recent years, ornithologists in the Netherlands have noted that many birds are laying their eggs earlier in the year. In general, natural selection favours early breeding because, with changes in climate, trees now tend come into leaf earlier and so small invertebrates that inhabit these trees are also available earlier. Early egg production means that there is abundant food for the birds' offspring at the time when it is needed.

The eventual extent of early breeding may in turn be limited by natural selection, because egg production is very costly and so birds' energy needs may come to restrict their laying behaviour. There may simply not be enough food around very early in the year for parents to produce eggs.

There are many other examples of animal behaviour that increase the chances of survival and reproduction and some of these are summarised below. Consider the examples and notice how learned behaviour, which is not genetically determined, can spread through a population or be lost from it far more quickly than innate behaviour, which is genetically determined and can only be changed by natural selection acting on genetic variation within the population.

Reciprocal altruism in vampire bats

Altruistic behaviour is 'unselfish' behaviour that does not benefit the individual itself but benefits another, which may be genetically related. Altruistic behaviour may decrease the individual's chance of survival and reproduction but increase the number of offspring produced by another animal. Good examples of altruistic behaviour are seen in naked mole rats and in vampire bats.

The common vampire bat (*Desmodus rotundus*) is found in tropical South America, including Mexico, Argentina and Chile, especially where cattle are present in large herds (Figure **A.32**). Bats emerge from their roosts at night to feed on the blood of large warm-blooded animals while they are asleep. Bats have a rapid metabolism and need a regular supply of food; they will begin to starve if they have to go without food for more than 48 hours. Female bats form close long-term associations with small groups of other females and these are the basis of the bats' social structure. Within the groups, a bat that has fed will regurgitate food into the mouth of an individual that has been unable to feed. Food sharing seems to be altruistic; a bat gives up food that could have helped to sustain its own body to another individual whose chances of survival are therefore increased. Zoologists who have studied these animals for many years have suggested that bats share blood only with those who have fed them in the past or with bats that are related to them. This indicates that this is an example of reciprocal altruism. Bats that are newcomers to the colony do not receive donations of food so easily. Altruistic behaviour between related animals increases the chance of genes that are shared by these individuals being passed on to the next generation, and so this behaviour is favoured by natural selection (Subtopic **5.2**).

Figure A.32 Despite their reputation, vampire bats demonstrate altruistic behaviour towards others in their colony by sharing meals.

Synchronised oestrus in female lions – innate behaviour that increases chances of survival

Lions do not breed with the seasons as other mammals do, but within a pride, female lions – which often live in groups of related animals – come into oestrus and are ready to mate at the same time as other females in the group. Synchronised oestrus is also well known in other animals such as rats and hamsters that are kept in laboratories. Cubs that are born into synchronised litters have several advantages. They are suckled and protected by more than one female in the pride and the adult males will remain close by to protect them. When the time comes for the young lions to leave the pride and establish themselves, they are more likely to leave along with other animals of the same age that will help them survive.

In addition there is evidence that oestrus is also stimulated if the pride is taken over by an incoming male lion. Incoming males will attack and kill dependent cubs. Females with cubs will not be ready to mate for 1–2 years but if their cubs are lost, they will come into synchronised oestrus and mate with the new dominant male.

Figure A.33 Blue tits will pierce the foil on a milk bottle to feed on the milk inside.

Blue tits – learned behaviour developed and lost

Until the start of the twenty-first century, most milk in the UK was delivered to customers' doors in milk bottles. At the beginning of the twentieth century some of the milk containers that were delivered had no tops so that birds that perched on the edge of the container had easy access to the cream floating on the top of the milk. The blue tit (*Parus caeruleus*) was one species that quickly learned to feed on the cream.

From the 1920s onwards, dairies started to seal their milk bottles with aluminium foil tops, but blue tits modified their behaviour to cope with the new situation and by the early 1950s all the blue tits in the UK had learned how to pierce the tops with their beaks (Figure **A.33**). Blue tits had not only learned a new behaviour but also passed on the skill to other members of their species. Even though some other species such as the robin occasionally took cream, only the blue tits passed on the behaviour.

This learned behaviour has largely been lost today because many people now buy milk from a supermarket rather than having a delivery to their doorstep, and where milk delivery still occurs, it comes in cartons rather than bottles. Changes in human dietary preferences have also meant that even households that have milk delivered may choose low fat or homogenised milk, which has no cream on the top for the blue tits to feed on.

