Chapter 4 – Neurones and Synapses

Students should be able to:

- **4.3.4** Describe the structure of a neurone
- **4.3.5** Understand the generation and transmission of nerve impulses
- **4.3.6** Describe the structure and functioning of a synapse

Coordination in animals, as in plants, involves hormones (called plant growth substances in plants). However, animals also have a **nervous system**. The nervous system is based on a system of **neurones** (nerve cells) that transmit electrical **nerve impulses** throughout the body. Fine control and integration is provided through a system of **synapses** (junctions) between neurones that can control the nerve pathways involved.

Note: Do not confuse neurones with nerves – nerves are bundles of neurones (nerve cells) grouped together (analagous to how individual electrical wires are grouped in electrical cabling).

In general, nervous control is **faster** and more **precise** than hormone action.

Nervous control usually involves **receptors** and **effectors** with an interlinking **coordinator**. Receptors are found in, for example, the eye, ear and nose, and each type of receptor is sensitive to a particular type of **stimulus**. Using the examples in the previous sentence, a stimulus is something we see, hear or smell. **Effectors** are parts of the body that produce the **response**; in mammals effectors are often muscles. Coordination invariably involves the **central nervous system (CNS)** comprising the brain and the spinal cord. Consequently, many of the neurones in the body travel **to** the CNS from receptors and **from** the CNS to effectors.

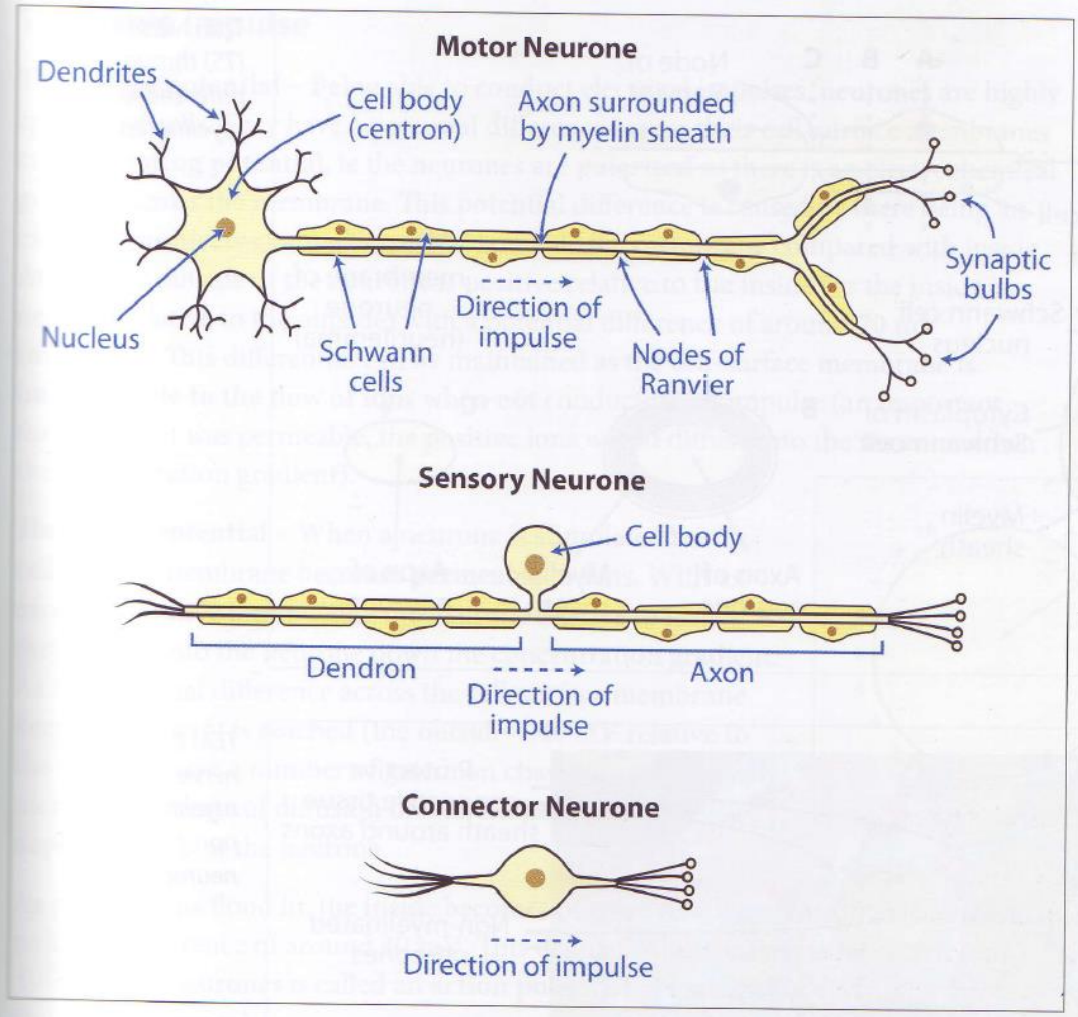
Neurones

There are three main types of neurone:

- **Motor neurones** – carry impulses from the CNS (brain or spinal cord) to effectors (muscles or glands).
- **Sensory neurones** – carry impulses from receptors to the CNS.
- **Connector** (relay, association or intermediate) neurones – connect neurones within the CNS.

Each type of neurone has the same function – to conduct **nerve impulses**. However, the three types differ in location as outlined above. Furthermore they have different shapes and sizes as seen in the following diagram.

Note: Neurones are much longer than they appear in the diagram. Some neurones can have a thousand or more Schwann cells along the length of the axon.

