

MODULE
5

CHAPTER
5.3

Communication, homeostasis and energy

NEURONAL COMMUNICATION

Introduction

The nervous system forms a complete communication network around the body. Sensory receptors detect changes in the environment and convert the stimuli to electrical impulses. These impulses, or action potentials, travel rapidly along sensory neurones to the central nervous system (CNS). They act as input to the control centres in the CNS. The CNS collects all the input from a variety of receptors and coordinates a response. It sends action potentials down motor neurones to the effectors. This is the output from the control centres.

Neurones have a resting state in which the plasma membrane is polarised. Action potentials consist of a series of ionic movements across the plasma membrane that cause depolarisation followed by repolarisation. The action potential is transmitted along the neurone by localised ion movements called local currents. In this chapter you will learn about how the resting potential is maintained and how action potentials are produced and transmitted.

Neurones communicate with one another at synapses, where the signal is transmitted as a neurotransmitter chemical. Synapses have a number of important functions in nervous communication.

All the maths you need

To unlock the puzzles of this chapter you need the following maths:

- Recognise and make use of appropriate units in calculations
- Estimate results
- Use an appropriate number of significant figures
- Construct and interpret frequency tables and diagrams, bar charts and histograms
- Understand and use the symbols: $=$, $<$, \leq , \geq , $>$, \sim
- Translate information between graphical, numerical and algebraic forms

What have I studied before?

- The eye as a sensory receptor
- The main parts of the nervous system
- The gross structure of neurones
- Nerves communicate via a neurotransmitter at synapses
- Nervous responses are rapid
- Voluntary responses are controlled by the brain
- The need for communication
- The structure of the plasma membrane and its role as a selectively permeable barrier
- How substances move across membranes
- Active transport and diffusion
- The role of the plasma membrane in cell signalling

What will I study later?

- How the nervous system is organised
- Somatic and autonomic nervous systems
- The structure of the brain
- Reflex actions
- The neuromuscular junction
- The action of muscles
- The coordination of responses by the nervous and endocrine systems

What will I study in this chapter?

- The role of sensory receptors as transducers of energy
- The structure and function of neurones
- The generation and transmission of action potentials
- The structure and roles of synapses

By the end of this topic, you should be able to demonstrate and apply your knowledge and understanding of:

- * the roles of mammalian sensory receptors in converting different types of stimuli into nerve impulses

KEY DEFINITIONS

Pacinian corpuscle: a pressure sensor found in the skin.

sensory receptors: cells/sensory nerve endings that respond to a stimulus in the internal or external environment of an organism and can create action potentials.

transducer: a cell that converts one form of energy into another – in this case to an electrical impulse.

DID YOU KNOW?

Sensory receptors detect a change in the environment. So if a stimulus is constant it will not continue to cause a response. This is the basis of some forms of behaviour where organisms become habituated to a stimulus.

Sensory receptors

Sensory receptors are specialised cells that can detect changes in our surroundings. Most are energy **transducers** that convert one form of energy to another.

Each type of transducer is adapted to detect changes in a particular form of energy. This may be a change in light levels, a change in pressure on the skin or one of many other energy changes. Other receptors detect the presence of chemicals.

Each change in the environment, whether it is a change in the energy level or the presence of a new chemical, is called a stimulus. Whatever the stimulus, the sensory receptors respond by creating a signal in the form of electrical energy. This is a called a nerve impulse.

Table 1 shows some different receptors and the energy changes that they detect.

Stimulus (change in environment)	Sensory receptor	Energy change involved
Change in light intensity	Light sensitive cells (rods and cones) in the retina	Light to electrical
Change in temperature	Temperature receptors in the skin and hypothalamus	Heat to electrical
Change in pressure on the skin	Pacinian corpuscles in the skin	Movement to electrical
Change in sound	Vibration receptors in the cochlea of the ear	Movement to electrical
Movement	Hair cells in inner ear	Movement to electrical
Change in length of muscle	Muscle spindles in skeletal muscles	Movement to electrical
Chemicals in the air	Olfactory cells in epithelium lining the nose	These receptors detect the presence of a chemical and create an electrical nerve impulse
Chemicals in food	Chemical receptors in taste buds on tongue	

Table 1 Sensory receptors and the energy changes that they detect.

Pacinian corpuscles

A **Pacinian corpuscle** is a pressure sensor that detects changes in pressure on the skin.

The corpuscle is an oval-shaped structure that consists of a series of concentric rings of connective tissue wrapped around the end of a nerve cell. When pressure on the skin changes this deforms the rings of connective tissue, which push against the nerve ending.

The corpuscle is sensitive only to changes in pressure that deform the rings of connective tissue. Therefore, when pressure is constant they stop responding.

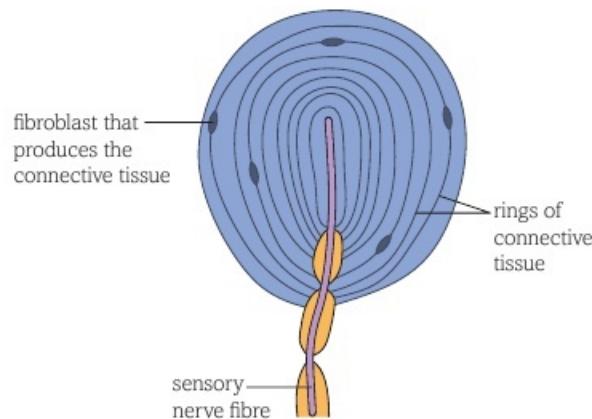


Figure 1 A Pacinian corpuscle.

Generating nerve impulses

Changing membrane permeability

As you may recall from your AS Biology work, all cell surface membranes contain proteins. Some proteins are channels that allow the movement of ions (charged particles) across the membrane by facilitated diffusion. Others are transport proteins that can actively move ions across the membrane against their concentration gradient; this requires the use of energy in the form of ATP.

LEARNING TIP

Remember that lipid bilayers are not permeable to charged particles. Such particles (ions) must pass through protein channels to cross the membrane.

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If the channel proteins are permanently open then ions can diffuse across the membrane and will do so until their concentrations on either side of the membrane are in equilibrium. If the channels can be closed then the action of the active pumps can create a concentration gradient across the membrane.

Cells associated with the nervous system have specialised channel proteins. Some of these, called **sodium channels**, are specific to sodium ions (Na^+). Others, called **potassium channels**, are specific to potassium ions (K^+). These channels also possess a gate that can open or close the channel.

The sodium channels are sensitive to small movements of the membrane, so when the membrane is deformed by the changing pressure the sodium channels open. This allows sodium ions to diffuse into the cell, producing a **generator potential** (also called a receptor potential).

