Date: 15/03/2020 - 19/03/2020 **Biology AL**

Topic 8

The nervous system & Neurones

The nervous system is the network of nerve cells and fibres that transmits impulses around the body. The nervous system is divided into the central and peripheral nervous systems.

Central nervous system = brain and **spinal cord**

Peripheral nervous system =

- **Sensory nerves** – carry sensory information from the receptors à CNS
- **Motor nerves –** carry motor commands from CNS à effectors

Peripheral nervous system is sub-divided into:

- **Somatic nervous system** – voluntary, stimulates skeletal muscle
- **Autonomic nervous system** – involuntary, stimulates smooth muscle, cardiac muscle and glands

Autonomic nervous system divided into:

- **Sympathetic** – Prepares body for fight or flight response – increases activity e.g. speeding up heart rate
- **Parasympathetic** – Prepares body for rest and digest – decreases activity e.g. lowering breathing rate

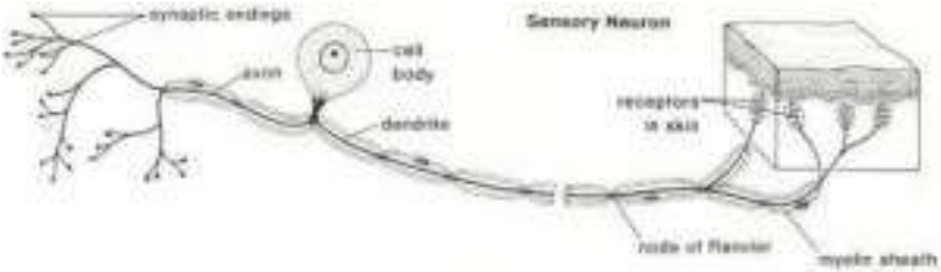
The nervous system carries messages around the body using neurones. **Neurones** are nerve cells which are highly specialised and adapted for the rapid transmission of electrical impulses (action potentials) around the body. Most neurones have a similar basic structure – they:

- Most are long – can transmit the action potential over a long distance

- The cell surface membrane has gated ion channels that control the movement of Na, K or calcium ions
- Have Na/K pumps that use ATP for active transport
- Maintain a potential difference across their cell surface membrane
- Have a cell body containing the nucleus, mitochondria and ribosomes

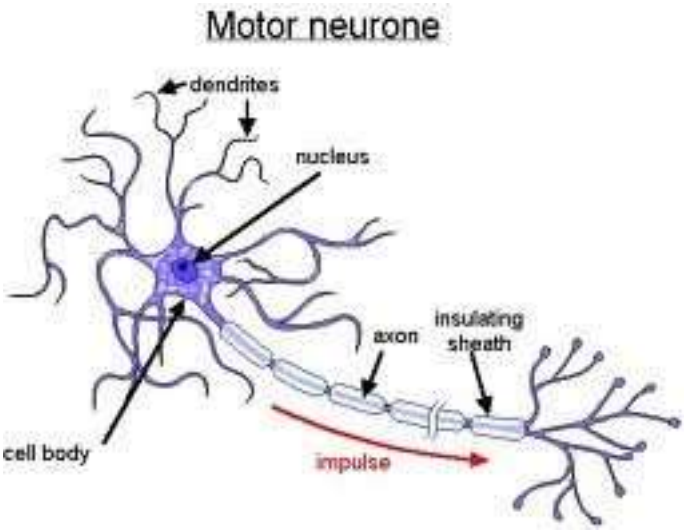
Sensory neurones:

- Carry impulses from receptors to CNS
- Cell body is attached to the middle



Motor/effector neurone:

- Conducts impulses from CNS to effectors (muscles or glands)
- In CNS
- Can have long axons
- Cell body is at the end



Relay/connector neurones:

- Connect sensory and motor neurones
- Mostly in CNS
- Large number of connections with other nerve cells
- Cell body is in the middle of the axon

Stimulus à Receptor cells à Sensory neurone à CNS à Motor neurone à Effectors à Response

There are two types of main extensions from the cell body of a neurone:

- **Dendrites –** Conduct impulses towards cell body
- **Axons –** Transmits impulses away from cell body

Myelin sheath:

- Some neurones have a fatty insulating layer around the axon
- Made of many layers of Schwann cells wrapped around the axon
- Acts as an electrical insulator
- Between Schwann cells are exposed patches of membrane – nodes of Ranvier
- Speeds up the transmission of action potentials – impulse jumps from node to node (saltatory conduction)

Nerve impulses

Neurones have sodium-potassium pumps in their surface membranes. These actively pump Na+ (sodium) ions out of the cell by active transport. This uses ATP as ions are moved against their concentration gradients.