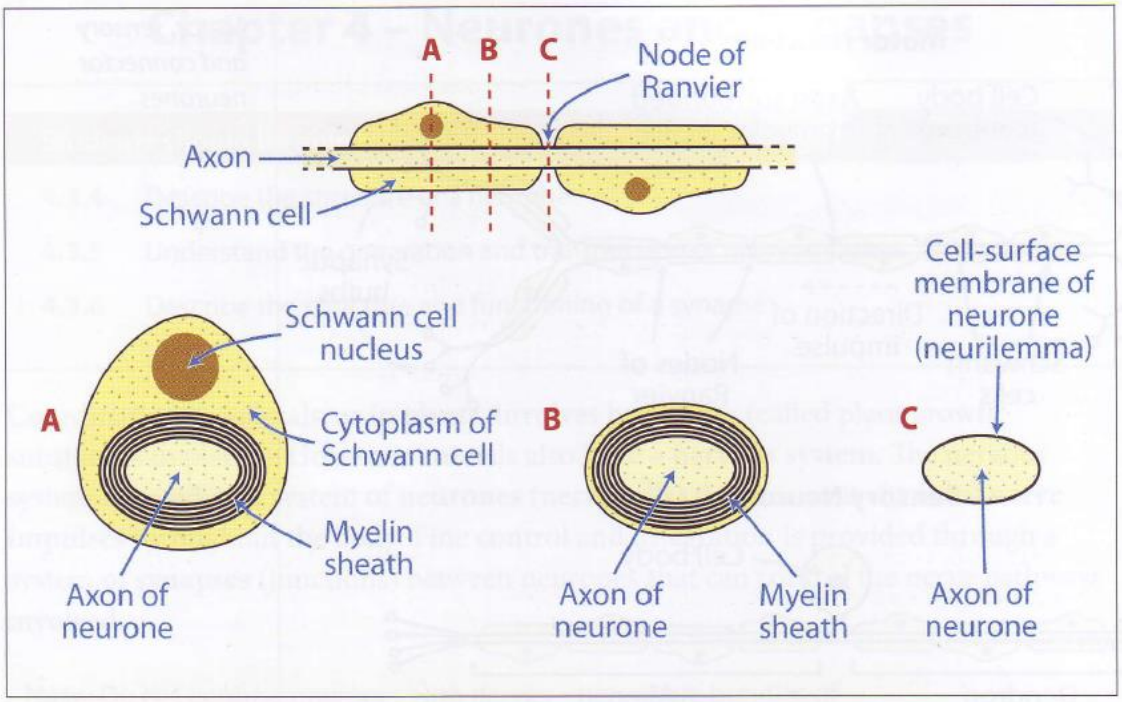


Motor, sensory and connector neurones

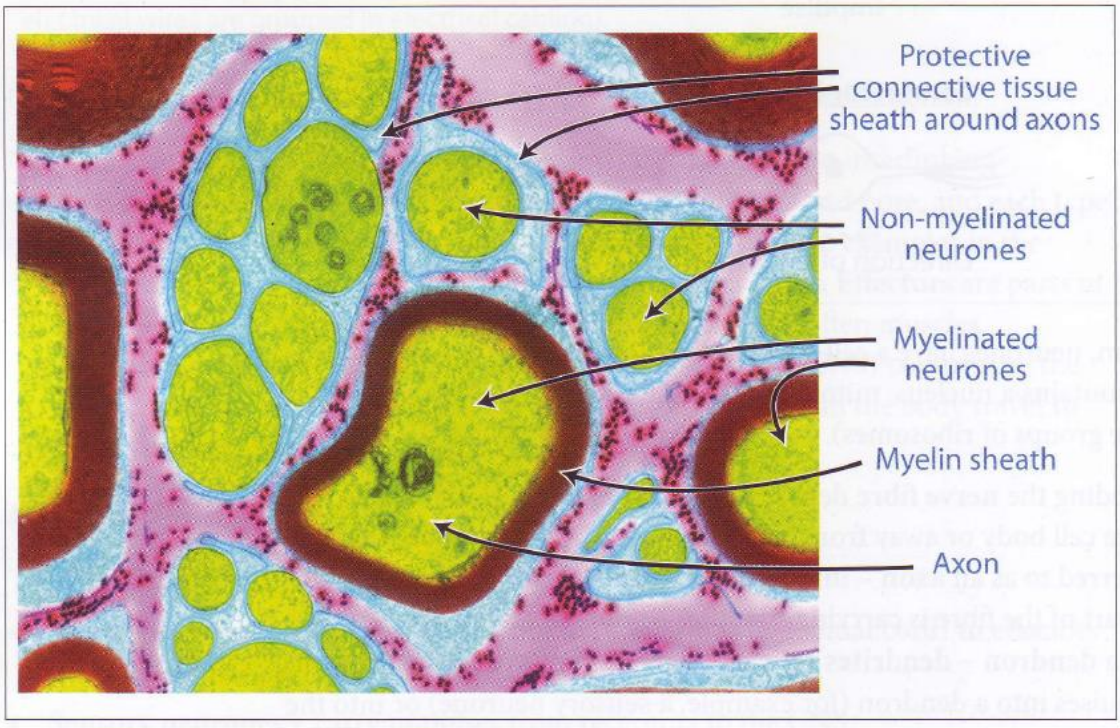
As seen in the diagram, neurones have a cell body and an extended nerve fibre. The **cell body** (**centron**) contains a nucleus, mitochondria and other organelles as well as Nissl's granules (large groups of ribosomes).

Terminology surrounding the **nerve fibre** depends on whether the part involved carries impulses to the cell body or away from it. If it transmits impulses away from the cell body, it is referred to as an **axon** – in motor neurones the entire fibre is an axon. However, if a part of the fibre is carrying impulses to the cell body (as in sensory neurones) it is called a **dendron** – **dendrites** are very small (and numerous) extensions that can conduct impulses into a dendron (for example, a sensory neurone) or into the cell body directly (for example, a motor neurone). Axons terminate in **synaptic bulbs** (knobs). Nerve fibres can range in length from less than a millimetre (some connector neurones) to over a metre.

