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Neural Signalling

IB Biology - Revision Notes

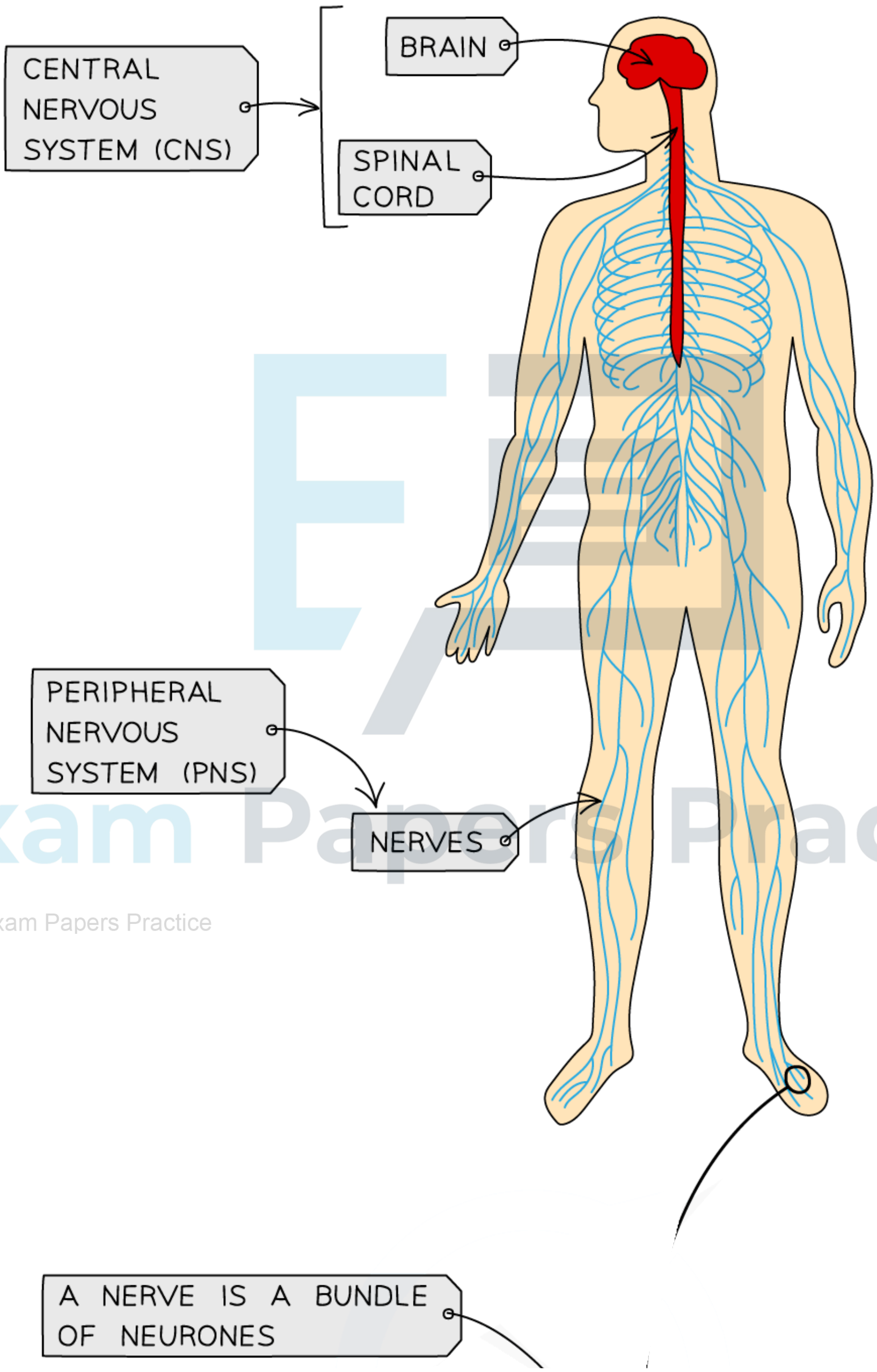
Neurones: Function & Structure

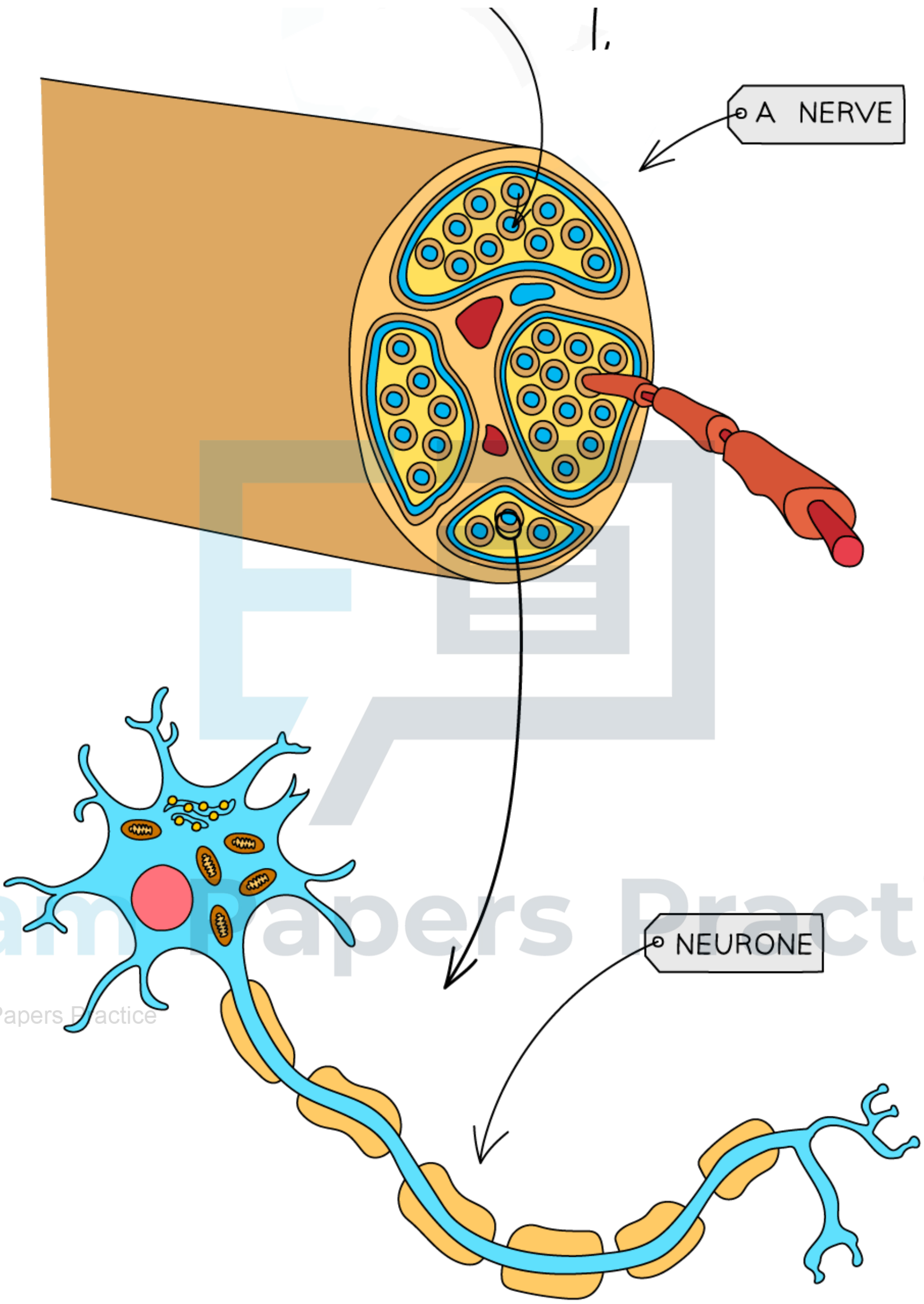
Neurones: Function & Structure

The nervous system

- The human nervous system consists of:
  - **Central nervous system** (CNS) – the **brain** and **spinal cord**
  - **Peripheral nervous system** (PNS) – all of the **nerves** in the body
- It allows us to make sense of our surroundings and respond to them, and to **coordinate and regulate body functions**
- Information is sent through the nervous system in the form of **electrical impulses** – these are electrical signals that pass along **nerve cells** known as **neurones**
  - A **bundle of neurones** is known as a **nerve**
- The nerves spread out from the central nervous system to **all other regions of the body** and importantly, to all of the **sense organs**
  - The **CNS** acts as a **central coordinating centre** for the impulses that come in from, and are sent out to, any part of the body