Foraging behaviour in shore crabs – optimising prey choice

Efficient feeding behaviour is essential for survival and reproduction. But in hunting and foraging there is an energy cost in finding, catching and consuming food. This has to be balanced with the energy the animal gains from the food. Animals are able to change their behaviour so as to ensure the overall benefit is greater than the cost.

The shore crab (*Carcinus maenas*) feeds on mussels. A shore crab will investigate a mussel by handling it in its claws for about two seconds before deciding whether it is a suitable size to feed on. Each differently sized crab will have a size of mussel for which the ratio of energy content to handling time is at its maximum efficiency. This ratio is known as the

prey value and can be calculated for each crab size. The optimal mussel size for an individual increases with the size of the crab.

If there is an abundance of food available, crabs will choose prey that are close to the predicted optimal size. But if this size is scarce, they will select less suitable mussels, which may be either above or below the optimal size. When a crab is forced to eat larger mussels, the prey value decreases because it must use a slower feeding method.

Crabs are able to adapt their feeding habits by eating sub-optimal mussels in proportion to the relative numbers of mussels present. Mussels tend to be distributed in groups of mixed sizes so crabs always take a mussel of optimum size if they find one. They will reject a sub-optimal mussel after one encounter, but take one after a series of encounters with mussels of sub-optimal size.

Similar prey selection behaviour is seen in the bluegill sunfish. The bluegill sunfish (*Lepomis macrochirus*) is a well-studied species that feeds on water fleas (*Daphnia* sp.) and other small pond invertebrates. Table **A.7** shows how the foraging behaviour of the bluegill sunfish varies depending on the amounts of *Daphnia* available. When there is a low density of prey available the fish consume all sizes of *Daphnia*, but at medium densities they consume only middle-sized or larger prey. When food is abundant they actively select only the largest *Daphnia*. Feeding on small numbers of large prey takes less energy than catching large numbers of small prey, if they are nearby. If the density of food is low, the fish will eat whatever they can rather than go hungry.

Density of *Daphnia* in pond habitat	Sizes of *Daphnia* selected as prey by bluegill sunfish
low	all
medium	middle-sized or large
high	largest

Table A.7 The foraging behaviour of the bluegill sunfish depends on the amount of prey available.

Mate selection – courtship in birds of paradise

The elaborate tail of the peacock (*Pavo cristatus*) has fascinated biologists for many years; even Charles Darwin wondered why such an elaborate and impractical structure had evolved and what purpose it served. But research has shown that females of the species (peahens) prefer males with larger tails, so these males have more reproductive success and are more likely to pass on their genes to the next generation.

Similar elaborate displays of plumage and behaviour are seen in many bird species but the birds of paradise of Papua New Guinea are thought to have some of the most complex displays of all. The courtship behaviour of Queen Carola's Six-wired Parotia (*Parotia carolae*) bird of paradise has been extensively studied and its complex behaviour has been observed. Male birds are mostly black and have three ornamental head 'wires' attached above each eye. They also have display feathers that form a skirt during courtship, white flank plumes and iridescent throat and breast feathers (Figure **A.34**). A male bird performs an elaborate courtship ritual involving dance, display and calls. His first strategy is to select a display

Exam tip
Make sure you can describe examples of animal behaviour that increase the chances of survival and reproduction.

area, which he clears of debris and prepares with a mat of fungi. This 'stage' is decorated with fur and brightly coloured leaves. The male may also remove leaves from the branches of surrounding plants so that females can get a clearer view of his display. Females perch on branches above the stage and watch as the male shakes out his feathers to form a fan, dances and shakes his body and head, and pirouettes to impress them. He may also call and rattle his feathers. In some other species, such as the blue bird of paradise, males flip upside-down on branches to perform hanging displays, spreading their breast plumes into a fan as they bounce and wave their tail wires. Other species' displays involve several males displaying together. Females select a mate from the quality of the displays.

It seems that female birds of paradise prefer males with elaborate and attractive displays, but the reasons for this are not fully understood. Females may prefer such males because they are likely to produce attractive (and therefore reproductively successful) male offspring, or because an elaborate dance is a sign of good health.

Figure A.34 Six-wired bird of paradise.