In mammals, many nerve fibres (but not all) are **myelinated**. This means that their dendrons and axons are covered with an insulating **myelin sheath**. The myelin sheath, rich in the lipid myelin, is formed from the greatly extended cell-surface membrane of **Schwann cells** repeatedly being wrapped round the axon (or dendron). The Schwann cells (each about 1 mm in length) are arranged at intervals along the nerve fibre with small gaps between each cell called **nodes of Ranvier**. At these nodes the dendron or axon is exposed. The myelin sheath is both protective in function and also serves to speed up nervous conduction.



Transverse sections (TS) through different parts of a myelinated axon

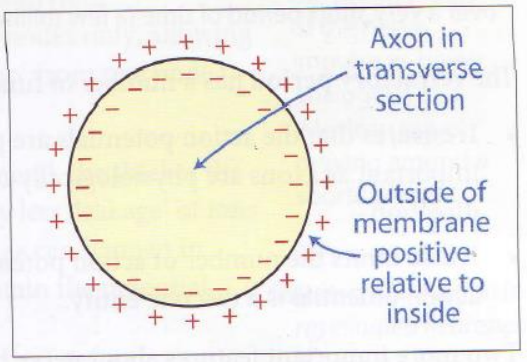


TEM through a nerve showing myelinated and non-myelinated neurones

Note: Nerves are bundles of neurones protected within an outer protective layer. Nerves can contain sensory neurones only, motor neurones only, or can be mixed and contain both types.

The nerve impulse

The resting potential – Being able to conduct electrical impulses, neurones are highly specialised cells. They have a potential difference across their cell-surface membranes called a **resting potential**, ie the neurones are **polarised** as there is an electrochemical gradient across the membrane. This potential difference is caused by there being an excess of positively charged ions (Na^+) outside the membrane compared with inside. At rest, the outside of the neurone is positive relative to the inside (or the inside is negative relative to the outside) with a potential difference of around **70 mV** (millivolts). This differential can be maintained as the cell-surface membrane is **impermeable to the flow of ions** when not conducting an impulse (an important feature as if it was permeable, the positive ions would diffuse into the neurone down the concentration gradient).



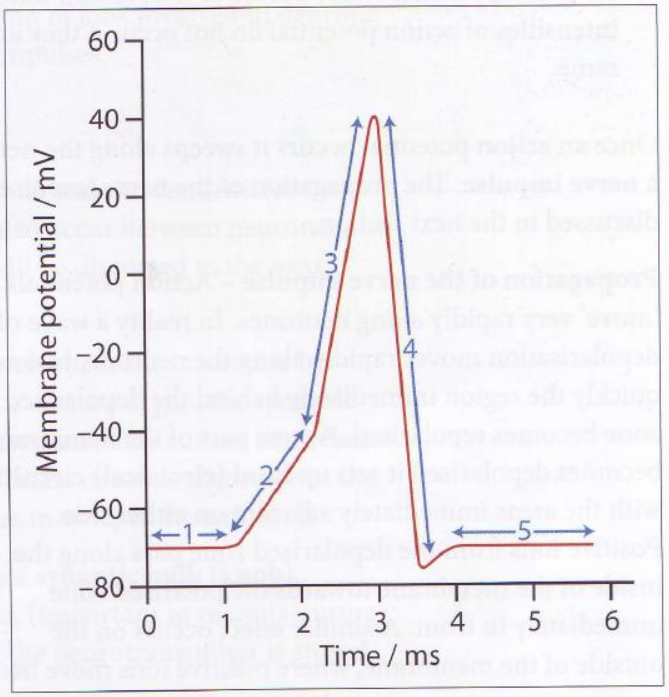
The resting potential

The action potential – When a neurone is stimulated the cell-surface membrane becomes **permeable** to ions. With an excess of positive ions outside the neurone relative to inside, they diffuse into the neurone down the concentration gradient. As the potential difference across the cell-surface membrane decreases, a point is reached (the outside + 40 mV relative to the inside) where a number of gated ion channels open, rapidly increasing the rate of diffusion of ions leading to **depolarisation** of the neurone.

As positive ions flood in, the inside becomes positive relative to the outside, reaching a potential difference of around 40 mV. This depolarisation and reversal of potential difference in neurones is called an **action potential**, a sequence of events that takes about 1 millisecond.

At the peak of the action potential (inside of neurone + 40 mV relative to outside) the recovery phase starts and the positive ions both **diffuse** and are **pumped out** of the neurone. This rapidly restores the resting potential and the cell-surface membrane becomes impermeable again. During this recovery phase (**refractory period**) a further impulse cannot occur as the gated ion channels are closed and the resting potential has not been fully restored. The entire electrochemical sequence of events associated with an action potential takes about 4 milliseconds.

Changes in the potential difference across the axon membrane as an action potential occurs



Explanation of diagram

1. Resting potential with inside of axon – 70 mV relative to outside (another way of saying outside of membrane is + 70 mV relative to inside).
2. Membrane becomes permeable and positive ions diffuse into the axon – membrane is starting to become depolarised.
3. At – 40 mV (inside relative to the outside) gated channels open and positive ions flood in at an

even more rapid rate. Rapid depolarisation of the membrane takes place and the inside becomes + 40 mV relative to the outside – the action potential.

4. Positive ions diffuse out and are also pumped out of the axon. This stage is called the refractory period as the membrane cannot be depolarised again until the resting potential is restored. At the end of this stage there is a slight 'overshoot' as the inside of the axon membrane becomes slightly more negative than in the normal resting potential (hyperpolarisation).
5. The resting potential is restored and the axon can conduct another nerve impulse if stimulated.

Note: The sequence of events in the diagram representing the action potential describes the sequence as it occurs at one point on the axon over a very short period of time (a few milliseconds).