The membranes also contain **sodium/potassium pumps** that actively pump sodium ions out of the cell, and potassium ions into the cell. Three sodium ions are pumped out for every two potassium ions pumped into the cell. When the channel proteins are all closed, the sodium/potassium pumps work to create a concentration gradient. The concentration of sodium ions outside the cell increases, while the concentration of potassium ions inside the cell increases. The membrane is more permeable to potassium ions, so some of these leak out of the cell. The membrane is less permeable to sodium ions, so few of these are able to leak into the cell.

The result of these ionic movements is a potential gradient across the cell membrane. The cell is negatively charged inside compared with outside. This negative potential is enhanced by the presence of negatively charged anions inside the cell.

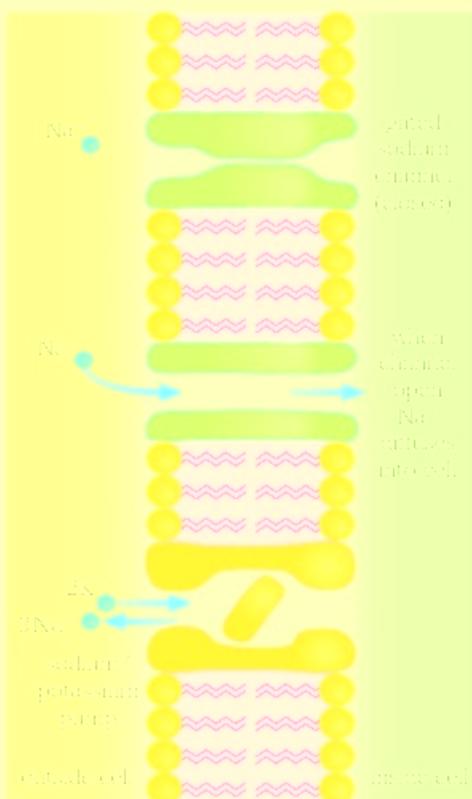


Figure 2 The action of the sodium-potassium pump and sodium ion channels.

Creating a nerve impulse

When the cell is inactive the cell membrane is said to be **polarised**, that is negatively charged inside compared with the outside.

A nerve impulse is created by altering the permeability of the nerve cell membrane to sodium ions. This is achieved by opening the sodium ion channels. As the sodium ion channels open, the membrane permeability is increased and sodium ions can move across the membrane down their concentration gradient into the cell. The movement of ions across the membrane creates a change in the potential difference (charge) across the membrane. The inside of the cell becomes less negative (compared with the outside) than usual. This is called **depolarisation**. The change in potential across a receptor membrane is often called a generator potential.

If a small stimulus is detected only a few sodium channels will open. The larger the stimulus (the change in energy levels in the environment) the more gated channels will open. If enough gates are opened and enough sodium ions enter the cell, the potential difference across the cell membrane changes significantly and will initiate an impulse or **action potential**.

Questions

- 1 Why do membranes need special channel proteins to enable the movement of ions?
- 2 Explain why a constant sound will often become almost inaudible after a short time.
- 3 Why is energy required to produce a concentration gradient?
- 4 Explain why a concentration gradient is needed to ensure sodium ions move rapidly into the cell.
- 5 What is meant by facilitated diffusion?

By the end of this topic, you should be able to demonstrate and apply your knowledge and understanding of:

- * the structure and functions of sensory, relay and motor neurones

KEY DEFINITIONS

motor neurones: neurones that carry an action potential from the CNS to the effector.

myelinated neurone: has an individual layer of myelin around it.

non-myelinated neurone: has no individual layer of myelin.

relay neurones: join sensory neurones to motor neurones.

sensory neurones: neurones that carry an action potential from the sensory receptor to the CNS.

Structure of neurones

All neurones have a similar basic structure that enables them to transmit the action potential. Neurones are specialised cells with the following features.

- Many are very long so that they can transmit the action potential over a long distance.
- The cell surface (plasma) membrane has many gated ion channels that control the entry or exit of sodium, potassium or calcium ions.
- Sodium/potassium pumps use ATP to actively transport sodium ions out of the cell and potassium ions into the cell.
- Neurones maintain a potential difference across their cell surface (plasma) membrane.
- A cell body contains the nucleus, many mitochondria and ribosomes.
- Numerous dendrites connect to other neurones. The dendrites carry impulses towards the cell body.
- An axon carries impulses away from the cell body.
- Neurones are surrounded by a fatty layer that insulates the cell from electrical activity in other nerve cells nearby. This fatty layer is composed of Schwann cells closely associated with the neurone.

Function of neurones

Once a stimulus has been detected and its energy has been converted to a depolarisation of the receptor cell membrane, the impulse must be transmitted to other parts of the body. The impulse is transmitted along neurones as an action potential. The action potential is carried as a rapid depolarisation of the membrane caused by the influx of sodium ions.

There are a number of different types of neurone. These include:

- **motor neurones** that carry an action potential from the central nervous system (CNS) to an effector such as a muscle or gland
- **sensory neurones** that carry the action potential from a sensory receptor to the CNS
- **relay neurones** that connect sensory and motor neurones.