Breeding strategy affects chances of survival – coho salmon

Coho salmon (*Oncorhynchus kisutch*) live in the North Pacific Ocean but return to fresh water to mate and spawn in gravel beds of the streams where they were born. After spawning once, the adult fish die. Young fish live for one or two years in the streams, growing and feeding in fresh water, but travel to the sea for the rest of their life cycle. Coho salmon have blue backs and silver sides in the ocean, but spawning fish are darker with red colouration on their sides (Figure **A.35**). Adults usually spawn when they are about 3 years old but some precocious males, known as 'jacks', spawn early at the age of 2 years. Males adopt one of two irreversible life-history strategies in their mating behaviour; either they mature early at a smaller body size ('jacks') or delay maturation until they are larger, when they are known as 'hooknoses'.

At spawning time, the males develop a hooked snout and large teeth and a distinctive colouration. Male mating strategy depends on body size and their competitive fighting ability. Hooknoses are more brightly coloured with larger hooked jaws and sharp teeth and fight with other males for access to females. Jacks are smaller, less colourful and poor fighters so they must use a 'sneaking' strategy to get close to females. Jacks mate in shallow water and hiding places where their less vivid colouration enables them to remain hidden. The 'fitness' or lifetime reproductive success of jacks and hooknoses depends on the probability that they will survive to maturity. On one hand, the jacks' strategy reduces the exposure of a fish to the dangers (such as predators) in the ocean, by 1 year. But the opportunities for 'sneaking' mating behaviour are limited by the number of shallow water hiding places. If too many males become jacks, the number of opportunities for sneaking is reduced. For a hooknose, survival is influenced by the number of other hooknoses – more hooknoses means more competition.

Human activity and changes to the environment are affecting coho salmon populations, which are declining. It is probable that the number of fish becoming jacks and the behaviour of the species will change as a result of, for example, if larger fish are taken by fishing or their numbers decline due to pollution.

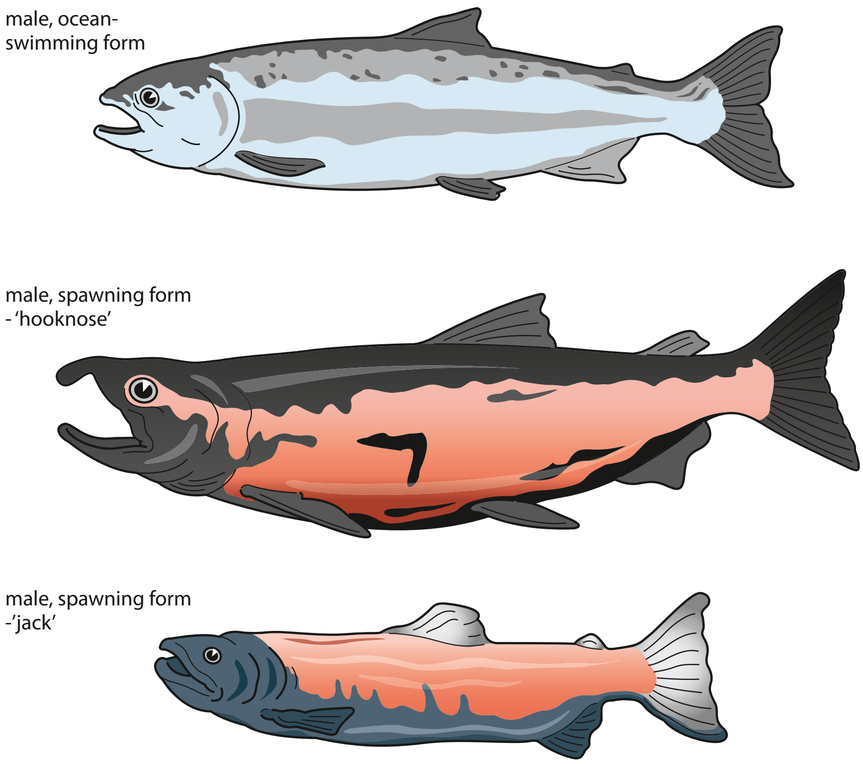


Figure A.35 Male coho salmon in oceanic and spawning phases.

Animal behaviour in literature

British author Rudyard Kipling's 'Just So Stories' were first published in 1902. They tell the stories of different animals and their appearance and behaviour in a series of fanciful descriptions. For example, 'How the Camel got its hump' tells how the camel was given a hump as a punishment for refusing to work, and other stories tell 'How the rhinoceros got his skin' and 'How the leopard got his spots'. The stories are imaginative descriptions, which were written for children, and are very different from scientific observations of animal behaviour and physiology.

Questions to consider

- What are the features of a scientific explanation of animal behaviour?
- How does this differ from a historical or literary view?