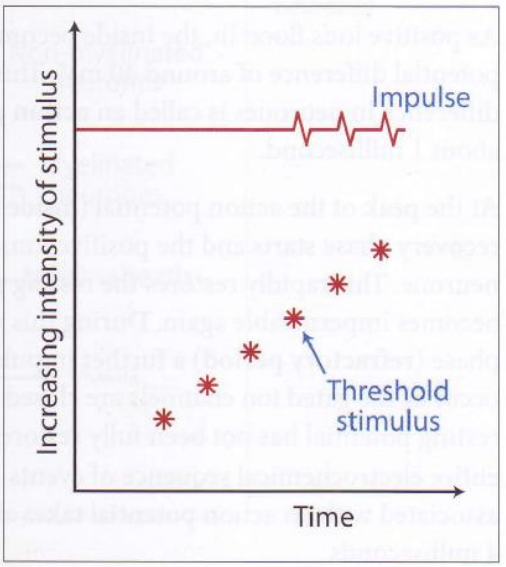
The **refractory period** has a number of functions.

- It ensures that the action potentials are propagated in one direction only. This is important as axons are physiologically capable of transmitting an impulse in either direction.
- It also limits the number of action potentials that can be fired and ensures that each action potential is a discrete entity.

Two more important features about nerve impulses:

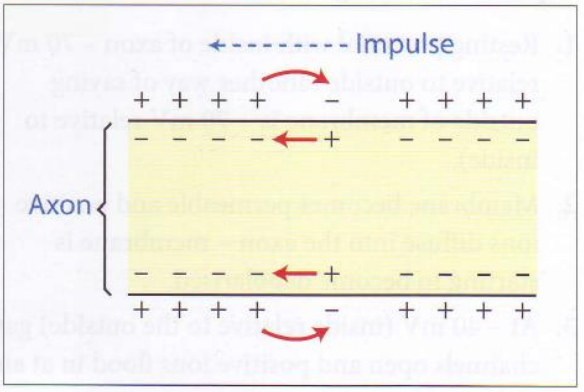
- The **threshold stimulus** refers to the level of stimulus a neurone requires before an action potential is produced, for example, a small degree of depolarisation in the cell-surface membrane of the neurone can occur without resulting in an action potential but at a critical point (the threshold potential) an action potential will result.
- The **all-or-nothing-law** refers to the principle that once the threshold stimulus is reached the action potential results, ie an action potential either occurs or it does not; different intensities of action potential do not occur – they are all the same.

The threshold stimulus and the all-or-nothing-law



Once an action potential occurs it sweeps along the neurone as a **nerve impulse**. The propagation of the nerve impulse is discussed in the next section.

Local circuits and nerve impulse propagation



Propagation of the nerve impulse – Action potentials 'move' very rapidly along neurones. In reality a wave of depolarisation moves rapidly along the neurone. Just as quickly the region immediately behind the depolarised zone becomes repolarised. As one part of the membrane becomes depolarised it sets up **local (electrical) circuits** with the areas immediately adjacent on either side. Positive ions from the depolarised zone pass along the inside of the membrane towards the polarised zone immediately in front. A similar effect occurs on the outside of the membrane, where positive ions move back

from the (as yet) still polarised zone into the depolarised zone. It is these processes occurring continuously that creates a wave of depolarisation that moves rapidly along the neurone. Similar circuits enable the resting potential to be restored directly behind the action potential.

Note 1: The zone of depolarisation is the part of the neurone where polarity is reversed, ie the inside is positive relative to the outside.

Factors affecting the speed of the nerve impulse – The speed of the nerve impulse is affected by a number of factors including the presence or absence of a myelin sheath and the thickness of the axon.

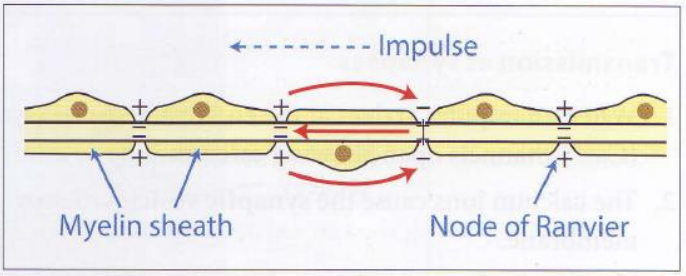
The **myelin sheath** acts as an electrical insulator in myelinated neurones. As an insulator it prevents depolarisation in that part of the neurone. However, every 1–2 mm along the neurone the sheath is disrupted – these breaks are the junctions between adjacent Schwann cells. At these points, called **nodes of Ranvier**, depolarisation can take place. The local circuits form between the nodes only, allowing sections of the neurone to be bypassed. The action potentials 'jump' from one node to the next in a process called **saltatory conduction**.

Note 2: Many textbooks refer to the propagation of the nerve impulse as being analogous to a 'Mexican wave' moving around a sports arena.

The **diameter of the axon** also affects the speed of impulse. In general, the thicker the axon the faster the impulse. This is because there is proportionally less 'leakage' of ions in a neurone with a larger diameter. If there is too much leakage, as can happen in axons with very small diameters, it makes it very difficult to maintain the potential gradients required to form resting and action potentials.

Saltatory conduction in myelinated neurones

In myelinated neurones, there are relatively few ion channels under the fatty myelin sheath (they are concentrated at the nodes of Ranvier). Consequently myelination tends to overcome the problems presented by neurones of small diameter, in addition to producing the faster speeds associated with saltatory conduction, for example, up to 100 m s^{-1}.



As with many metabolic processes, the speed of nerve impulse is affected by **temperature**. As temperature affects the rate of diffusion of ions involved in neurone action it affects the speed that neurones can conduct impulses.