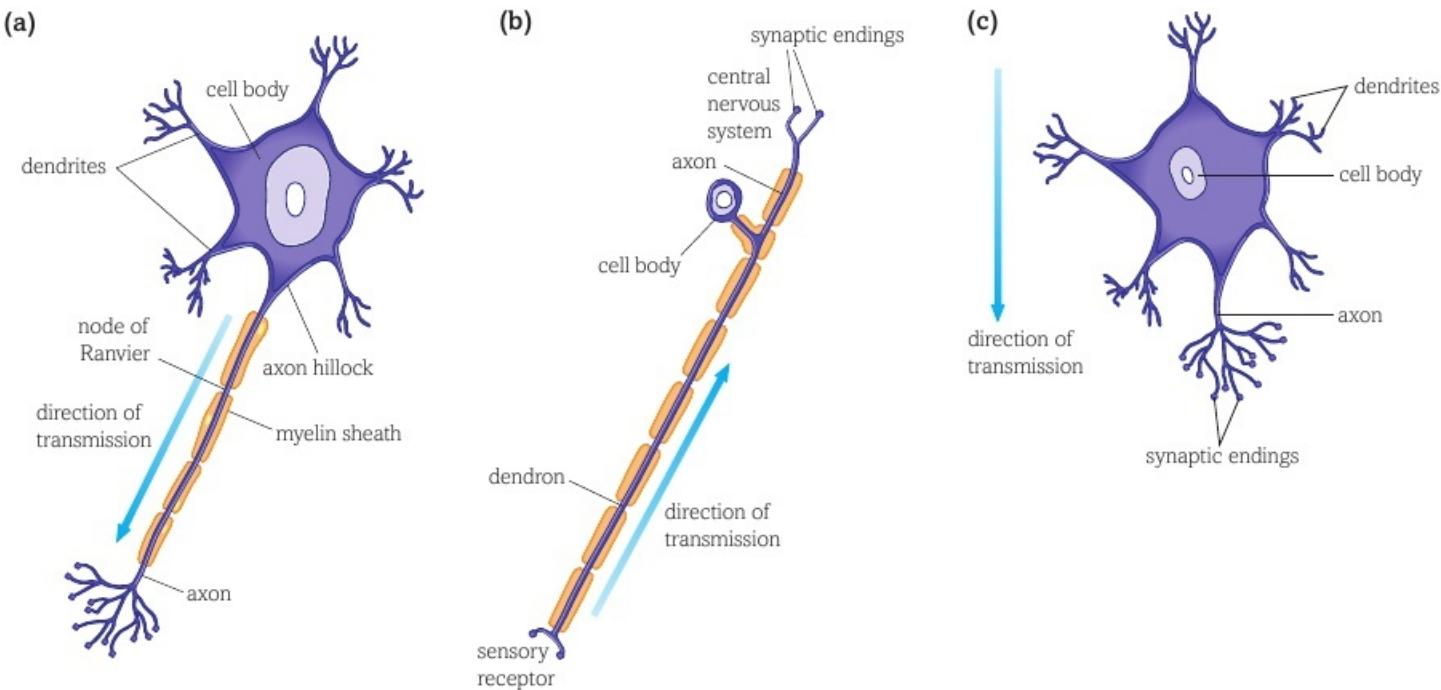


Figure 1 (a) A motor neurone, (b) a sensory neurone and (c) a relay neurone.

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Differences between types of neurone

- Motor neurones have their cell body in the CNS and have a long axon that carries the action potential out to the effector.
- Sensory neurones have a long dendron carrying the action potential from a sensory receptor to the cell body, which is positioned just outside the CNS. They then have a short axon carrying the action potential into the CNS.
- Relay neurones connect the sensory and motor neurones together. They have many short dendrites and a short axon. The number of dendrites and the number of divisions of the axon is variable. Relay neurones are an essential part of the nervous system, which conduct impulses in coordinated pathways.

Myelinated and non-myelinated neurones

Around one-third of the peripheral neurones in vertebrates are **myelinated neurones** – that is, they are insulated by an individual **myelin sheath**. The remainder of the peripheral neurones and the neurones found in the CNS are not myelinated.

Myelinated neurones

Most sensory and motor neurones are associated with many Schwann cells, which make up a fatty sheath called the myelin sheath. These Schwann cells are wrapped tightly around the neurone so the sheath actually consists of several layers of membrane and thin cytoplasm from the Schwann cell.

At intervals of 1–3 mm along the neurone there are gaps in the myelin sheath. These are called the **nodes of Ranvier**. Each node is very short (about 2–3 μm long).

Because the myelin sheath is tightly wrapped around the neurone it prevents the movement of ions across the neurone membranes. Therefore, movement of ions across the membrane can only occur at the nodes of Ranvier. This means that the impulse, or action potential, jumps from one node to the next. This makes conduction much more rapid.

Non-myelinated neurones

Non-myelinated neurones are also associated with Schwann cells, but several neurones may be enshrouded in one loosely wrapped Schwann cell. This means that the action potential moves along the neurone in a wave rather than jumping from node to node as seen in myelinated neurones.

DID YOU KNOW?

You can notice the difference in speed of conduction when you stub your toe or drop something on your foot. You feel the contact very quickly, but a greater sensation of pain arrives almost a second later – this is conducted by non-myelinated neurones.

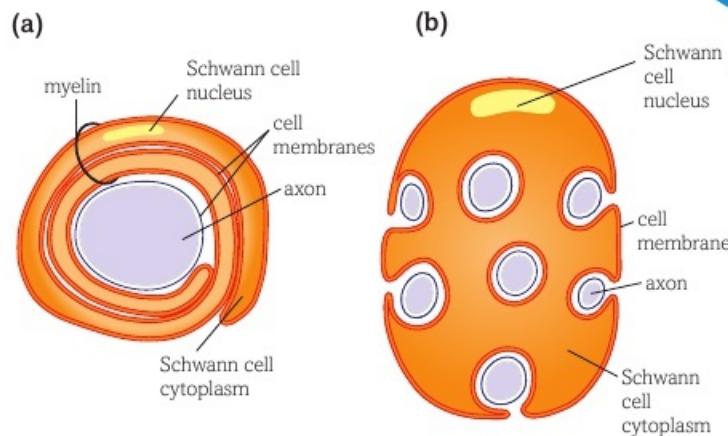


Figure 2 (a) Myelinated and (b) non-myelinated neurones.

Advantages of myelination

Myelinated neurones can transmit an action potential much more quickly than non-myelinated neurones can. The typical speed of transmission in myelinated neurones is $100\text{--}120 \text{ m s}^{-1}$. A non-myelinated neurone may only reach transmission speeds of $2\text{--}20 \text{ m s}^{-1}$.

Myelinated neurones carry action potentials from sensory receptors to the CNS and from the CNS to effectors. They carry action potentials over long distances – the longest neurone in a human can be about 1 m in length. The increased speed of transmission means that the action potential reaches the end of the neurone much more quickly. This enables a more rapid response to a stimulus.

Non-myelinated neurones tend to be shorter and carry action potentials only over a short distance. They are often used in coordinating body functions such as breathing, and the action of the digestive system. Therefore the increased speed of transmission is not so important.

Questions

- Draw a table to compare and contrast sensory and motor neurones.
- Suggest why neurones need to contain a large number of mitochondria.
- Draw a table to summarise the differences between myelinated and non-myelinated neurones.

By the end of this topic, you should be able to demonstrate and apply your knowledge and understanding of:

- * the generation and transmission of nerve impulses in mammals (continued in topic 5.3.4)

KEY DEFINITIONS

action potential: a brief reversal of the potential across the membrane of a neurone causing a peak of +40 mV compared to the resting potential of -60 mV.

positive feedback: a mechanism that increases a change taking the system further away from the optimum.

resting potential: the potential difference across the membrane while the neurone is at rest.