Nature of science

Testing a hypothesis – changing migratory patterns

The behaviour of migratory black caps has been extensively monitored since it was proposed that their migration patterns might be affected by climate change. To provide more conclusive evidence, experiments involving relocating their eggs were carried out to test the hypothesis that behaviour was changing.

Researchers have also carried out experiments to test the hypothesis that European starlings migrate using set patterns of distance and direction as aids to navigation. These birds make short migrations in a southwesterly direction from the Netherlands to France and southern England. When populations of starlings were moved to Switzerland by experimenters, they did not fly northwest to their usual winter homes but travelled in the same southwesterly direction and the same distance so that they arrived in Spain, where they were retrieved. Testing their hypothesis enabled the researchers to conclude that direction and distance were cues for the starlings' migration pattern.

Test yourself

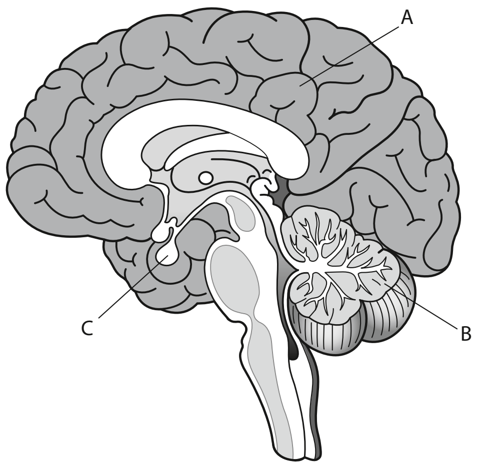
19 Give an example of a learned behaviour that has spread through an animal population.

20 How does synchronised reproduction benefit the offspring that are produced?

Exam-style questions

1 a Outline the role and functions of the visual cortex and Broca's area of the brain. [4]

b Name the parts labelled A, B and C in the diagram of the brain. [3]



2 Discuss how the pupil reflex is used to test for brain death. [4]

3 Draw a labelled diagram of a reflex arc and outline the pathway of a withdrawal reflex. [6]

4 Outline what is meant by the term 'contralateral processing'. [2]

5 Outline the role of hair cells in the cochlea in the processing of sound. [3]

6 Distinguish between innate and learned behaviour. [2]

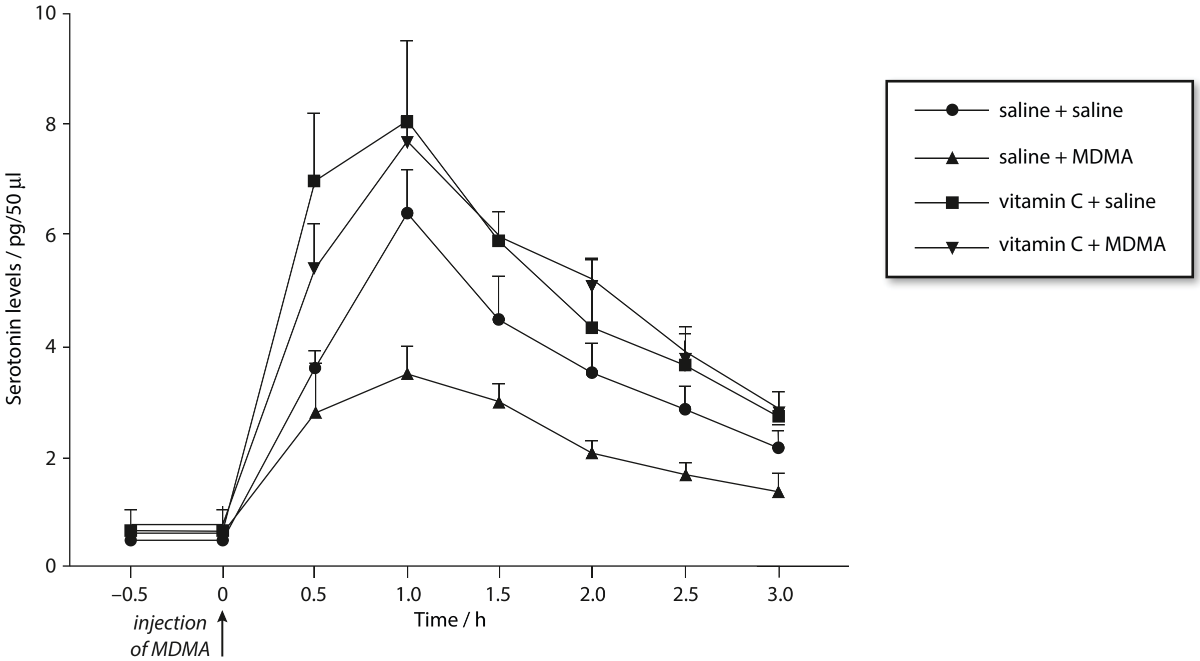
7 Discuss how learning may improve survival chances. [3]