When a neurone is not transmitting impulses, it is at rest. K+ (potassium) ions are pumped inside through channels. K+ and Na+ ions diffuse back down their concentration gradient but K+ diffuses faster back out than Na+ can diffuse back in – there is a net movement out of the cell, making the inside more negative. This is the **resting potential** (-70mV) and the membrane is **polarised.**

Generation of action potential:

- **Depolarisation…**
    - There is a change in permeability, causing Na+ channels to open so Na+ to enter the cell down the concentration gradient – inside of cell becomes more positive than outside
    - This reverses the resting potential, the membrane depolarises. The potential difference is +40mV (action potential)
    - If this reaches the threshold level, an action potential is generated and an impulse is fired. If it does not, nothing happens
- **Repolarisation…**
- Na+ gates close and membrane permeability to Na+ ions decreases
- Voltage-dependent K+ channels open, K+ ions move out of cell down electrochemical gradient
- Inside of cell becomes more negative – drops below the resting potential value **(hyperpolarisation)**
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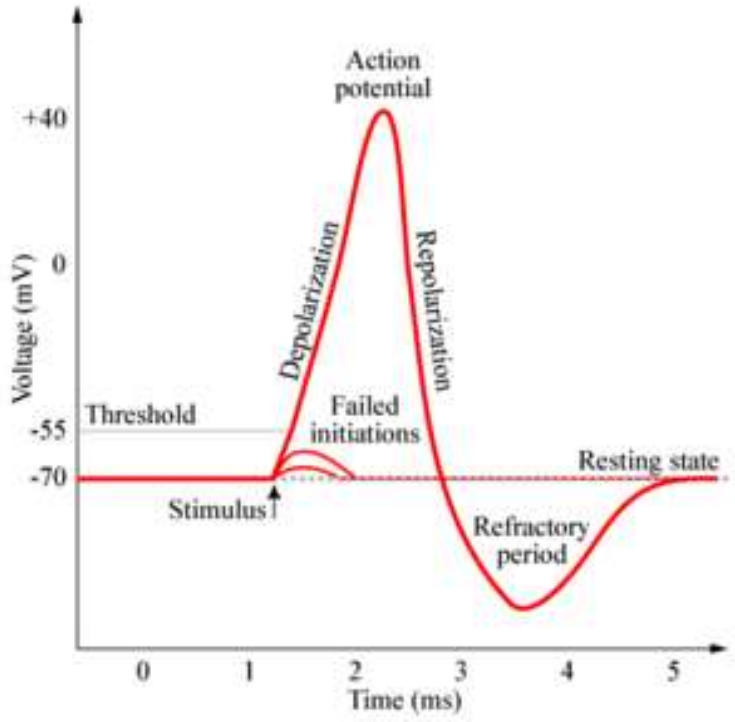
- **Restoring resting potential…**
- K+ channels close, sodium-potassium pump restarts, restoring the normal distribution of ions either side of the cell surface membrane
- Potassium ions diffuse into axon

The **refractory period** is a time delay between action potentials, when the axon restores its resting potential after the action potential. Ion channels are recovering and cannot be opened and the axon is unable to generate another action potential until the refractory period is over and all voltage-dependent K+ and Na+ channels are closed, ensuring impulses only travel in one direction.

When the threshold is reached, the action potential always fires with the same voltage, no matter the size of the stimulus. If it isn't reached, the action potential will not fire. A larger stimulus does not cause a larger action potential but it causes more frequent action potentials.

Summary:

1. Membrane is polarised (resting state)
2. Ion channels open, Na+ ions diffuse into cell
3. Membrane depolarises – less negative
4. Voltage-dependent Na+ channels open – more enter – positive
5. Potential difference reaches -40mV
6. Na+ ion channels close and K+ channels open
7. K+ ions diffuse out – negative inside – repolarisation
8. Potential difference overshoots – hyperpolarisation
9. Potential difference restored – returns to resting state



The action potential travels rapidly along the axon or dendron. This is because the repolarisation of one part of the membrane sets up local currents with the areas either side of it – these regions depolarise too as some Na+ flow sideways.

Propagation of an impulse along an axon:

1. At resting potential there is a positive charge on the outside of the membrane and negative charge on the inside, with higher sodium ion concentration outside and higher potassium ion concentration inside

2. When stimulated, voltage-dependent sodium ion channels open and sodium ions flow into the axon, depolarising the membrane. Localised electric currents are generated. Sodium ions move to the adjacent polarised (resting0 region causing a change in electrical charge (potential difference) across this part of the membrane
3. This change in potential difference initiates a second action potential. At the site of the first action potential, the voltage-dependent sodium ion channels close and voltage-dependent potassium ion channels open. Potassium ions leave the axon, repolarising the membrane. The membrane is hyperpolarised
4. A third action potential is initiated by the second. In this way, local electric currents cause the nerve impulse to move along the axon. At the site of the first action potential, potassium ions diffuse back into the axon, restoring resting potential

In a myelinated neurone, local currents cannot be set up where the myelin sheath is as the Na+ and K+ cannot flow through the fatty myelin sheath. Instead the action potential jumps from one **node of Ranvier** to the next where the ions move through the cytoplasm (**saltatory conduction)**. This increases the speed at which it travels along the axon.

How is the impulse propagated along a myelinated axon?

- Depolarisation occurs at Node of Ranvier
- Local electric currents occur between nodes
- Potential difference is reduced at next node, initiating another action potential
- Impulses jump between nodes by saltatory conduction

Action potentials are conducted faster along axons with large diameters, as there is less resistance to the flow of ions so depolarisation travels faster. They also are faster at higher temperatures (up to 40oc).

Synapses

Two neurones are not in direct contact, there is a small gap called the **synaptic cleft**. The synapse is the junction between the two neurones. The presynaptic

neurone has a swelling, called a **synaptic knob** which contains vesicles filled with neurotransmitter. The presynaptic knob has mitochondria to provide energy to make neurotransmitters and vesicles. The electrical impulse cannot cross the synaptic cleft, so a neurotransmitter is released at the end of the first neurone from the presynaptic membrane. It diffuses across the synapse, binds with the second neurone on the postsynaptic membrane, generating an action potential.