Neurones at rest

When a neurone is not transmitting an **action potential** it is said to be at rest. In fact, it is actively pumping ions across its cell surface (plasma) membrane. Just like the sensory receptor described in topic 5.3.1, sodium/potassium ion pumps use ATP to pump three sodium ions out of the cell for every two potassium ions that are pumped in. The gated sodium ion channels are kept closed. However, some of the potassium ion channels are open, and therefore the plasma membrane is more permeable to potassium ions than to sodium ions. Potassium ions tend to diffuse out of the cell. The cell cytoplasm also contains large organic anions (negatively charged ions). Hence, the interior of the cell is maintained at a negative potential compared with the outside. The cell membrane is said to be polarised. The potential difference across the cell membrane is about -60 mV. This is called the **resting potential**. Note that in myelinated neurones, the ion exchanges described occur only at the nodes of Ranvier.

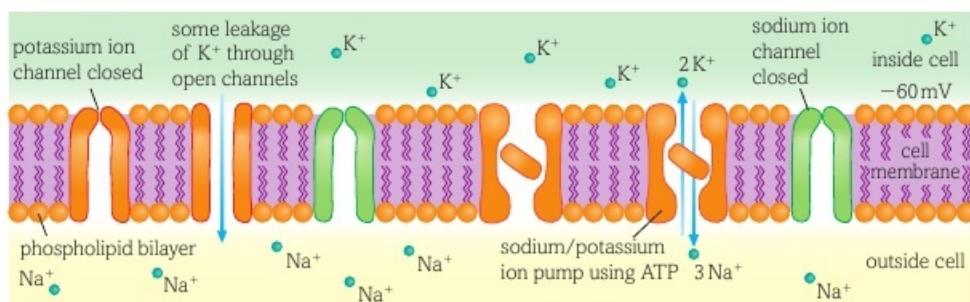


Figure 1 A neurone at rest.

Generating an action potential

While the neurone is at rest it maintains a concentration gradient of sodium ions across its plasma membrane – the concentration is higher outside than inside. Equally the concentration of potassium ions is higher inside than outside.

If some of the sodium ion channels are opened, then sodium ions will quickly diffuse down their concentration gradient into the cell from the surrounding tissue fluid. This causes a depolarisation of the membrane.

In the generator region of a neurone the gated channels are opened by the action of the **synapse** (a nerve junction) (see topic 5.3.5). When a few gated channels open they allow a few sodium ions into the cell and produce a small depolarisation. This is known as a generator potential. It may go no further. However, when more gated channels are opened the generator potentials are combined to produce a larger depolarisation. If the depolarisation reaches a particular magnitude it passes a threshold and will cause an action potential.

Most of the sodium ion channels in a neurone are opened by changes in the potential difference across the membrane – they are called **voltage-gated channels**. When there are sufficient generator potentials to reach the threshold potential they cause the voltage-gated channels to open. This is an example of **positive feedback** – a small depolarisation of the membrane causing a change that increases the depolarisation further.

The opening of voltage-gated sodium ion channels allows a large influx of sodium ions and the depolarisation reaches +40 mV on the inside of the cell. Once this value is reached the neurone will transmit the action potential. The action potential is self-perpetuating – once it starts at one point in the neurone, it will continue along to the end of the neurone. All action potentials are the same magnitude (+40 mV). Therefore they are referred to as an 'all-or-nothing' response.

LEARNING TIP

'All-or-nothing' refers to the fact that all nerve impulses are identical – they are not graduated. The strength of a stimulus is transmitted as more frequent action potentials, not as larger potentials.

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Stages of an action potential

The following stages of an action potential are shown in Figure 2.

1. The membrane starts in its resting state – polarised with the inside of the cell being -60 mV compared to the outside.
- There is a higher concentration of sodium ions outside than inside and a higher concentration of potassium ions inside than outside.
2. Sodium ion channels open and some sodium ions diffuse into the cell.
3. The membrane depolarises – it becomes less negative with respect to the outside and reaches the threshold value of -50 mV.
4. Positive feedback causes nearby voltage-gated sodium ion channels to open and many sodium ions flood in. As more sodium ions enter, the cell becomes positively charged inside compared with outside.
5. The potential difference across the plasma membrane reaches $+40$ mV. The inside of the cell is positive compared with the outside.
6. The sodium ion channels close and potassium channels open.
7. Potassium ions diffuse out of the cell bringing the potential difference back to negative inside compared with the outside – this is called repolarisation.
8. The potential difference overshoots slightly, making the cell hyperpolarised.
9. The original potential difference is restored so that the cell returns to its resting state.

DID YOU KNOW?

Autoimmune diseases such as multiple sclerosis are caused by demyelination of the motor neurones – the neurones lose their myelin sheath and are unable to conduct impulses properly.

Refractory period

After an action potential the sodium and potassium ions are in the wrong places. The concentrations of these ions inside and outside the cell must be restored by the action of the sodium/potassium ion pumps. For a short time after each action potential it is impossible to stimulate the cell membrane to reach another action potential. This is known as the refractory period and allows the cell to recover after an action potential. It also ensures that action potentials are transmitted in only one direction.

Questions

- 1 Explain why a neurone is active while it is said to be resting.
- 2 Why is it essential to maintain a concentration gradient across the cell membrane?
- 3 What is the role of the organic anions inside the neurone?
- 4 What is the difference between the sodium channels in the generator region and those elsewhere along the neurone?
- 5 Explain why it is not possible to stimulate a neurone immediately after an action potential.
- 6 Explain the role of positive feedback in the generation of an action potential.