Synapses

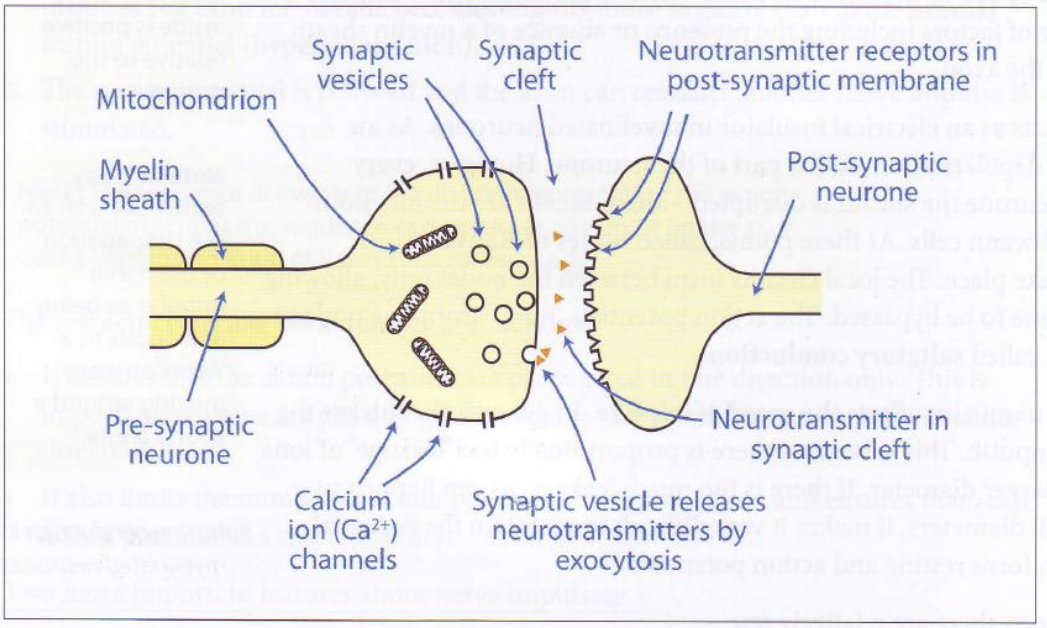
Synapses are junctions between the axon of one neurone and the dendrite (or dendron/centron) of an adjacent neurone. Synapses also occur between neurones and muscle – these specialised neuromuscular junctions will be discussed in the next chapter, in the section on muscle.

Structure of synapses – Impulses are transmitted from one neurone to another by chemicals called **neurotransmitters** that diffuse across a very small gap, **the synaptic cleft**, which is 20–30 nm wide. Both the **pre-synaptic neurone**, the neurone that releases the transmitter, and the **post-synaptic neurone**, the adjacent neurone that receives the diffusing neurotransmitter, are specialised for their roles in synaptic transmission.

The end of the pre-synaptic neurone is thickened into a **synaptic bulb (knob)**. Synaptic bulbs contain large numbers of mitochondria (important in manufacturing the neurotransmitter) and **synaptic vesicles** in which the neurotransmitter is stored.

The post-synaptic membrane contains **receptors** complementary to the type of neurotransmitter involved in that particular synapse. In general, the principle is that the neurotransmitters that pass across the synaptic cleft will cause depolarisation in the post-synaptic neurone allowing the nerve impulse to continue from one neurone to the next.

Note: A synapse includes the synaptic bulb, the synaptic cleft and the post-synaptic neurone membrane. If you get a question about synaptic transmission you will probably be expected to account for what takes place in each of these areas.