Neurotransmitter release à stimulation of postsynaptic membrane à inactivation of neurotransmitter

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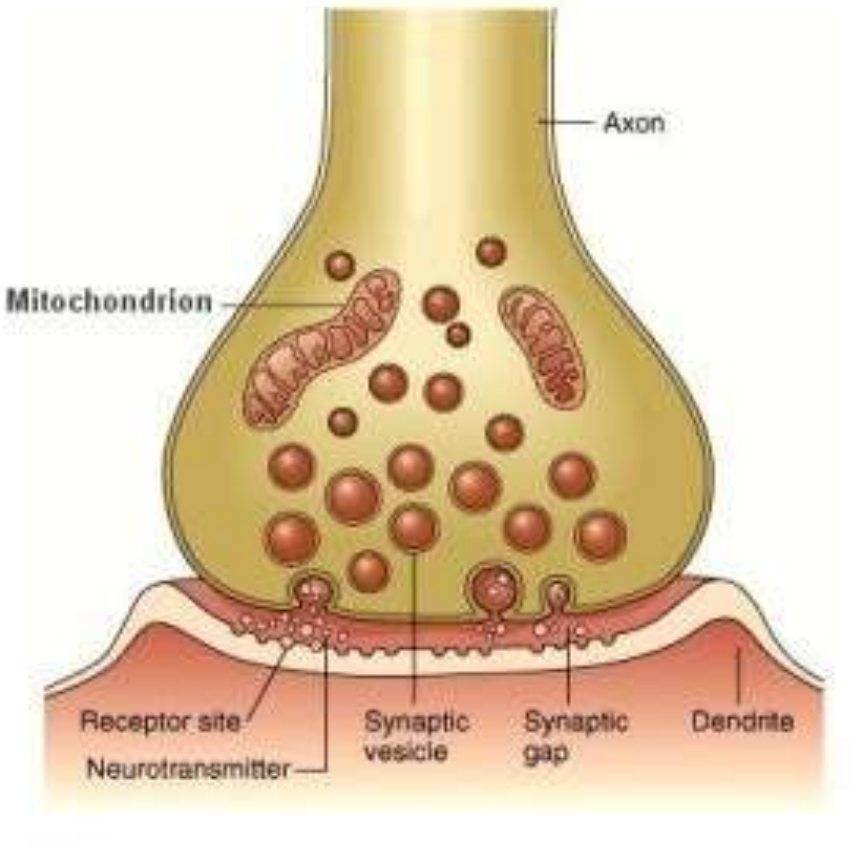
1. Action potential arrives at presynaptic membrane/synaptic knob
2. Membrane depolarises causing voltage-dependent calcium ion channels to open – calcium ions enter neurone down their concentration gradient
3. Calcium ions cause synaptic vesicles containing neurotransmitter to fuse with presynaptic membrane
4. Neurotransmitter released into synaptic cleft by exocytosis and diffuses across the cleft
5. Neurotransmitter binds with complementary receptor proteins on postsynaptic membrane, causing cation channels to open so Na+ ions flow through into the cytoplasm of the neurone
6. Postsynaptic membrane depolarises, setting up an action potential in the postsynaptic neurone
7. To stop action potentials, the released neurotransmitter is taken up by the presynaptic membrane or diffuses away and is broken down by enzymes

Two examples of neurotransmitters are **acetylcholine** (ACL) and noradrenalin. They are synthesised in vesicles, which requires energy. Therefore the synaptic knobs have many mitochondria to produce ATP.



Synaptic transmission:

The structure of a cholinergic synapse and neuromuscular junction should be known. The acetylcholine receptor in the first image on the left is more better known as nicotinic cholinergic receptor.

In a cholinergic synapse (this is the only synapse you need to know) an action potential increases permeability of the presynaptic membrane by stimulating the Ca2+ ion gated channels to open. This causes an influx of Ca2+ ions into the presynaptic knob down its concentration gradient by facilitated diffusion. The high concentration of Ca2+ ions causes the vesicles of acetylcholine (neurotransmitters) to fuse with the presynaptic membrane.

NB: It is best to say acetylcholine than Ach because it gives you more of an understanding and helps with questions if it says 'acetylcholine' instead of Ach.
If you are going to use Ach it is important that you know what it is.

Acetylcholine leaves the presynaptic knob by exocytosis into the synaptic cleft. Acetylcholine diffuses across the synaptic cleft and binds to the cholinergic receptors causing the Na ligand gated channels to open. This causes an influx of Na+ ions into the postsynaptic neurone making the postsynaptic neurone depolarised and if the threshold is met, an action potential is generated. The acetylcholine is removed from the synaptic cleft by the enzyme acetylcholine esterase into products by complementary shapes to prevent a continuous impulse.

NB: Acetylcholine esterase can be abbreviated into Ache however it is best also to refer to this enzyme as acetylcholine esterase as it will help you in questions that have this name.