Central Nervous System Diagram


CENTRAL
NERVOUS
SYSTEM (CNS)
BRAIN
SPINAL
CORD
PERIPHERAL
NERVOUS
SYSTEM (PNS)
NERVES
A NERVE IS A BUNDLE
OF NEURONES

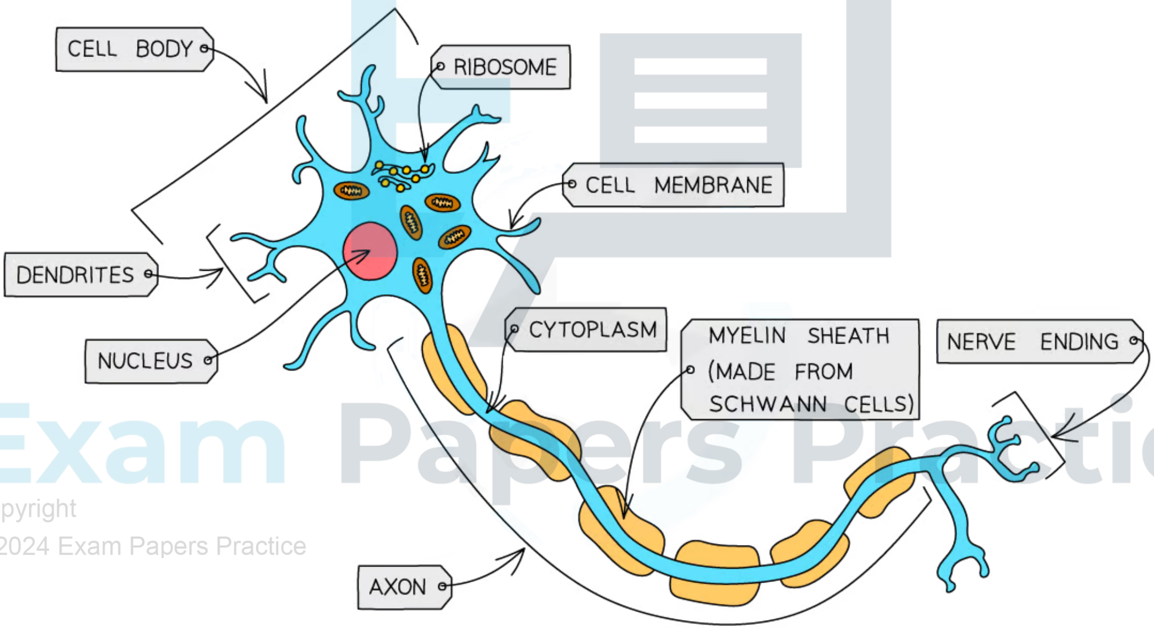


The human nervous system is comprised of the CNS and the PNS

Neurones

- The following features are found in neurones:
  - Neurones have a **main, long, fibre** known as an **axon**
  - The axon is often **insulated** by **Schwann cells** which form the **myelin sheath** which prevents loss of nerve impulses along the axon
  - They have a **cell body** that contains the **nucleus** and other cellular structures
  - Their **cell bodies** and **axon terminals** contain many extensions called **dendrites**
  - These **dendrites** allow them to **connect** to **many other neurones** and receive **impulses** from them, forming a **network** for easy **communication**

Structure of a Neurone Diagram



Neurones have a characteristically elongated structure which allows them to transfer information between the central nervous system and the rest of the body