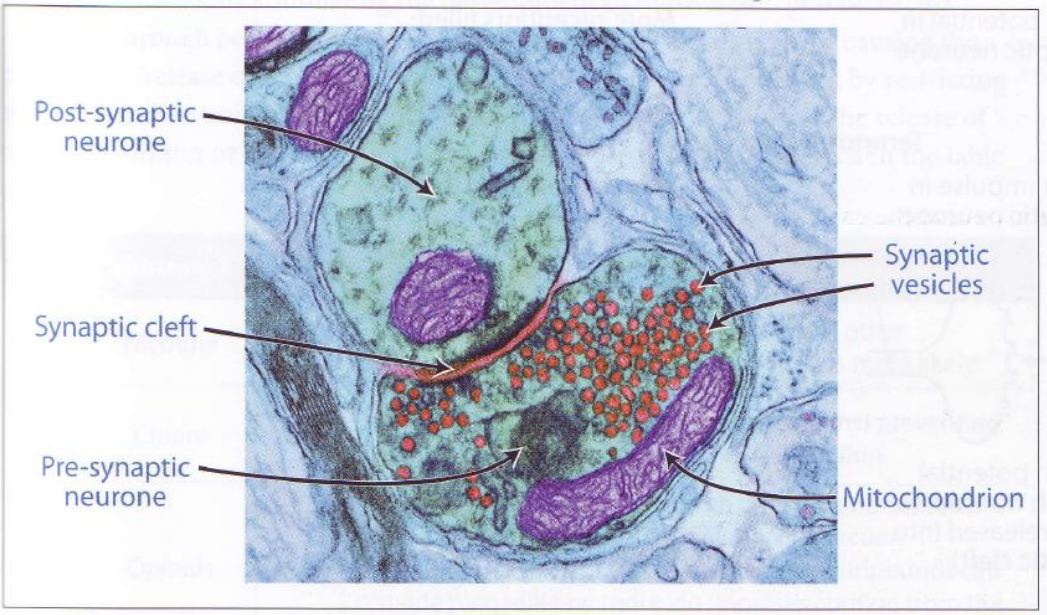
A typical synapse

Transmission at synapses

1. When an impulse arrives at the end of a neurone (synaptic bulb), calcium ion (Ca^{2+}) channels open allowing **calcium ions** to diffuse into the synaptic bulb.
2. The calcium ions cause the **synaptic vesicles** to move towards the pre-synaptic membrane.
3. The vesicles fuse with the pre-synaptic membrane, releasing the neurotransmitter (typically **acetylcholine**) by **exocytosis** into the synaptic cleft.
4. The acetylcholine diffuses across the synaptic cleft and binds to acetylcholine **receptors** in the post-synaptic membrane.
5. This causes the opening of ion (Na^{+}) channels in the membrane of the post-synaptic neurone. As positive ions diffuse in, the membrane becomes gradually depolarised and an **excitatory post-synaptic potential (EPSP)** is generated.
6. If sufficient depolarisation takes place (dependent on the number of neurotransmitter molecules filling receptor sites) the EPSP will reach the **threshold** intensity required to produce an **action potential** in the post-synaptic neurone.
7. The enzyme **acetylcholinesterase** (attached to the post-synaptic membrane) breaks down the acetylcholine. The breakdown products, **choline** and **ethanoic acid** (acetyl), are released into the cleft. It is very important that the acetylcholine is broken down and does not continually remain in a receptor – this prevents it continuously generating a new action potential in the post-synaptic neurone.
8. The breakdown products diffuse across the cleft and are reabsorbed into the synaptic bulb. They are subsequently **resynthesised** into **acetylcholine** which is stored in the synaptic vesicles to be used again. The ATP required is produced by the **mitochondria**.

Function of synapses – The diffusion of chemicals across a short gap is necessarily slower than the conduction of an impulse along myelinated neurones. However, due to the very short distances involved it is still very fast! Nonetheless, the presence of synapses gives the nervous system many advantages.

- They ensure **unidirectionality** – Nerve impulses can only pass from the pre-synaptic neurone to the post-synaptic neurone as the neurotransmitter is only made in the pre-synaptic neurone and neurotransmitter receptors are only in the membrane of the post-synaptic neurone.
- They **prevent** the **overstimulation** of effectors (for example, muscles) – Too many impulses passing along the same neurone in a short period of time will exhaust the supply of the neurotransmitter more quickly than it can be built up – the synapses **fatigue**.
- They provide **integration** – This may involve a number of pre-synaptic neurones forming junctions with one post-synaptic neurone. In effect, synapses provide **flexibility** – if there were no synapses, nervous activity would be little more than a series of reflexes with a particular stimulus producing an automatic and never-changing response. Integration is aided through the process of summation, which is discussed in the next section.



TEM of a synapse in the brain

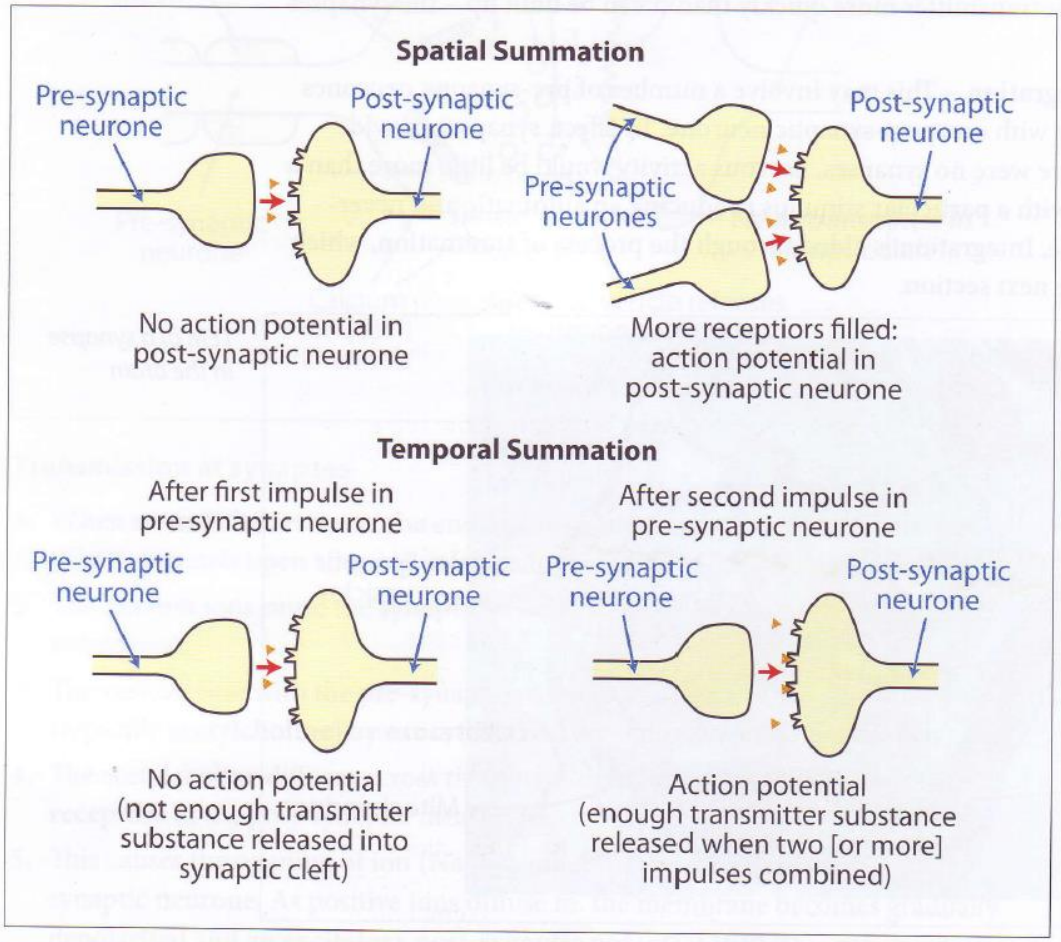
Note 1: In the TEM (transmission electronmicrograph) the axons of the two neurones extending beyond the synapse are not evident. This is because they were in different planes to the very thin section chosen for this photograph.