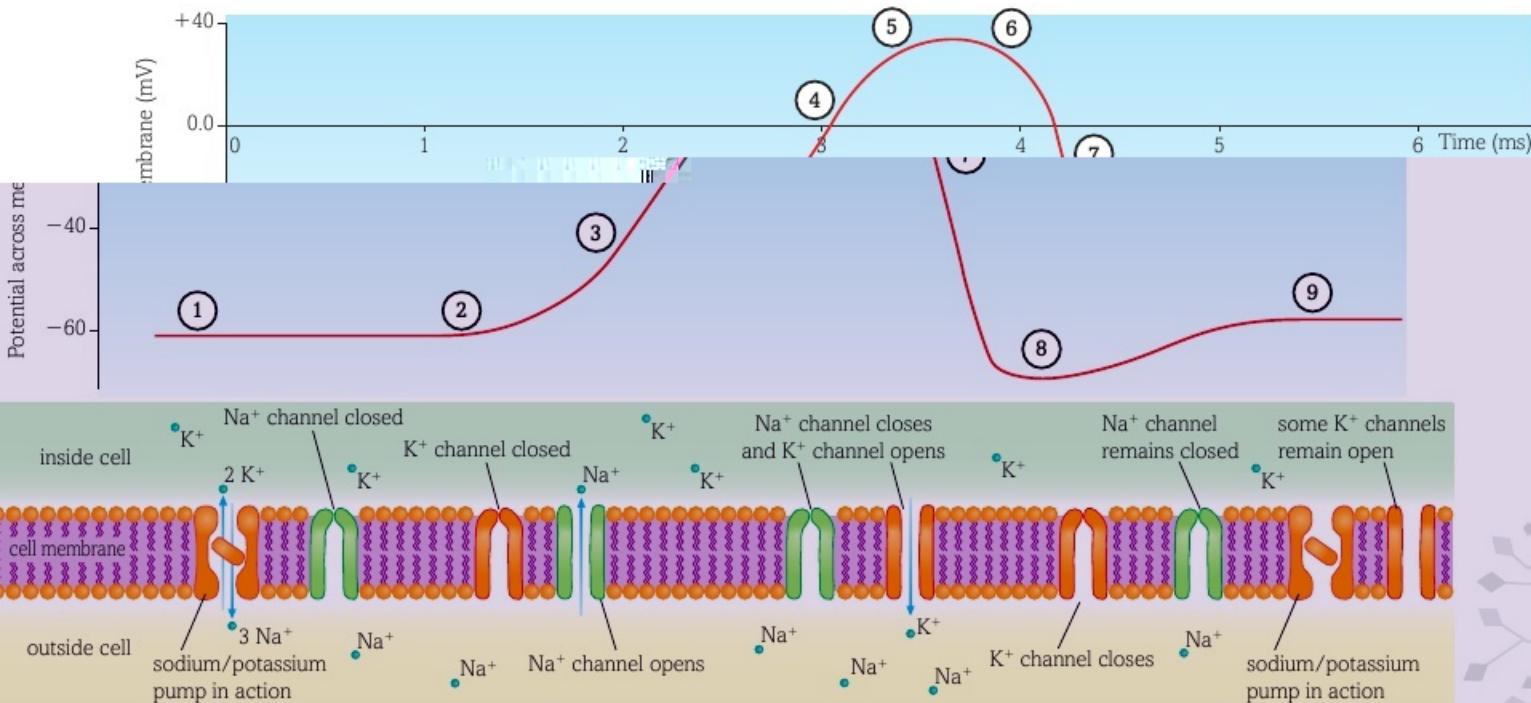


Figure 2 The ionic movements during an action potential.

By the end of this topic, you should be able to demonstrate and apply your knowledge and understanding of:

- * the generation and transmission of nerve impulses in mammals

LEARNING TIP

Remember that the sodium ion channels are opened by slight changes in the potential across the membrane.

In topic 5.3.3 we saw how an action potential can be generated. We also saw how the action potential consists of a series of movements of ions across the cell surface membrane of the neurone. The role of the neurone is to transmit information in the form of action potentials to other parts of the body. So how does that action potential travel along the neurone?

Local currents

The opening of sodium ion channels at one particular point of the neurone upsets the balance of sodium and potassium ions set up by the action of the sodium/potassium pumps. When sodium ions are allowed to flood into the neurone causing depolarisation, this creates **local currents** in the cytoplasm of the neurone. Sodium ions begin to move along the neurone towards regions where their concentration is still lower. These local currents cause a slight depolarisation of the membrane and cause sodium ion channels further along the membrane to open (positive feedback).

The steps in the formation of local currents and the transmission of a nerve impulse (see Figure 1) are as follows.

1. When an action potential occurs the sodium ion channels open at that point in the neurone.
2. The open sodium ion channels allow sodium ions to diffuse across the membrane from the region of higher concentration outside the neurone into the neurone. The concentration of sodium ions inside the neurone rises at the point where the sodium ion channels are open.
3. Sodium ions continue to diffuse sideways along the neurone, away from the region of increased concentration. This movement of charged particles is a current called a local current.
4. The local current causes a slight depolarisation further along the neurone which affects the voltage-gated sodium ion channels, causing them to open. The open channels allow rapid influx of sodium ions causing a full depolarisation (action potential) further along the neurone. The action potential has therefore moved along the neurone.

The action potential will continue to move in the same direction until it reaches the end of the neurone – it will not reverse direction, because the concentration of sodium ions behind the action potential is still high.

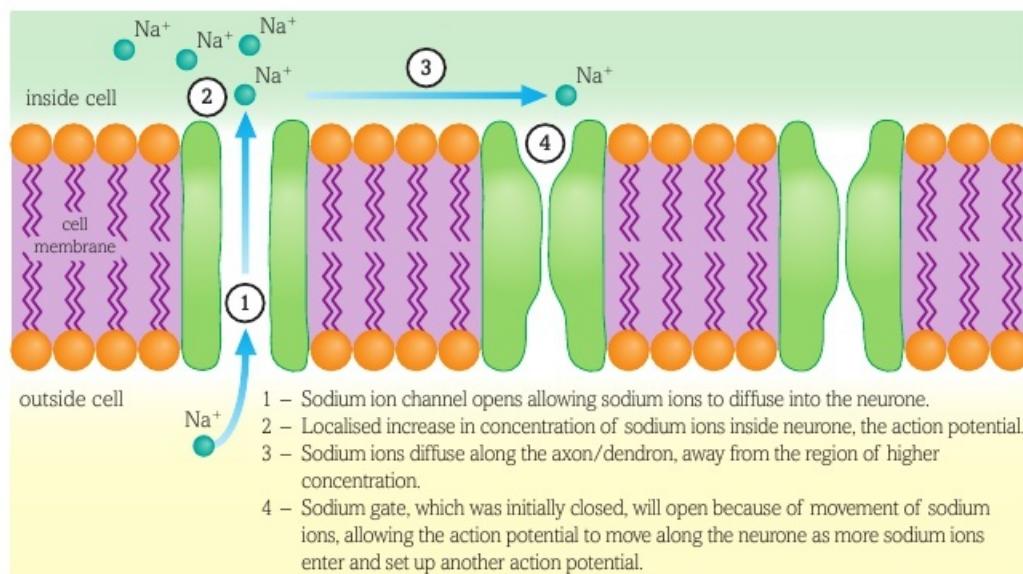


Figure 1 How local currents are formed.