The products are actively transported into the presynaptic knob by the use of Pi from ATP into vesicles to make acetylcholine. The Ca2+ ions are actively transported out of the presynaptic knob by the use of Pi from ATP.
Above is an example of excitatory neurotransmitters. This is where the postsynaptic neurone is depolarised leading to an action potential being fired when the threshold is met. Neurotransmitters can also be inhibitory where they hyperpolarise the postsynaptic neurone by opening the K= ion gated channels open.

Neuromuscular junctions work in exactly the same way however:

- **Postsynaptic membrane:** The postsynaptic membrane of the muscle is deeply folded to form clefts. This is where acetylcholine esterase is stored.

- **NB: It is important that you say postsynaptic membrane of the muscle and not postsynaptic membrane of a neurone as a postsynaptic neurone is not involved in a neuromuscular junction.**

- **Receptors:** There are many more receptors on the postsynaptic membrane of the muscle than on the postsynaptic membrane of a neurone.
- **Neurotransmitters:** The acetylcholine are excitatory in every neuromuscular junction whereas in the synapse it can be excitatory or inhibitory.
  Spatial summation is where many presynaptic neurones connect to one postsynaptic neurone. A small amount of excitatory neurotransmitters can be enough for the threshold to be met in the postsynaptic neurone and causing

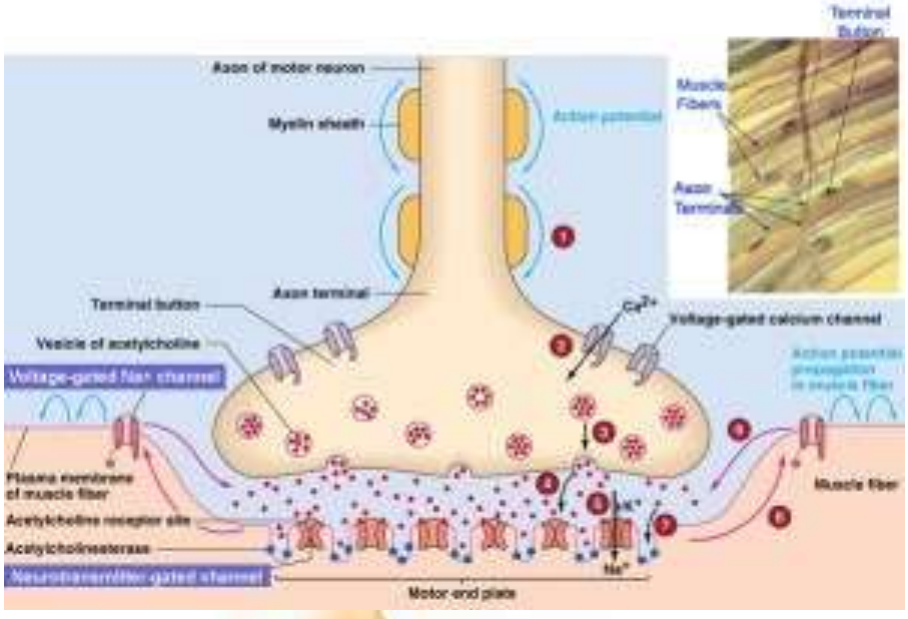
an action potential to be created. If some neurotransmitters are inhibitory then the overall effect may not be an action potential as it will be difficult to meet the threshold in the postsynaptic neurone. Temporal summation is where there is a quick-fire of two or more action potentials arriving at the same time from one presynaptic neurone. This means more neurotransmitters are released into the cleft making an action potential more likely to occur as the threshold may be met.

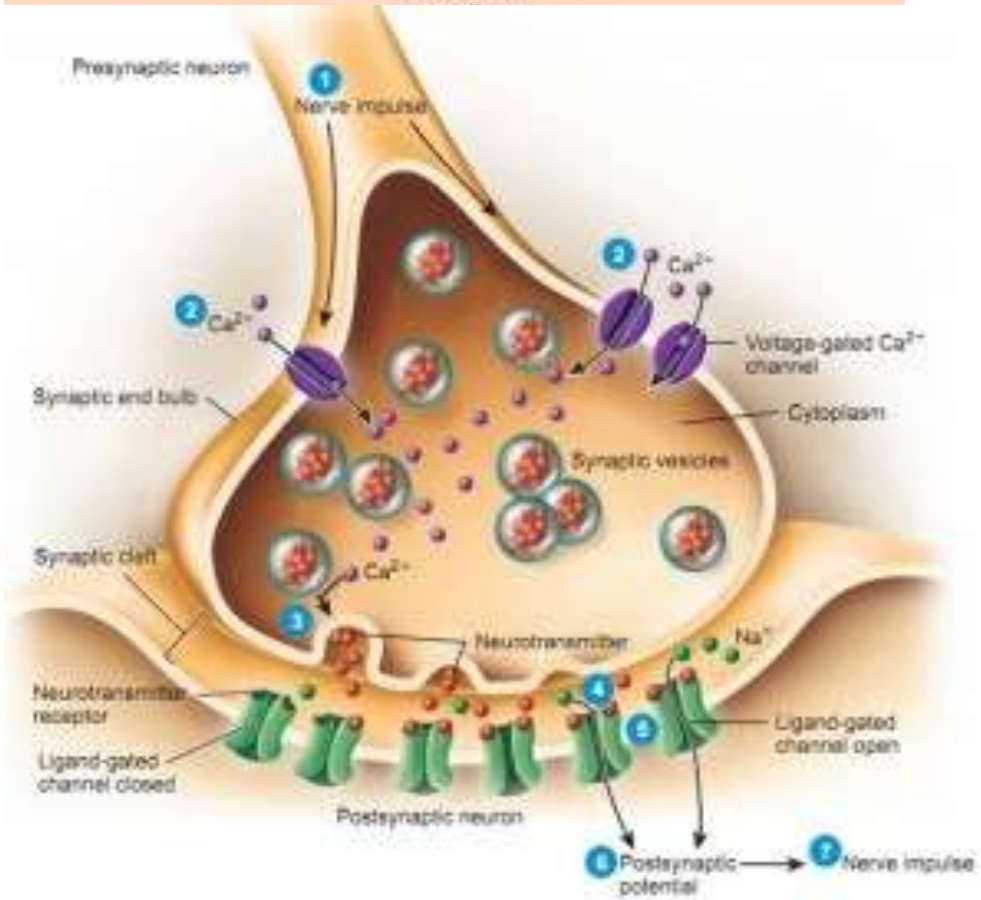
Some drugs mimic or inhibit the action of neurotransmitters:

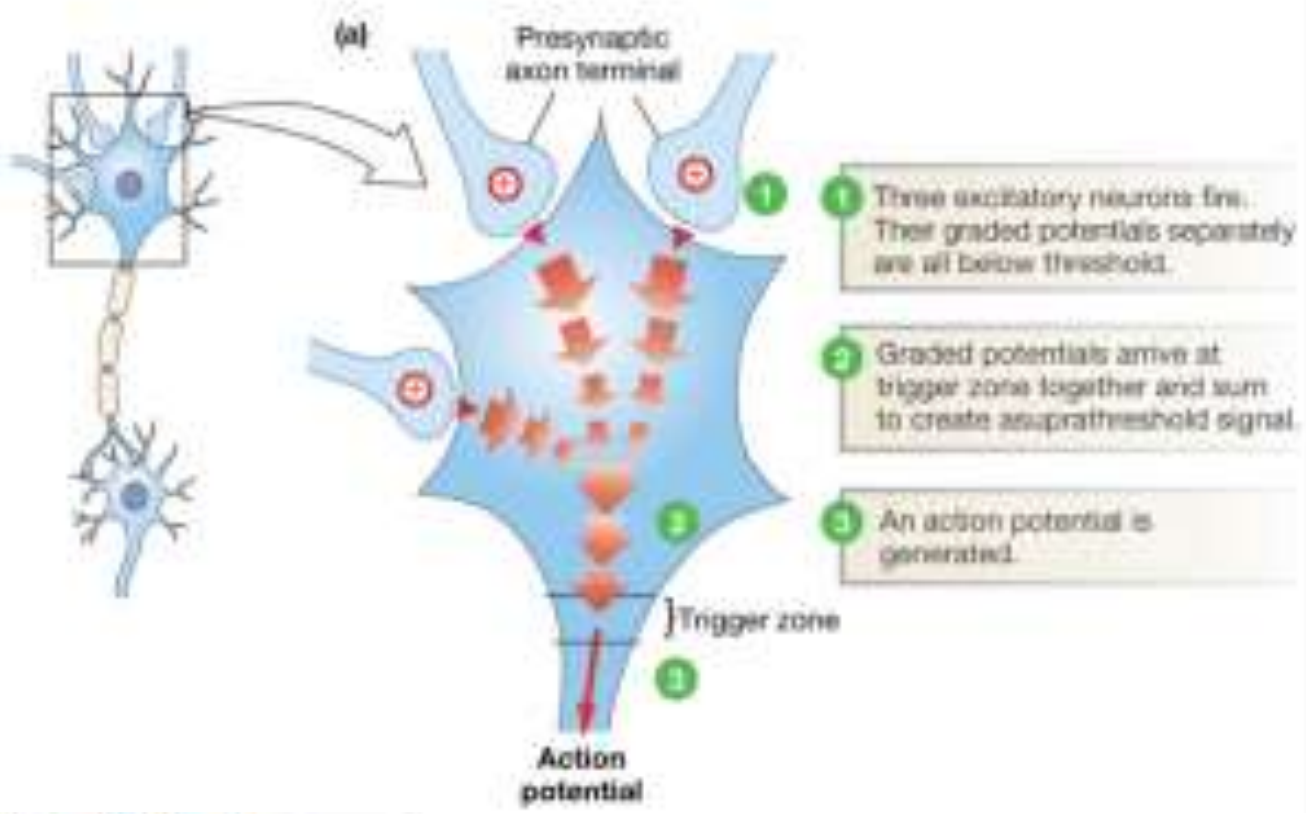
- If a drug causes an action potential to be triggered, then this is because the drug and the receptor have complementary shapes where it is mimicking the neurotransmitter. These type of drugs are said to be agonists.
- If a drug does not cause action potential but it is binded to the receptors, then this means that the drug is complementary to the receptor but blocks the receptor so not many receptors are activated. These type of drugs are said to be antagonists.
- If a drug binds to an acetylcholine esterase, then this means fewer enzyme-substrate complexes will be formed with acetylcholine creating a continuous impulse.
- If more receptors are stimulated, then this is because the drug releases more neurotransmitters than usual.
- If less receptors are stimulated, then this is because the drug inhibits the release of neurotransmitters.