Note 2: A2 examinations will test synoptic knowledge, ie AS knowledge important in understanding A2 content. For example, you could be asked for the evidence that shows that the image is a transmission electron micrograph rather than a SEM (scanning electronmicrograph).

Summation is important in providing the complexity and flexibility that synapses demonstrate. For example, an infrequent action potential reaching a synapse may not be sufficient to cause an action potential in the adjacent post-synaptic neurone. However, a series of impulses travelling along the same neurone or a number of pre-synaptic neurones operating in unison, each releasing neurotransmitter chemicals, may be enough to cause a sufficient EPSP to trigger an impulse in the post-synaptic neurone.

The two types of summation just described are spatial and temporal summation. In **spatial summation** a number of different pre-synaptic neurones can together release enough neurotransmitter to produce an EPSP above the threshold level to produce an action potential in the post-synaptic neurone, whereas one on its own may not.

In **temporal summation**, a single pre-synaptic neurone releases neurotransmitter several times over a short timeframe (as a consequence of a series of action potentials passing along the neurone). Each pulse of neurotransmitter contributes to the depolarisation of the post-synaptic membrane, although any one action potential on its own may not be enough. As with spatial summation, if the EPSP reaches the threshold potential, an action potential is produced.



Spatial and temporal summation

Note: In the diagram, for explanatory purposes, each pre-synaptic neurone produces two molecules of neurotransmitter each time a nerve impulse reaches the synaptic bulb – in reality many more are produced.

The synapses discussed so far refer to **excitatory synapses** – neurotransmitter chemicals are released with the function of causing an EPSP and a subsequent action potential. **Inhibitory synapses** have the function of making it more difficult for synaptic transmission to take place. The neurotransmitter they release makes it more difficult for an EPSP to form in the post-synaptic membrane. Neurotransmitters in inhibitory synapses can, for example, lead to an influx of negative ions in the post-synaptic membrane, making the inside of the membrane even more negative (hyperpolarisation) than normal resting potential values. Consequently, this makes it more difficult than normal for excitatory synapses to produce an EPSP that reaches threshold level.

Whether an impulse will actually take place in the post-synaptic neurone depends on the relative contribution excitatory and inhibitory synapses make in promoting or inhibiting depolarisation.

Why have inhibitory synapses? They can help by reducing the input of background stimuli that would clutter up the nervous activity in the brain or may prevent some reflex actions.

The effects of summation and the action of inhibitory synapses provide integration and fine control through the synapse **integrating** all the different inputs (there may be hundreds) at synaptic junctions. Synapses also have an important role in filtering out low-level background stimuli thus preventing overload and overstimulation.

Neurotransmitter substances

Acetylcholine is the primary transmitter substance in the central nervous system (CNS) of vertebrates, although **noradrenaline** (typically used in involuntary nervous control, for example, the regulation of gut movements) is one of several other types. However, each synaptic bulb only produces one type of neurotransmitter.

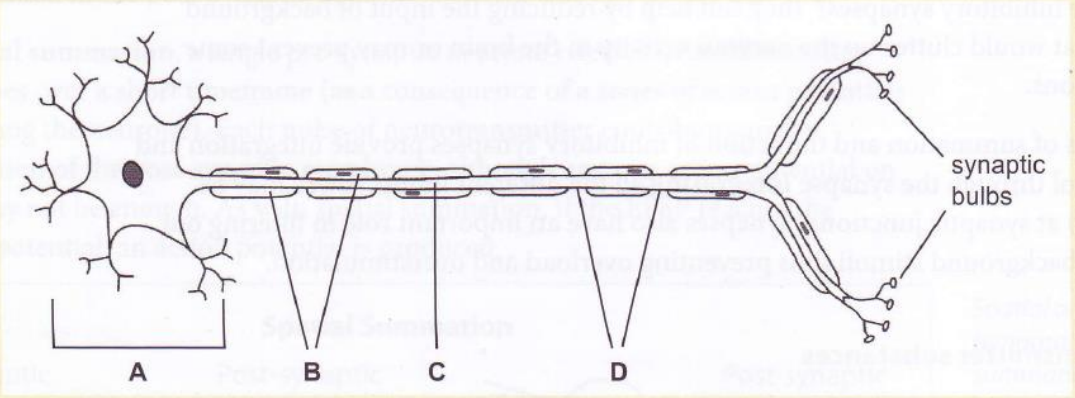
Many drugs work by stimulating the development of more action potentials, for example, through being similar in shape to the 'normal' transmitter or causing the production/release of more neurotransmitter at synapses. Others work by restricting the number of action potentials produced, for example by preventing the release of neurotransmitter or by blocking receptor sites. Three examples are given in the table below.

Substance	Effect
Nicotine	Stimulates the release of acetylcholine and other neurotransmitters making action potentials more likely.
Curare	Blocks receptors (at neuromuscular junctions) preventing synaptic transmission – loss of muscle function.
Opioids	Block the calcium channels in the pre-synaptic neurone. Less transmitter substance is released and action potentials less likely. Opioids and related compounds can provide pain relief by reducing impulses coming from the pain receptors.

Note: Many examination questions involve drugs that either stimulate, or are antagonistic to, neurotransmitters. The questions often provide information concerning the function of the drug involved (as in the table above) and you would be expected to deduce the effect they would have on synaptic transmission.