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Saltatory conduction

As described in topic 5.3.2, the myelin sheath is an insulating layer of fatty material, composed of Schwann cells wrapped tightly around the neurone. Sodium and potassium ions cannot diffuse through this fatty layer. In between the Schwann cells are small gaps – the nodes of Ranvier. Therefore, the ionic movements that create an action potential cannot occur over much of the length of the neurone: they occur only at the nodes of Ranvier. In myelinated neurones the local currents are therefore elongated and sodium ions diffuse along the neurone from one node of Ranvier to the next. This means that the action potential appears to jump from one node to the next. This is called **saltatory conduction** (Latin, meaning 'to jump').

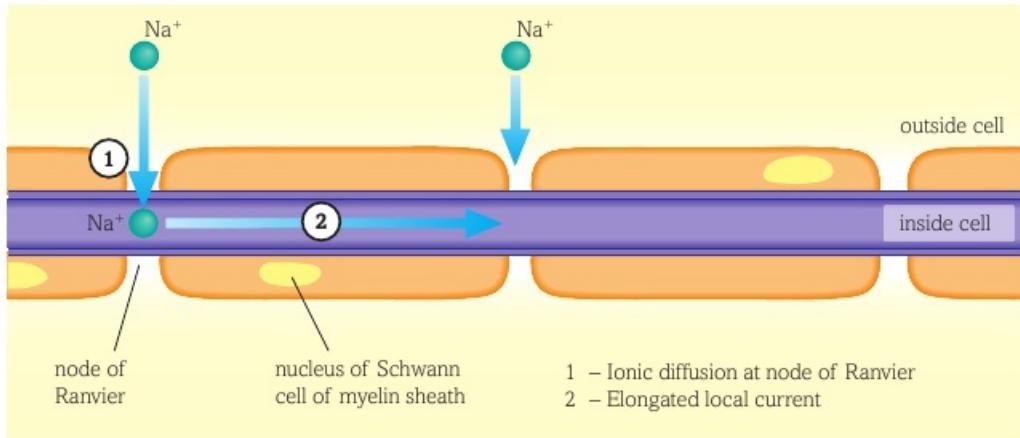


Figure 2 Saltatory conduction.

Advantages of saltatory conduction

The myelin sheath means that action potentials can only occur at the gaps between the Schwann cells that make up the myelin sheath. Effectively the action potential jumps from one node of Ranvier to the next. This speeds up the transmission of the action potential along the neurone. Myelinated neurones conduct action potentials more quickly than non-myelinated neurones. A myelinated neurone can conduct an action potential at up to 120 m s^{-1} .

LEARNING TIP

The flow of sodium ions along the axon in a local current is much more rapid than the movement of an action potential involving exchange of ions across the membrane. Therefore a myelinated neurone will transmit the impulse much more quickly along the neurone.

Frequency of transmission

The impulse carried by a neurone is an action potential. All action potentials are the same intensity: each one produces a depolarisation of +40 mV. This is the 'all-or-nothing' rule (topic 5.3.3).

Although the size of the action potential is unrelated to the intensity of the stimulus that caused the action potential, we can still detect stimuli of different intensities, such as loud or quiet sounds. Our brains determine the intensity of the stimulus from the frequency of action potentials arriving in the sensory region of the brain. A higher frequency of action potentials means a more intense stimulus.

When a stimulus is at higher intensity more sodium channels are opened in the sensory receptor. This produces more generator potentials. As a result there are more frequent action potentials in the sensory neurone. Therefore there are more frequent action potentials entering the central nervous system.

DID YOU KNOW?

Frequency of transmission is not the only way that the intensity of a stimulus can be transmitted. Similar stimuli, but of different intensity, may stimulate different receptors. For example, the skin contains a range of receptors that detect touch and pressure. Free nerve endings in the epidermis detect the lightest of touches. Meissner's corpuscles are very close to the surface of the skin and detect touch and light pressure. Pacinian corpuscles are deeper and do not detect touch – they need substantial pressure to be stimulated.

Questions

- 1 What causes the sodium ion channels to open?
- 2 Explain how the myelin sheath causes saltatory conduction.
- 3 Suggest why saltatory conduction makes conduction more rapid.
- 4 Explain why the maximum frequency of action potentials is limited.

By the end of this topic, you should be able to demonstrate and apply your knowledge and understanding of:

- * the structure and roles of synapses in neurotransmission (continued in topic 5.3.6).

KEY DEFINITIONS

- cholinergic synapse:** a synapse that uses acetylcholine as its neurotransmitter.
- neurotransmitter:** a chemical used as a signalling molecule between two neurones in a synapse.

The structure of a cholinergic synapse

A synapse is a junction between two or more neurones, where one neurone can communicate with, or signal to, another neurone. Between the two neurones is a small gap called the **synaptic cleft**, which is approximately 20 nm wide.

As described in topic 5.3.3, an action potential travels along a neurone as a series of ionic movements across the neurone membrane. This action potential cannot bridge the gap between two neurones. Instead, the action potential in the pre-synaptic neurone causes the release of a chemical (the **neurotransmitter**) that diffuses across the synaptic cleft and generates a new action potential in the post-synaptic neurone. Synapses that use acetylcholine as the neurotransmitter are called **cholinergic synapses**.

The pre-synaptic bulb

The pre-synaptic neurone ends in a swelling called the **pre-synaptic bulb** (or pre-synaptic knob). This bulb contains a number of specialised features (see Figure 1):

- many mitochondria – indicating that an active process needing ATP is involved
- a large amount of smooth endoplasmic reticulum, which packages the neurotransmitter into vesicles
- large numbers of vesicles containing molecules of a chemical called **acetylcholine**, the transmitter that will diffuse across the synaptic cleft
- a number of voltage-gated calcium ion channels on the cell surface membrane.

The post-synaptic membrane

The post-synaptic membrane contains specialised sodium ion channels that can respond to the neurotransmitter (see Figure 2). These channels consist of five polypeptide molecules. Two of these polypeptides have a special receptor site that is specific to acetylcholine. The receptor sites have a shape that is complementary to the shape of the acetylcholine molecule. When acetylcholine is present in the synaptic cleft it binds to the two receptor sites and causes the sodium ion channel to open.