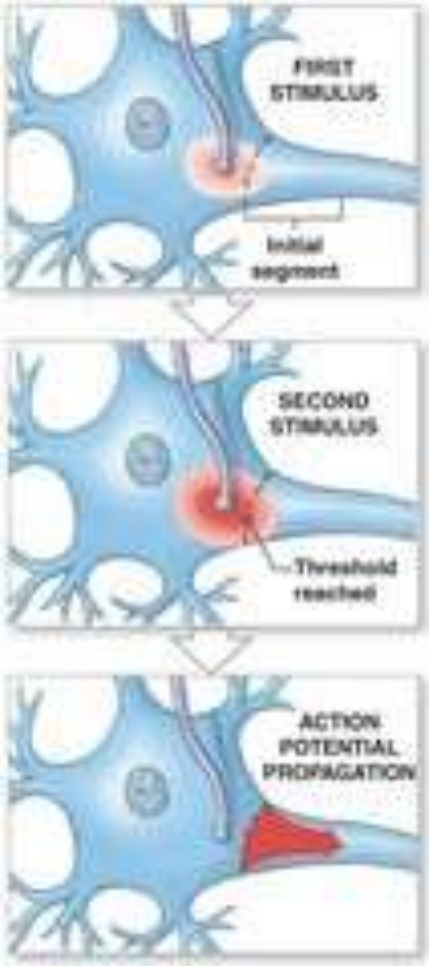
NB: Recall of names of drugs and the mechanism of drugs do not need to be recalled in the exam. A piece of information will be given in the exam about a drug and its mechanism and only you have to explain why that has happened which are the bullet points above. These are the only explanations you need to know and are highlighted in green.

The Neuromuscular Junction






(a)
Presynaptic axon terminal
1 Three excitatory neurons fire. Their graded potentials separately are all below threshold.
2 Graded potentials arrive at trigger zone together and sum to create asuprathreshold signal.
3 An action potential is generated.
Trigger zone
Action potential


FIRST STIMULUS
Initial segment
SECOND STIMULUS
Threshold reached
ACTION POTENTIAL PROPAGATION

Although synapses slow the transmission of impulses, they are useful:

- Ensure impulses travel only in one direction because receptors are only on the postsynaptic membrane
- Allows neurones to connect with many other neurones – increases range of possible responses to a particular stimulus
- Control nerve pathways an give flexibility of response
- Integrate information from different neurones to give a coordinated response

Extent of depolarisation:

- Depends on how much neurotransmitter reaches the postsynaptic membrane
- – Depends partly on the frequency of impulses reaching the presynaptic membrane
- A single impulse usually won't release enough neurotransmitter to depolarise and postsynaptic membrane
- Also depends on the number of receptor sites on the postsynaptic membrane

Excitatory synapses (depolarise)
Make the postsynaptic membrane more permeable to Na+ ions
Makes it more likely that an action potential will be generated
Several impulses together release enough – summation

Inhibitory synapses (hyperpolarise)
Inhibitory synapses make it less likely that an action potential will result.

- The neurotransmitters open channels for Cl- and K+ ions in the postsynaptic membrane
- These move through the channels down their diffusion gradients
- Cl- ions move into the cell and K+ ions move out
- This causes a greater potential difference across the membrane as the inside becomes more negative than usual (-90mV)
- This makes depolarisation less likely as more excitatory synapses are needed

If the stimulus is small, little neurotransmitter will be released and this might not be enough to excite the posysynaptic membrane to the threshold level – more than one synapse/neurone is needed to provide sufficient depolarisation – **summation** is when each impulse adds to the effect of another

- **Spatial summation:** Impulses are from different synapses connect to one neurone, there is enough neurotransmitter for an action potential
- **Temporal summation:** Several impulses arrive at a synapse one after another

The combined release of neurotransmitter generates an action potential in the postsynaptic membrane.

Generator potentials

Receptor cells respond to changes in the environment.
When a stimulus is detected, the membrane becomes more permeable – gated Na+ ion channels open and Na+ ions diffuse into the cell
Small change in potential – **generator potential**
The larger the stimulus, the more gated channels will open – the larger the generator potential
If enough Na+ ions enter, the potential difference changes significantly and will initiate an impulse or action potential.

Synapses can **amplify** or **disperse** information – one neurone connects to many other neurones – information dispersed around the body – **synaptic divergence** or many neurones connect to one neurone – information amplified (made stronger) – **synaptic convergence**.