Different types of neurone

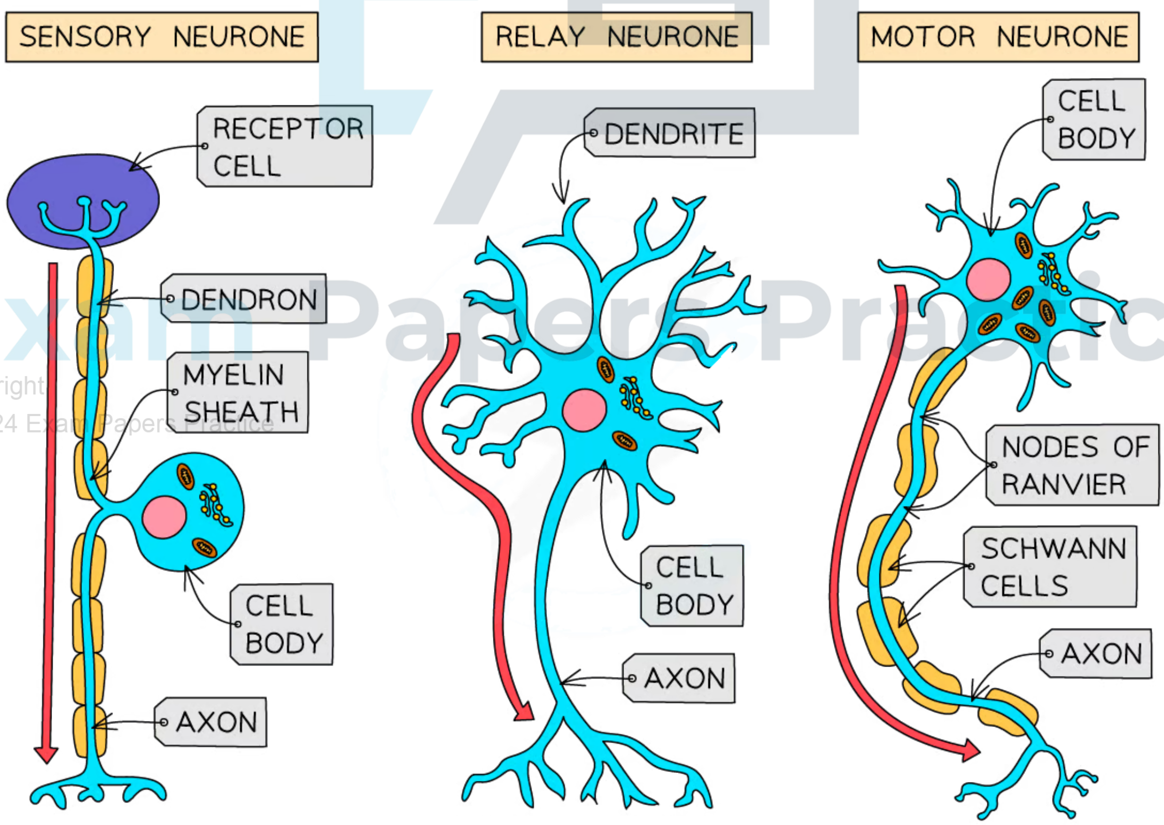
- There are **three main types** of neurone: **sensory, relay and motor**
  - **Sensory** neurones carry impulses from **receptors** to the **CNS** (brain or spinal cord)

- **Relay** (intermediate) neurones are found entirely within the CNS and **connect sensory** and **motor** neurones
- **Motor** neurones carry impulses from the **CNS** to **effectors** (muscles or glands)

- Each type of neurone has a **slightly different structure**
- **Motor neurones** have:
  - A large **cell body at one end** that lies within the spinal cord or brain
  - A nucleus that is always in its cell body
  - Many highly-branched dendrites extending from the cell body, providing a large surface area for the axon terminals of other neurones

  Relay neurones have:
  - Short, but highly branched, axons and dendrites
- **Sensory neurones** have:
  - A **cell body** that branches off in the **middle** of the cell
  - A single long dendron that carries impulses to the cell body and a single long axon that carries impulses away from the cell body

Three Types of Neurone Diagram



The three types of neurone – the red line shows the direction of impulses. Note that the axon always carried impulses away from the cell body.

Nerve Impulses

Generating the Resting Potential

- **Neurones** transmit information in the form of **impulses**, which travel extremely quickly along the neurone from one end to the other
  - Note that an impulse is **not** an electrical current that flows along neurones as if they were wires
  - Instead, an impulse is a **momentary reversal in the electrical potential difference** across the **neurone cell surface membrane**
    - The electrical potential difference across a membrane can also be described as the **voltage** across a membrane, the **difference in charge** across a membrane, or the **membrane potential**
- In an axon that is **not transmitting an impulse** the **inside** of the axon always has a **negative electrical potential**, or charge, compared to **outside** the axon, which has a **positive electrical potential**
  - This membrane potential in a resting neurone is known as **resting potential**
- The **resting potential** is usually about **-70 millivolts (mV)**
  - This means that the **inside** of the resting axon has a **more negative** electrical charge than the **outside** by about 70 mV
- Two main processes contribute to establishing and maintaining resting potential:
  - **The active transport of sodium ions and potassium ions**
  - **A difference in rates of diffusion of sodium ions and potassium ions**
- In addition to these two main processes, **negatively charged proteins** inside the axon also contribute to the negative resting potential

The active transport of sodium ions and potassium ions

- Carrier proteins called **sodium-potassium pumps** are present in the cell surface membranes of neurones
- These pumps use **ATP** to actively transport **sodium ions** (Na^+) **out** of the axon and **potassium ions** (K^+) **into** the axon
- The two types of ion are pumped at an unequal rate; for every **3 sodium ions that are pumped out** of the axon, only **2 potassium ions are pumped in**
- This creates a concentration gradient across the membrane for both sodium ions and potassium ions