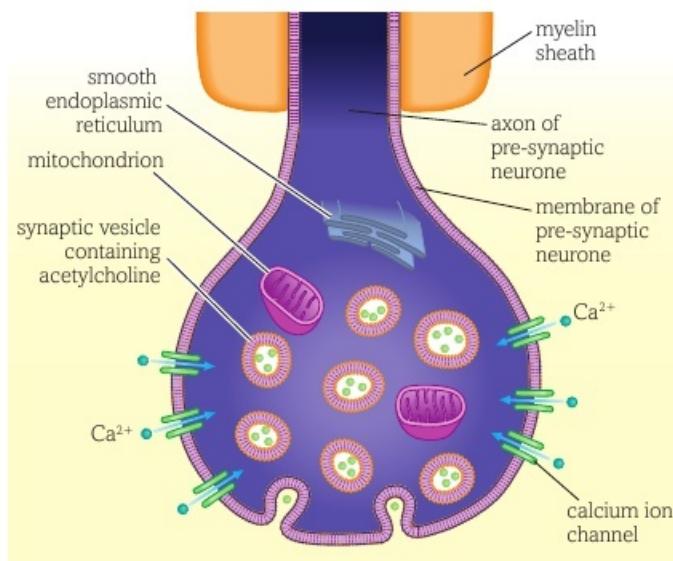


Figure 1 The pre-synaptic bulb.

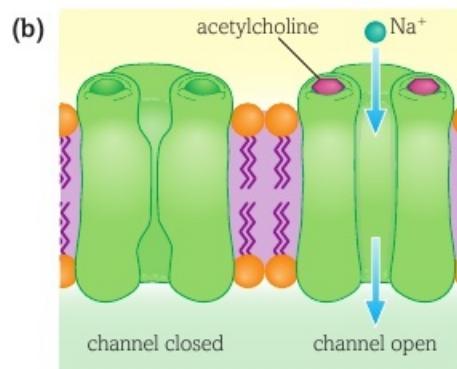
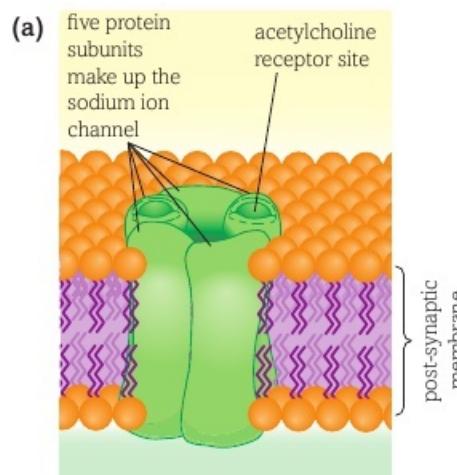


Figure 2 (a) The post-synaptic membrane contains sodium ion channels.
(b) The channels are opened by acetylcholine.

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Transmission across the synapse

The sequence of events in the transmission of a signal across the synaptic cleft is as follows (see Figure 3).

1. An action potential arrives at the synaptic bulb.
2. The voltage-gated calcium ion channels open.
3. Calcium ions diffuse into the synaptic bulb.
4. The calcium ions cause the synaptic vesicles to move to, and fuse with, the pre-synaptic membrane.
5. Acetylcholine is released by exocytosis.
6. Acetylcholine molecules diffuse across the cleft.
7. Acetylcholine molecules bind to the receptor sites on the sodium ion channels in the post-synaptic membrane.
8. The sodium ion channels open.
9. Sodium ions diffuse across the post-synaptic membrane into the post-synaptic neurone.
10. A generator potential or excitatory post-synaptic potential (EPSP) is created (see topic 5.3.6).
11. If sufficient generator potentials combine then the potential across the post-synaptic membrane reaches the threshold potential.
12. A new action potential is created in the post-synaptic neurone.

Once an action potential is achieved it will pass down the post-synaptic neurone.

LEARNING TIP

Remember that acetylcholine molecules are released from the vesicles by exocytosis and diffuse across the synaptic cleft. Your description should make it clear that vesicles do not pass across the synaptic cleft.

The role of acetylcholinesterase

If acetylcholine is left in the synaptic cleft it will continue to open the sodium ion channels in the post-synaptic membrane and will continue to cause action potentials. **Acetylcholinesterase** is an enzyme found in the synaptic cleft. It hydrolyses the acetylcholine to ethanoic acid (acetic acid) and choline. This stops the transmission of signals, so that the synapse does not continue to produce action potentials in the post-synaptic neurone.

The ethanoic acid and choline are recycled. They re-enter the synaptic bulb by diffusion and are recombined to acetylcholine using ATP from respiration in the mitochondria. The recycled acetylcholine is stored in synaptic vesicles for future use.

DID YOU KNOW?

Organophosphate insecticides work by permanently inhibiting acetylcholinesterase, causing convulsions and paralysis. Farmers who are over-exposed to these pesticides can suffer conditions associated with poor synaptic function.

Nicotine acts as a stimulant by activating the acetylcholine receptor sites.

Questions

- 1 Suggest why the pre-synaptic neurone ends in a bulb.
- 2 Explain why the pre-synaptic bulb contains:
 - (a) many mitochondria
 - (b) a lot of smooth endoplasmic reticulum.
- 3 Explain why the calcium ion channels are voltage-gated.
- 4 Why is it important that the synaptic cleft contains the enzyme acetylcholinesterase?
- 5 What deductions can you draw about the shape of the nicotine molecule?

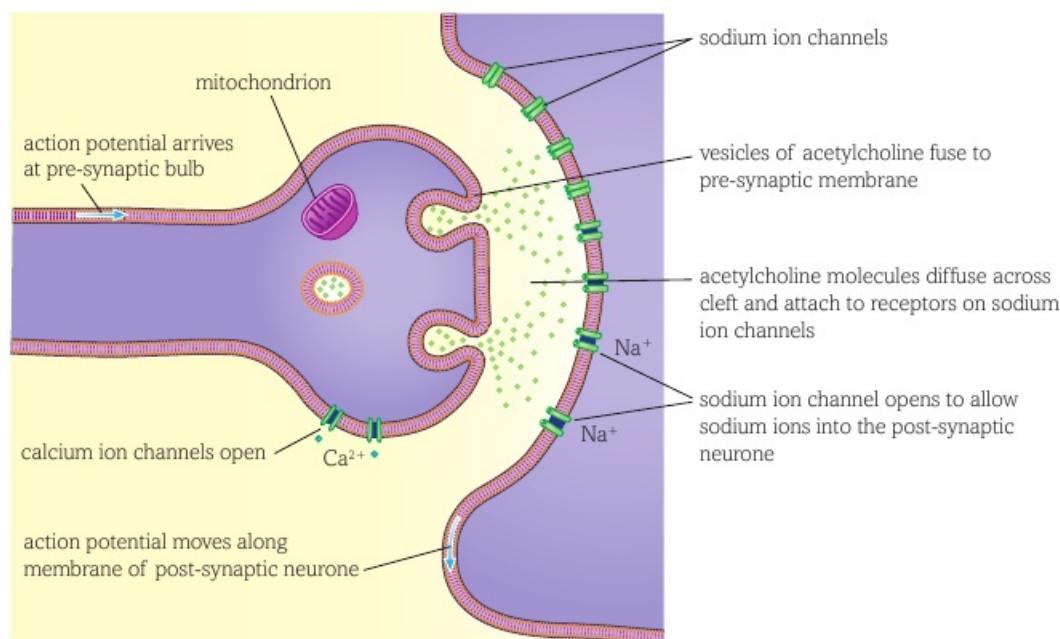


Figure 3 Transmission across a synapse.