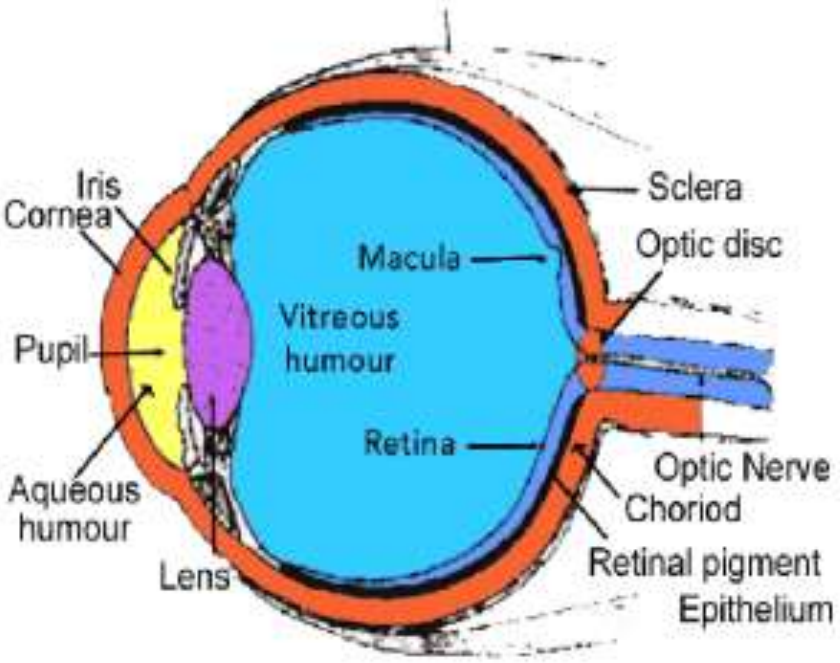
Sensory receptors

- Specialised cells that detect changes in the environment. They are specific to one type of stimulus
- Energy transducers – convert one form of energy to another. Each type of transducer is adapted to detect changes in a particular energy form
- May be a change in light levels/pressure on the skin
- Each change in energy levels in the environment is a stimulus
- Sensory receptors can convert any stimulus energy into a form of electrical energy (a nerve impulse)

Examples of receptors:

Receptors	**Energy changes detected**
Light sensitive cells (rods and cones) in eye retina	Light intensity and range of wavelengths
Olfactory cells lining the inner surface in the nasal cavity	Presence of volatile chemicals
Taste buds in the tongue, hard palate, epiglottis & oesophagus	Presence of soluble chemicals
Pressure receptors (pacinian corpuscles) in the skin	Pressure on skin
Sound receptors in the inner ear (cochlea)	Vibrations in air
Muscle spindles (proprioceptors)	Length of muscle fibres

The human eye



Light enters the eye through the **pupil**. The amount of light is controlled by the muscles of the **iris**. Light rays are focused by the **lens** onto the **retina**, which lines the inside of the eye and contains **photoreceptor cells** that detect the light. Nerve impulses are carried from the retina to the brain by the **optic nerve.**

- **Conjunctiva:** Protects the cornea

- **Cornea:** Bends light
- **Lens:** Focuses light on retina
- **Iris:** Controls amount of light entering eye by controlling pupil size
- **Sclera:** Protective layer, allows attachment of external muscles
- **Blind spot:** No light sensitive cells where optic nerve leaves eye
- **Fovea:** Most sensitive part of retina
- **Retina:** Contains light-sensitive cells
- **Vitreous humour:** Transparent jelly
- **Choroid:** Black layer prevents internal reflection of light
- **Cilary muscle:** Alters thickness of lens for focusing
- **Optic nerve:** Transmits impulses to brain
- **Pupil:** Circular opening for directing light to the lens

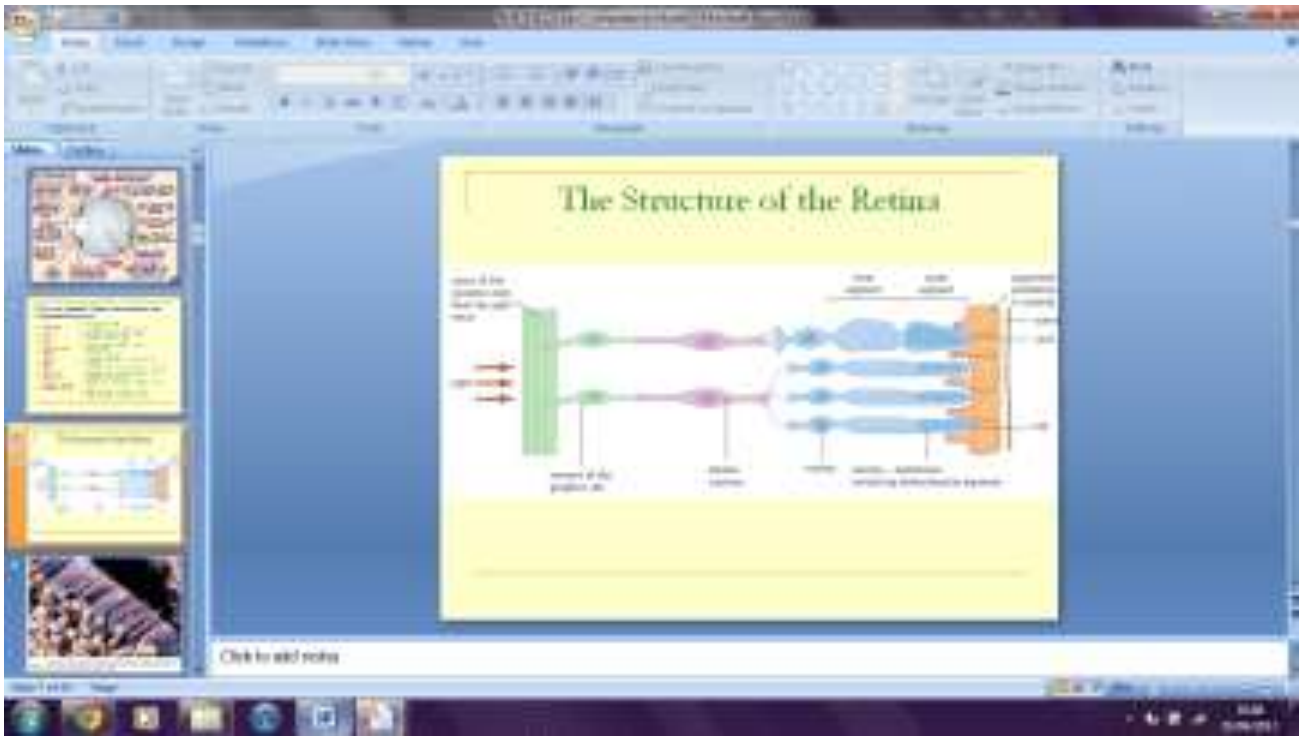
How do photoreceptors convert light into an electrical impulse?