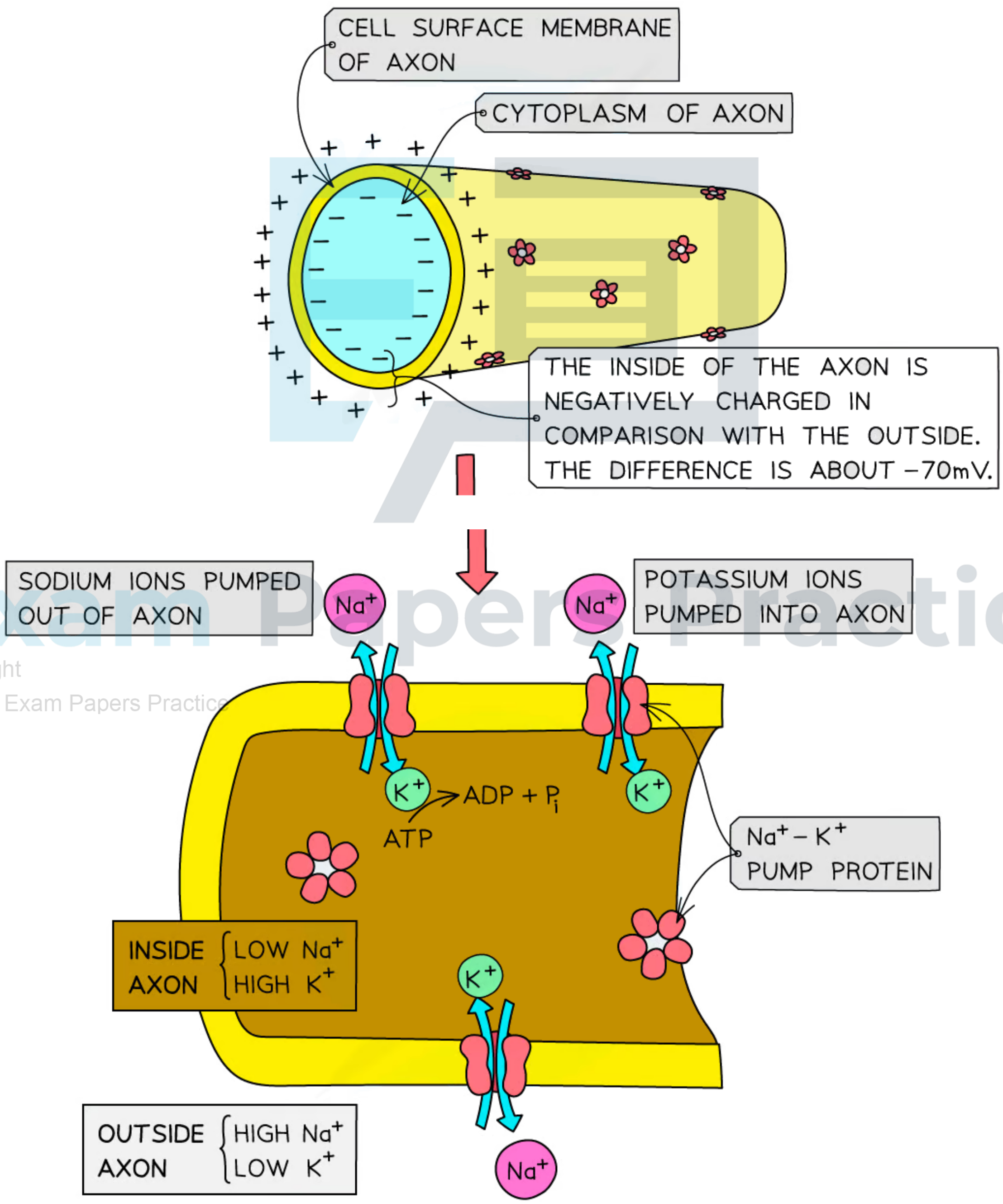
Difference in rates of diffusion of sodium ions and potassium ions

  - Because of the concentration gradient generated by the **sodium-potassium pumps**, both sodium and potassium ions will diffuse back across the membrane
    - The neurone cell surface membrane has **sodium ion channels** and **potassium ion channels** that allow sodium and potassium ions to move across the membrane

by **facilitated diffusion**

- The neurone membrane is much **less permeable** to sodium ions than potassium ions, so potassium ions inside the neurone can diffuse **out** at a **faster rate** than **sodium ions** can diffuse **back in**
- This results in **far more positive ions** on the **outside** of the neurone than on the inside, generating a **negative charge inside** the neurone in relation to the outside
- The result of this is that the neurone has a **resting membrane potential** of around **-70 millivolts (mV)**

Resting Potential Diagram



Sodium-potassium pumps in the membrane of a resting neurone generate a concentration gradient for both sodium ions and potassium ions. This process, together with the facilitated diffusion of potassium ions back out of the cell at a faster rate than sodium ions diffuse back into the cell, generates a negative resting potential across the membrane.

Nerve Impulses

- Once resting potential is reached, the neurone membrane is said to be **polarised**
- To initiate a nerve impulse in a neurone, the neurone membrane needs to be **depolarised**
  - Depolarisation is the **reversal of the electrical potential difference** across the membrane
- The depolarisation of the membrane occurs when an **action potential** is generated
  - Action potentials lead to the reversal of resting potential from around **-70 mV** to around **+40 mV**
- Action potentials involve the **rapid movement** of **sodium ions** and **potassium ions** across the **membrane** of the **axon**
- An action potential is the **potential electrical difference** produced across the axon membrane when a neurone is **stimulated** e.g. when an environmental stimulus is detected by a receptor cell