By the end of this topic, you should be able to demonstrate and apply your knowledge and understanding of:

- * the structure and roles of synapses in neurotransmission

KEY DEFINITION

summation: occurs when the effects of several excitatory post-synaptic potentials (EPSPs) are added together.

Action potentials and cell signalling

In topic 5.3.4 we saw that an action potential is an all-or-nothing response. Once the action potential starts, it will be conducted along the entire length of the neurone. The action potential does not vary in size or intensity. At the end of the neurone the pre-synaptic membrane releases neurotransmitter molecules into the synaptic cleft. The post-synaptic neurone responds to these molecules, which is an example of cell signalling. In cholinergic synapses the signal sent to the next neurone consists of molecules of acetylcholine.

These processes are the same in all neurones with cholinergic synapses. In topic 5.3.4 we also saw that a more intense stimulus is transmitted as more frequent action potentials.

Synapses and nervous communication

The main role of synapses is to connect two neurones together so that a signal can be passed from one to the other. However, nerve junctions can be much more complex than a simple connection between two neurones. Nerve junctions often involve several neurones – this could be several neurones from different places converging on one neurone, or it could be one neurone sending signals out to several neurones that diverge to different effectors.

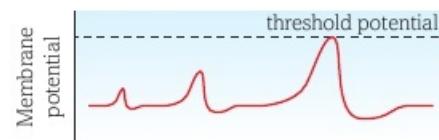
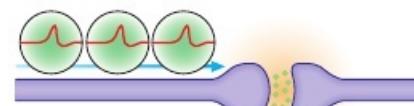
When one action potential passes down an axon to the synapse it will cause a few vesicles to move to, and fuse with, the pre-synaptic membrane. The relatively small number of acetylcholine molecules diffusing across the cleft produces a small depolarisation. This is an **excitatory post-synaptic potential (EPSP)**. This, on its own, will not be sufficient to cause an action potential in the post-synaptic neurone.

It may take several EPSPs to reach the threshold and cause an action potential. The effects of several EPSPs combine together to increase the membrane depolarisation until it reaches the threshold. This combined effect is known as **summation**.

Summation can result from several action potentials in the same pre-synaptic neurone (**temporal summation**), or from action potentials arriving from several different pre-synaptic neurones (**spatial summation**).

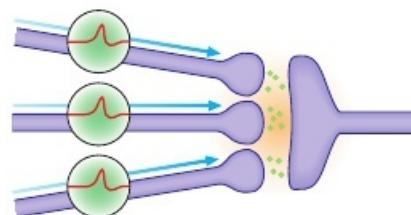
(a)

One action potential in the pre-synaptic neurone does not produce an action potential in the post-synaptic neurone – it requires a series of action potentials in the pre-synaptic neurone.



Small EPSPs (excitatory post-synaptic potentials) in post-synaptic neurone do not create an action potential until they act together.

(b)



Several pre-synaptic neurones may each contribute to producing an action potential in the post-synaptic neurone.

Figure 1 (a) Temporal summation and (b) spatial summation.

In addition, some pre-synaptic neurones can produce **inhibitory post-synaptic potentials (IPSPs)**. These can reduce the effect of summation and prevent an action potential in the post-synaptic neurone.

DID YOU KNOW?

In many synapses in the brain, EPSPs and IPSPs compete with each other and determine whether or not the post-synaptic membrane will generate an action potential. GABA (γ -aminobutyric acid) and glycine are common neurotransmitters involved in IPSPs. An IPSP can be achieved by opening chloride ion channels that allow chloride ions into the post-synaptic neurone or by opening potassium ion channels that allow potassium ions out of the cell. In both cases a temporary hyperpolarisation is produced.

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Control of communication

Because nerve junctions may involve several neurones, this enables synapses to control the communication passed along the nervous system:

- Several pre-synaptic neurones might converge on one post-synaptic neurone. This can allow action potentials from different parts of the nervous system to contribute to generating an action potential in one post-synaptic neurone – so creating a particular response. This is spatial summation. This could be useful where several different stimuli are warning us of danger.
- The combination of several EPSPs could be prevented from producing an action potential by one IPSP.
- One pre-synaptic neurone might diverge to several post-synaptic neurones. This can allow one action potential to be transmitted to several parts of the nervous system. This is useful in a reflex arc. One post-synaptic neurone elicits the response, while another informs the brain.
- Synapses ensure that action potentials are transmitted in the correct direction – only the pre-synaptic bulb contains vesicles of acetylcholine. Therefore, if an action potential happens to start half way along a neurone and ends at the post-synaptic membrane, it will not cause a response in the next cell.
- Synapses can filter out unwanted low-level signals. If a low-level stimulus creates an action potential in the pre-synaptic neurone it is unlikely to pass across a synapse to the next neurone, because several vesicles of acetylcholine must be released to create an action potential in the post-synaptic neurone.
- Low-level action potentials can be amplified by summation. If a low-level stimulus is persistent it will generate several successive action potentials in the pre-synaptic neurone. The release of many vesicles of acetylcholine over a short period of time will enable the post-synaptic EPSPs to combine together to produce an action potential.
- After repeated stimulation a synapse may run out of vesicles containing the neurotransmitter. The synapse is said to be fatigued. This means the nervous system no longer responds to the stimulus – we have become **habituated** to it. It explains why we soon get used to a smell or a background noise. It may also help to avoid overstimulation of an effector, which could cause damage.
- The creation and strengthening of specific pathways within the nervous system is thought to be the basis of conscious thought and memory. Synaptic membranes are adaptable. In particular, the post-synaptic membrane can be made more sensitive to acetylcholine by the addition of more receptors. This means that a particular post-synaptic neurone is more likely to fire an action potential, creating a specific pathway in response to a stimulus.

Questions

- 1 Explain the difference between an action potential and a cell signal.
- 2 What is meant by the term cholinergic synapse?
- 3 Explain what is meant by summation.
- 4 Explain how modifying the post-synaptic membrane could mean that one post-synaptic neurone is more likely to fire an action potential than another.
- 5 Suggest an example where the organism could benefit from preventing an action potential by creating an IPSP.