Exam questions

1. The diagram below represents the structure of a neurone.



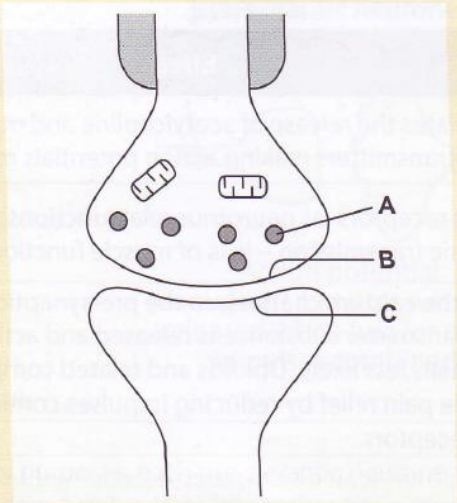
(a) Identify the structures labelled A to D. [3]

(b) Make a copy of the diagram above and draw an arrow to indicate the direction of a nerve impulse travelling along the neurone. [1]

(c) Explain why the neurone shown above might be expected to have a high speed of impulse conduction. [2]

Question taken from CCEA's Biology Assessment Unit A2 1, Physiology and Ecosystems, January 2010, © CCEA 2013

2. (a) (i) The diagram below shows two adjacent neurones at a synapse, as seen using an electron microscope. Three important features of the synapse are labelled A, B and C.



The table below lists four statements describing functions of certain features of a synapse.

Number	Statement
1	stores acetylcholine
2	location of acetylcholine receptor sites
3	provides energy for the re-synthesis of acetylcholine
4	location of exocytosis of acetylcholine

Make a copy of the following table and complete it by matching the labelled feature with the number of the most appropriate statement. [3]

Feature	Statement number
A	
B	
C	

(ii) Make a copy of the diagram in 2 (a) (i) and mark the following:

– with X, the location of an excitatory post synaptic potential.

– with Y, a structure necessary for saltatory conduction. [2]

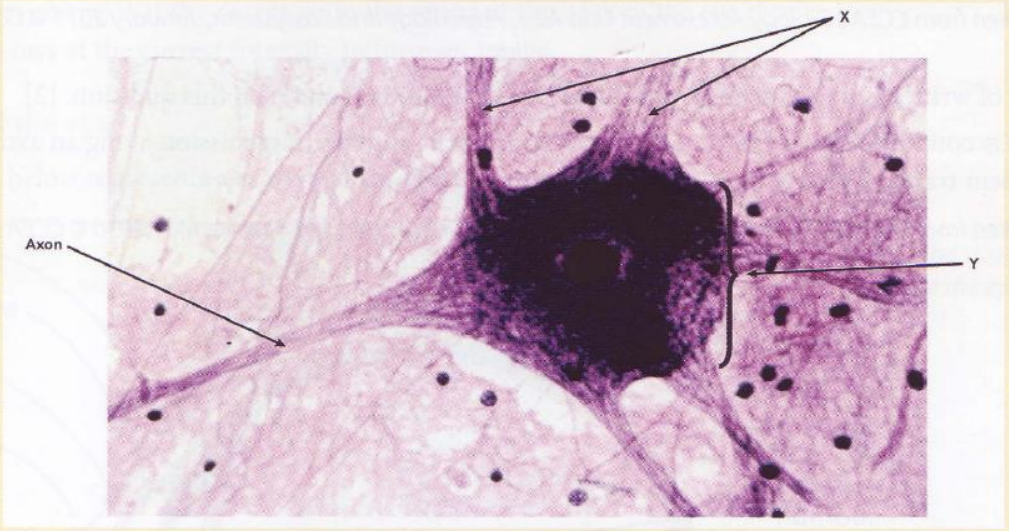
(b) Explain why transmission between neurones is unidirectional. [1]

Question taken from CCEA's Biology Assessment Unit A2 1, Physiology and Ecosystems, May 2011 © CCEA 2013

3. (a) The photograph below is a photomicrograph that shows part of a motor neurone cell.

(i) Identify the features labelled X and Y. [2]

(ii) Suggest which part of the body this photomicrograph was taken from. [1]



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(b) Attention-deficit disorder (ADD) is relatively common and is caused by a malfunctioning in neurotransmitter action. Recently it has been widely accepted that this disorder is genetic in origin as opposed to being a consequence of an individual's environment. Research published in *The Lancet* in October 2010 indicated that patients who had been given a clinical diagnosis of ADD were over twice as likely to have abnormalities in chromosome 16 compared with individuals without the condition. The data used in the research was based on 366 patients diagnosed with ADD with a control group of 1000.

(i) Outline the role of neurotransmitters in the functioning of the nervous system. [2]

(ii) State one reason why the conclusions of this research could be considered reliable. [1]

Research in scientific journals is 'peer-reviewed'. This means that other scientists working in the same field review the procedures used and the conclusions derived from the research.

(iii) Explain the importance of peer review in reviewing scientific research. [2]

Question taken from CCEA's Biology Assessment Unit A2 1, Physiology and Ecosystems, May 2012 © CCEA 2013

4. Almost all drugs taken by humans, including nicotine and alcohol, affect the nervous system, especially synapses.

(a) The drug nicotine, found in the leaves of the tobacco plant, binds to the acetylcholine receptor sites in synapses. After binding to these receptor sites, nicotine acts in a similar way to acetylcholine.

(i) Using your understanding of the nerve synapse, describe precisely where nicotine would bind. [1]

(ii) Describe and explain the effect of nicotine on the nervous system. [3]

(iii) Unlike acetylcholine, nicotine is not broken down within the synapse. Suggest one possible consequence of nicotine remaining in the synapse. [1]

(b) The drug alcohol, binds with gamma aminobutyric acid (GABA) receptors in synapses. After binding, alcohol acts in a similar way to GABA – the inside of the neurone membrane becomes more negative, a state known as hyperpolarisation.

(i) Suggest one way in which alcohol causes the inside of the membrane to become more negative. [1]

(ii) Alcohol is known to inhibit the nervous system. Suggest how this inhibition may be brought about. [2]

(iii) Suggest one consequence of alcohol inhibition of the nervous system. [1]

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5. Quality of written communication is awarded a maximum of 2 marks in this question. [2]

Give an account of the generation of an action potential, impulse transmission along an axon and subsequent transmission to a post-synaptic neurone. [16]

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