8 Outline Pavlov's experiments on conditioning in dogs. [3]

9 Explain how a pre-synaptic neuron can inhibit a post-synaptic neuron. [2]

10 Outline the reasons why learned behaviour can spread through a population or be lost from it more quickly than innate behaviour. [4]

11 The graph shows the effect of an injection of MDMA (ecstasy) on serotonin levels over a period of 3 hours in four groups of experimental rats. Two groups (indicated by the triangles) had been given MDMA either with a saline solution or with vitamin C 1 week prior to the experiment. The two other groups (indicated by the squares and circles) had not been pre-treated with MDMA. Serotonin is a neurotransmitter concerned with the regulation of mood, appetite and sleep.



a **i** Describe the effect of MDMA on the serotonin levels of rats which had not previously received doses of MDMA. **[2]**

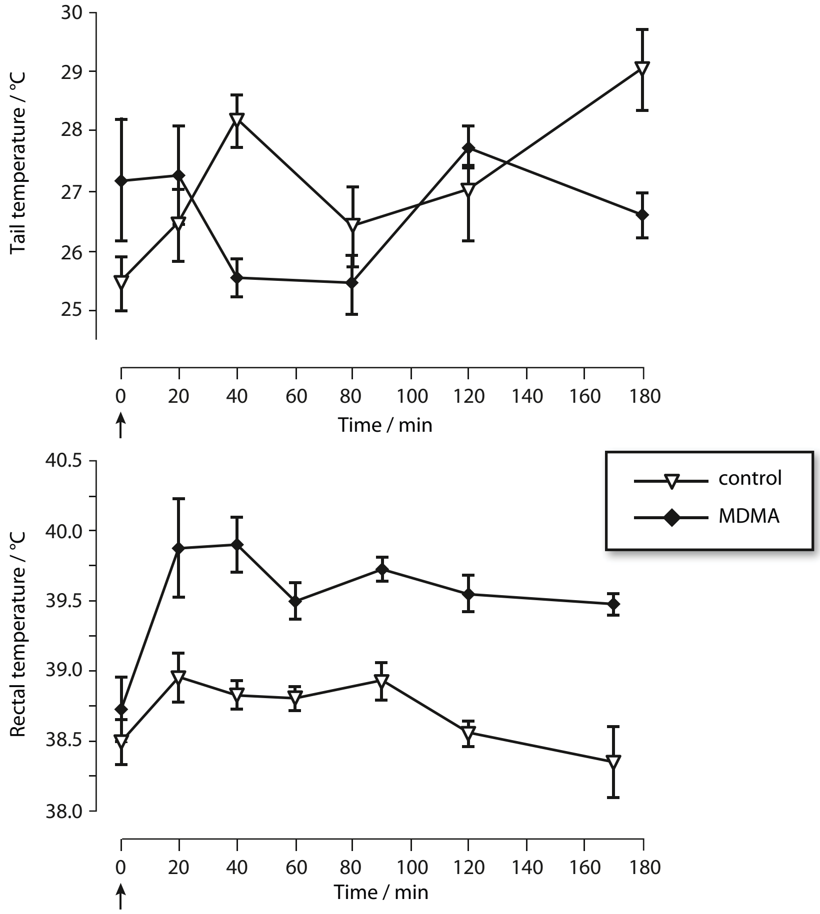
ii Identify the group of rats whose serotonin level was most affected by the MDMA. **[1]**

iii Estimate the time needed for the level of serotonin to return to its normal (pre-injection level) in the control group of rats, indicated by the circles. **[1]**

iv Compare the effect of MDMA on the group of rats which had received doses of vitamin C in the week before the experiment with the group that had not. **[1]**

v Explain the purpose of the saline + saline injection. **[1]**

One serious effect of ingestion of MDMA (ecstasy) by humans is hyperthermia, which can induce other clinical problems and occasionally death. MDMA also induces dose-dependent hyperthermia in experimental animals.



b **i** The average temperature of control rats was 38.5 °C. Calculate the average rectal temperature of the rats between 20 and 120 mins after administration of MDMA. **[2]**

ii Suggest a reason for the changes in the temperature of the rats' tails over this period. **[1]**