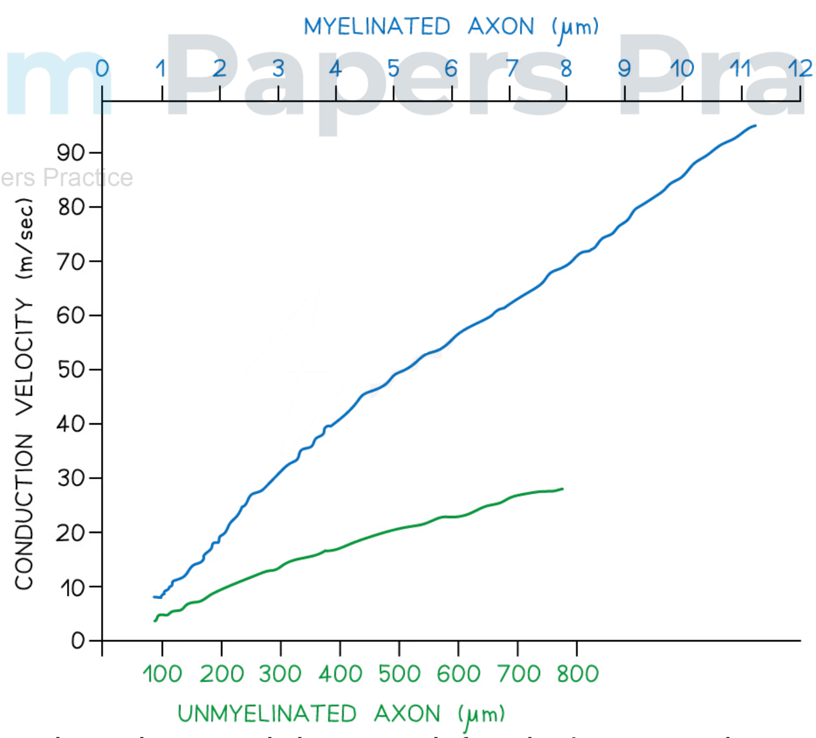
Nerve Impulses: Skills

Speed of Nerve Impulses

Comparing the speed of transmission

- There are well documented correlations between specific **structural features** of neurones and the **speed of transmission**
- Two key features that should be considered include
  - **Myelination** of the neurone
    - **Myelinated** neurones conduct electrical impulses **much more quickly** than unmyelinated fibres
    - This is because of the **insulation** offered by the myelin sheath which allows faster **saltatory conduction** along the neurone
  - **Diameter** of the neuron
    - An axon with a **wider diameter** conducts an electrical impulse **more quickly** than a narrow axon
    - This is because a wider axon offers **less resistance** to the action potential
- **Squid** have giant axons which are **unmyelinated** and can be up to **1 mm** wide, whereas the average diameter of a **human** neurone is somewhere between **4 and 100 µm**
- The graph shows the relationship between axon diameter and speed of transmission in a giant unmyelinated axon from a squid and a 'normal' sized myelinated axon of a mammal
- Despite the axon being significantly wider, the speed of transmission is much faster in the axon which is insulated by a myelin sheath

Comparing Speed of Nerve Transmission Graph

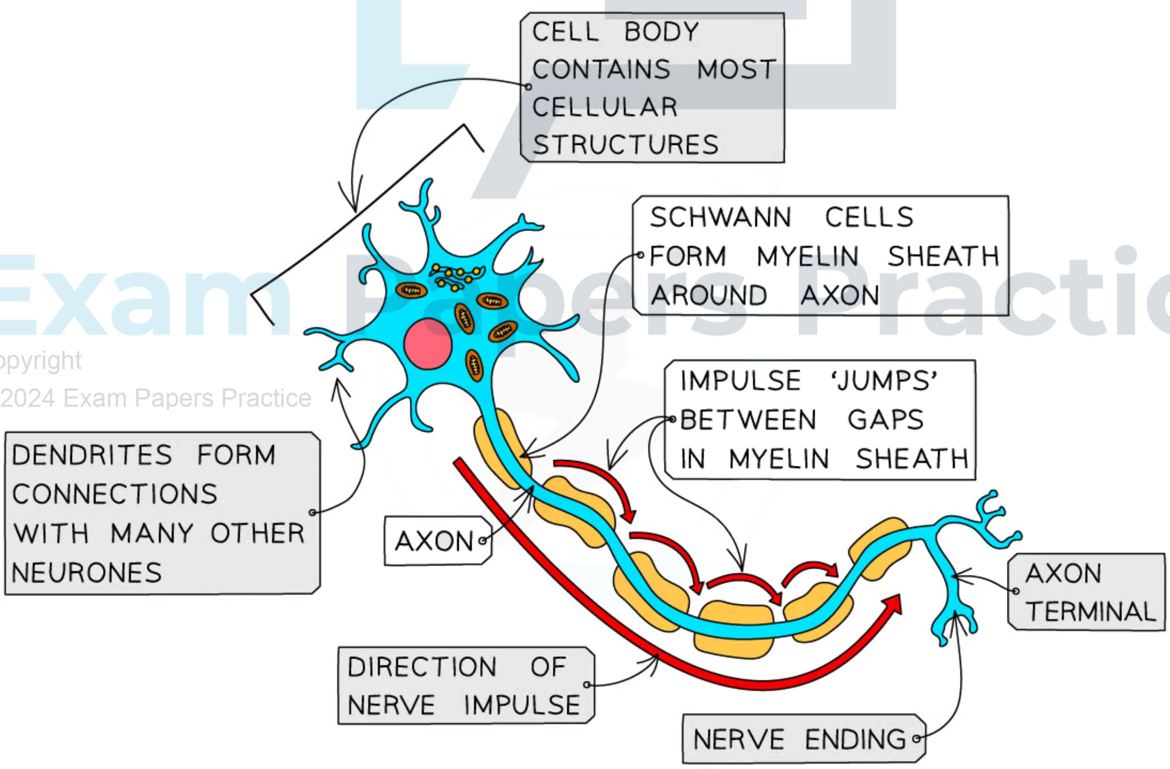


Unmyelinated axons have a much slower speed of conduction compared to a myelinated axon

Myelination

- Neurones have a **main, long, fibre** known as an **axon**
- The axons of neurones are **surrounded** by specialised cells called **Schwann cells**
- Schwann cells **wrap themselves around the axon**, forming a structure known as a **myelin sheath**
  - **Myelin** contains the **phospholipids** of the **Schwann cell membranes**; it is built up in layers as the Schwann cells grow around the axon
  - The **lipid** content of the myelin sheath gives it a **high electrical resistance**
- The myelin sheath acts as an **electrical insulator;** impulses cannot pass through the myelin sheath
- The myelin sheath has **small, uninsulated sections** in the gaps between the individual Schwann cells
  - These gaps are called **nodes of Ranvier**
- Electrical impulses effectively **jump** from one node of Ranvier to the next
  - This process is known as **saltatory conduction**
  - It greatly **speeds up the rate of transmission of impulses** along myelinated neurones
  - In non-myelinated neurones the axon is not insulated by myelin, so the impulse travels **more slowly**

Diagram to show the myelination of neurones



An impulse travels down a neurone via saltatory conduction

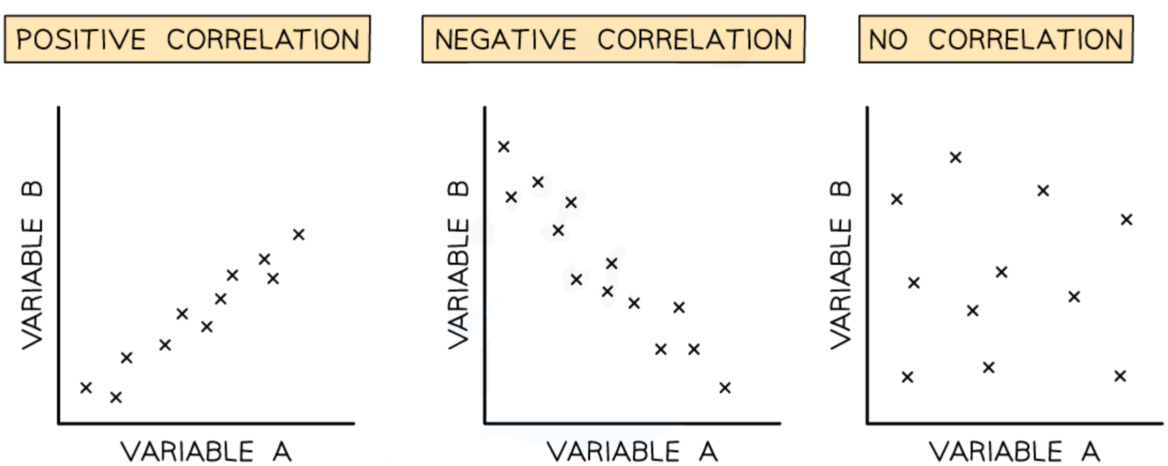
Describing a correlation using a correlation coefficient

- When studying the **relationship between two variables** such as diameter or myelination and speed of transmission, it is important to collect data which allows us to analyse the **strength of the correlation**
  - **Correlation** is an association or relationship between variables
  - There is a clear distinction between **correlation** and **causation**: a **correlation does not necessarily imply a causative relationship**
  - **Causation** occurs when one variable has an influence or is influenced by, another
- For the variables discussed here:
  - There may be a correlation **between diameter** of a neurone and the **speed** of impulse conduction
  - There may be a correlation **between the myelination** of a neurone and **speed** of impulse conduction
- The apparent correlation between variables can be analysed using **scatter graphs** and different **statistical tests**

Correlation between variables

- In order to get a broad overview of the correlation between two variables the data points for both variables can be plotted on a **scatter graph**
- The correlation coefficient (r) indicates the **strength of the relationship** between variables
- Perfect correlation occurs when **all of the data points lie on a straight line** with a **correlation coefficient of 1 or -1**
- Correlation can be **positive or negative**
  - Positive correlation: as variable A increases, variable B increases
  - Negative correlation: as variable A increases, variable B decreases
- If there is **no correlation** between variables the **correlation coefficient will be 0**

Correlation in Data Graphs



Different types of correlation in scatter graphs

- The **correlation coefficient (R)** can be calculated to determine whether a linear relationship exists between variables and how strong that relationship is
- The **coefficient of determination (R^2)** can then be calculated to test the strength of the association between the variables

Pearson's linear correlation

- Pearson's linear correlation is a **statistical test** that determines whether there is **linear correlation** between two variables
- The data must:
  - Be **quantitative**
  - Show normal distribution
- Method:
  - **Step 1:** Create a **scatter graph** of data gathered and identify if a linear correlation exists
  - **Step 2:** State a null hypthessis
  - **Step 3:** Use the following **equation** to work out Pearson's correlation coefficient *r*
- If the correlation coefficient r is close to 1 or -1 or the then it can be stated that there is a strong linear correlation between the two variables and the **null hypothesis can be rejected**

$$R = n\frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{[n\Sigma x^2 - (\Sigma x)^2][n\Sigma y^2 - (\Sigma y)^2]}}$$

$\sum x$ = total of the first variable value

$\sum y$ = total of the second variable value

$\sum xy$ = sum of the product of the first and second value

$\sum x^2$ = sum of the squares of the first value

$\sum y^2$ = sum of the squares of the second value

The coefficient of determination

$$\text{The coefficient of determination } (R^2) = (\text{ Pearson correlation coefficient})^2$$

The to find the coefficient of determination...

- Method:
  - **Step 1:** Square the value found for R
  - **Step 2:** Convert the value into a percentage
- An R^2 value of **closer to 1 (or 100%)** shows that the variables have a **strong correlation**, or, you can predict the dependent variable accurately from the independent variable
  - **The null hypothesis can be rejected**
- An R^2 value closer to **0** indicates that there is **no correlation**, or, the dependent variable cannot be predicted from the independent variable

Exam Tip

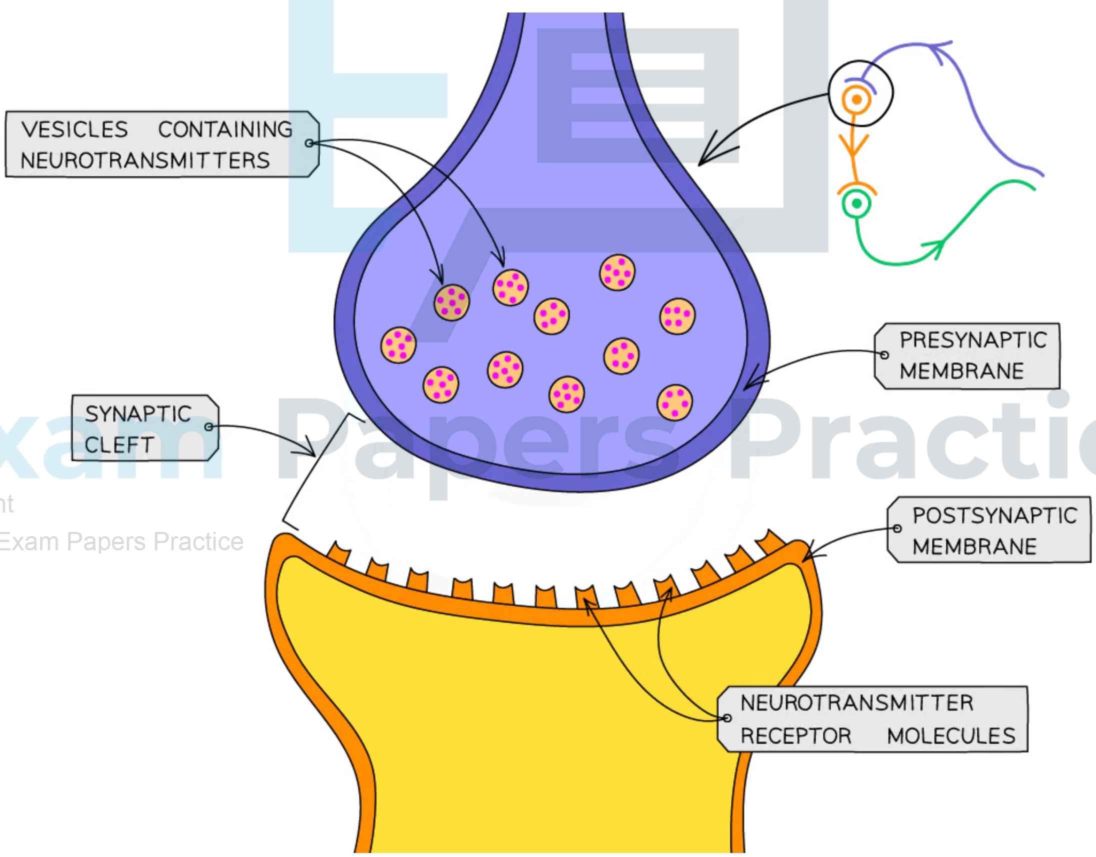
You will be provided with the formula for Pearson's linear correlation in the exam. You need to be able to carry out the calculation to test for correlation, as you could be asked to do this in the exam. You should understand when it is appropriate to use the different statistical tests that crop up in this topic, and the conditions in which each is valid.

Synapses

Synapses

- Where two neurones meet, they do not actually come into **physical contact** with each other
- Instead, a very small gap, known as the **synaptic cleft**, separates them
- The ends of the two neurones, along with the synaptic cleft, form a structure known as a **synapse**
- Synapses act as the junctions **between any cells in the nervous system**, e.g.
  - In the sense organs, there are synapses between **sensory receptor cells** and **sensory neurones**
  - In muscles, there are synapses between **motor neurones** and **muscle fibres**

Structure of a Synapse Diagram



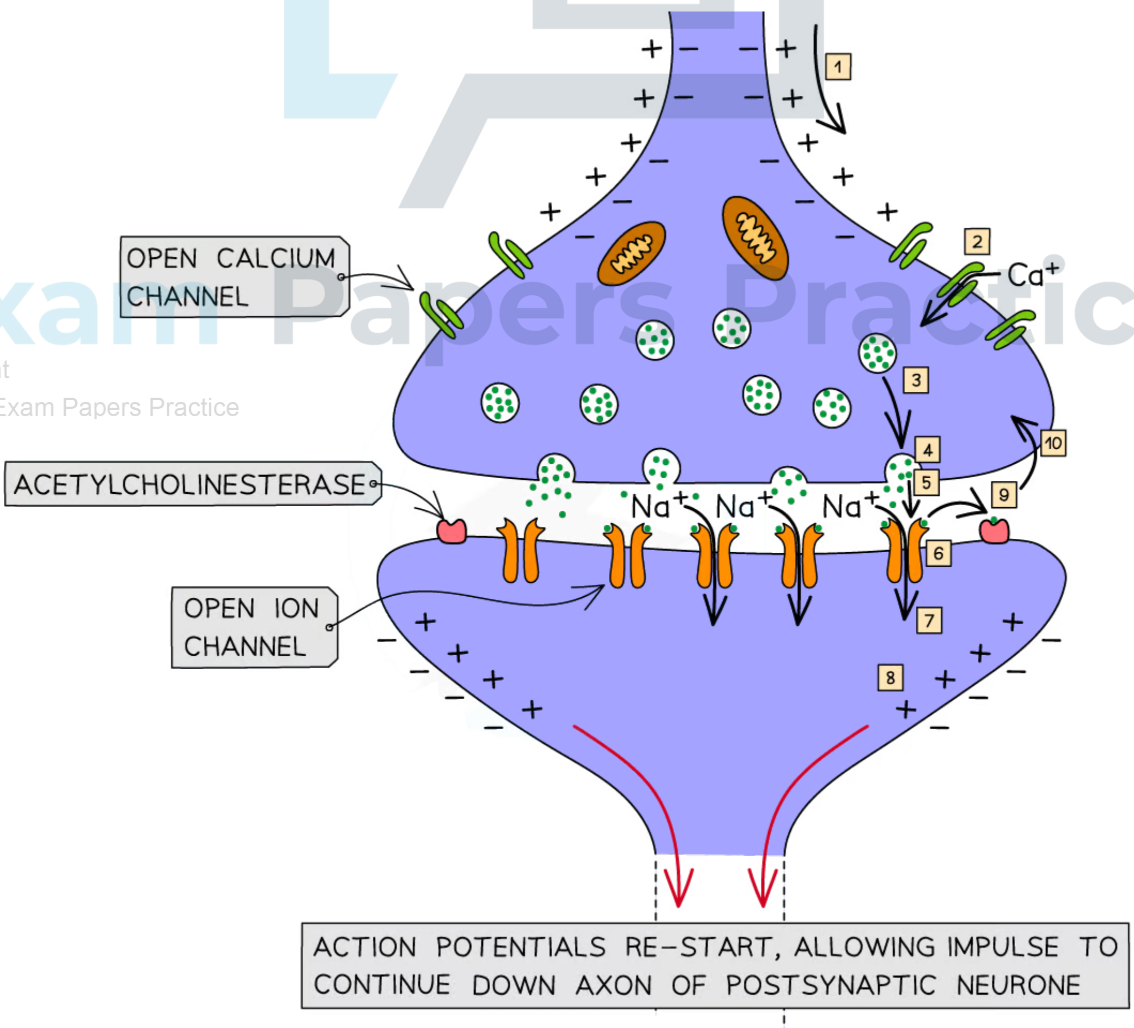
A synapse

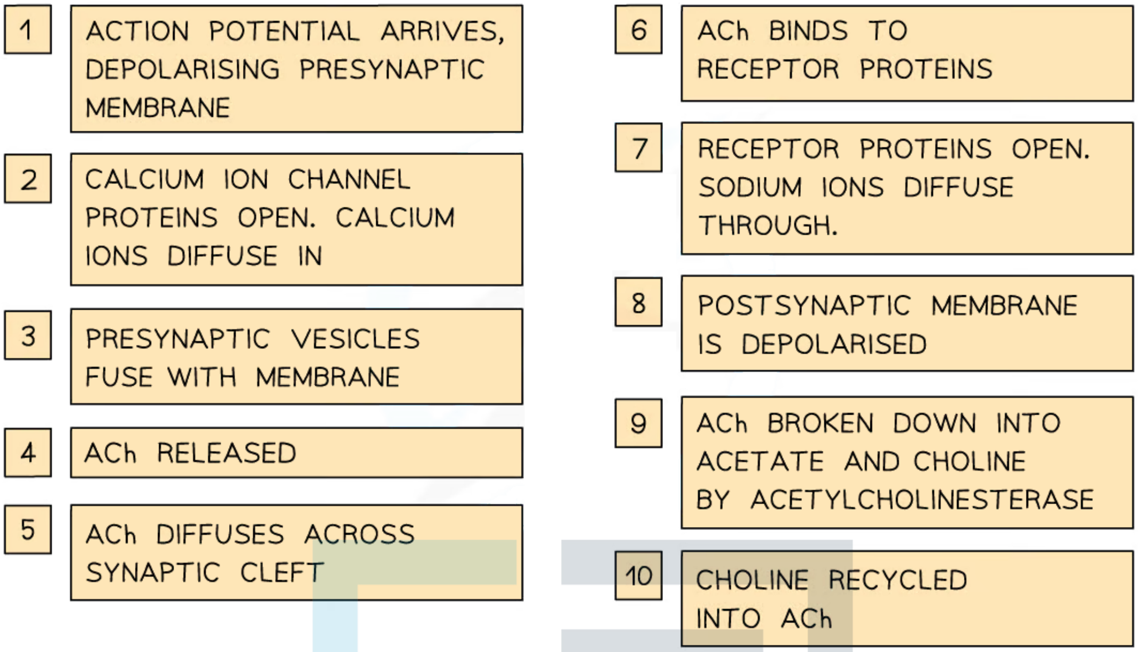
Release of Neurotransmitters

Synaptic transmission: How do synapses work?

- Electrical impulses cannot 'jump' across the synaptic cleft
- When an electrical impulse arrives at the end of the axon on the **presynaptic neurone**, the **membrane** of the presynaptic neurone becomes depolarised, triggering an influx of **calcium ions** into the presynaptic cell via **calcium ion channels** in the membrane
- The calcium ions cause vesicles in the presynaptic neurone to move towards the presynaptic membrane where they fuse with it and **release chemical messengers** called **neurotransmitters** into the synaptic cleft
  - A common neurotransmitter is **acetylcholine**, or **ACh**
- The neurotransmitters **diffuse** across the **synaptic cleft** and **bind with receptor molecules** on the **postsynaptic membrane**; this causes associated **sodium ion channels** on the postsynaptic membrane to open, allowing **sodium ions** to diffuse into the postsynaptic cell
- If enough neurotransmitter molecules bind with receptors on the postsynaptic membrane then an **action potential** is generated, which then travels down the **axon** of the **postsynaptic neurone**
- The neurotransmitters are then **broken down** to prevent continued stimulation of the postsynaptic neurone
  - The enzyme that breaks down acetylcholine is **acetylcholinesterase**

Transmission of a Nerve Impulse Diagram





Synaptic transmission using the neurotransmitter acetylcholine

Unidirectionality

- Synapses ensure the **one-way transmission** of impulses
- Impulses can only pass in **one direction** at synapses because **neurotransmitter is released on one side** and its **receptors are on the other** – chemical transmission cannot occur in the opposite direction
- This prevents impulses from travelling the wrong way

Generating a Postsynaptic Potential

- There are over 40 different known **neurotransmitters**
  - Examples include dopamine and noradrenaline
- One of the key neurotransmitters used throughout the nervous system is **acetylcholine (ACh)**
  - ACh is produced in the **presynaptic neurone** by combing **choline** with an **acetyl group**
  - Synapses that use the neurotransmitter ACh are known as **cholinergic synapses**
- Acetylcholine is released into the **synaptic cleft** when **ACh-containing vesicles** fuse with the **presynaptic membrane**, releasing ACh molecules into the **synaptic cleft**
- ACh **binds to specific receptors** on the postsynaptic membrane, where it can **generate an action potential** in the postsynaptic cell by opening **associated sodium ion channels** to allow sodium ions into the cytoplasm of the postsynaptic neurone until the **threshold** level is achieved
- To prevent the sodium ion channels staying permanently open and to stop permanent depolarisation of the postsynaptic membrane, the **ACh molecules are broken down** and **recycled**
  - The enzyme **acetylcholinesterase** catalyses the **hydrolysis** of ACh molecules into **acetate** and **choline**
  - The products of hydrolysis are then **absorbed back into the presynaptic neurone**, and the **active neurotransmitter** ACh is reformed