- Light enters the eye, hits the photoreceptors and is absorbed by light-sensitive pigments
- Light bleaches the pigments, causing a chemical change and a change in membrane permeability to sodium
- A generator potential is created, if it reaches threshold, a nerve impulse is sent along a bipolar neurone
- Bipolar neurones synapse with ganglion neurones whose axons make up the optic nerve – bipolar neurones connect photoreceptors to the optic nerve
- Optic nerve extends to several brain areas including the thalamus
- Before reaching the thalamus, some of the neurones branch off to the mid brain
- At the mid brain they connect to motor neurones that control pupil reflex and eye movement

There are two types of photoreceptors in the retina – **rods cells** and **cone cells:**

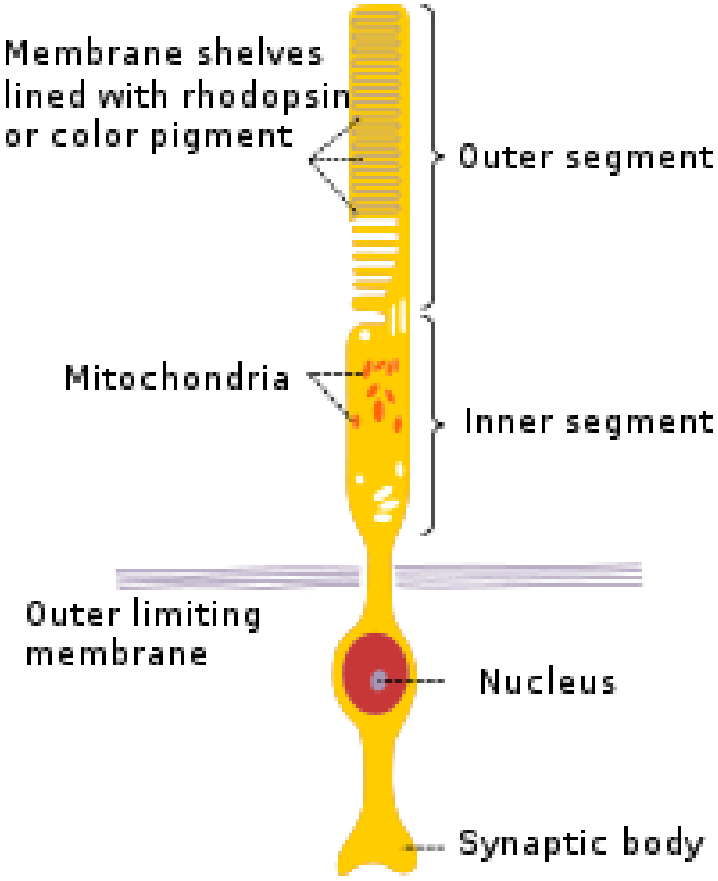
- **Rods** – sensitive to dim light because many join to one neurone. They give low visual acuity and only give information in black and white. Rods are found in the peripheral parts of the retina.
- **Cones** – Can only respond in bright light (less sensitive) as only one joins one neurone. They give high visual acuity because they are close together. They give information in colour. Cones are found packed together in the fovea.

	Rods	Cones
Number in retina	20:1	
Where in retina	All over retina but not fovea	Only fovea
Light-sensitive pigment	Rhodopsin	Iodopsin
Vision	Black and white vision Both dim and bright light	Colour vision Only bright light
Sensitivity	Intensity	Wavelength



Rod cells

The outer segment of a rod cell contains membranes, staked up parallel. Sodium-potassium pumps act across the membranes and cation channels remain open, so some sodium and potassium ions leak back through.



The membranes also contain a pigment called **rhodopsin** (in vesicles) which is made of a **retinal** molecule and an **opsin** molecule. When light hits rhodopsin, the retinal changes shape. This causes sodium and potassium ion channels in the membrane to close, but the sodium-potassium pump keeps working. As the ions cannot leak back in or out of the neurone, a greater potential than usual builds up (negative inside) and the membrane is hyperpolarised.

When no light falls onto a rod cell and the potential difference is normal, it constantly releases transmitter substances, which diffuses to the next neurone. This stops that neurone generating action potentials. When light falls on the rod cell and hyperpolarises the membranes, it stops releasing the transmitter substances and the neighbouring neurone can generate action

potentials. These are transmitted along axons to the optic nerve, which carry them to the visual centre in the brain.

The change in shape of retinal makes it unstable and it separates from opsin. If this happens to all the rhodopsin in all rod cells, you cannot see in dim light. If you walk from a sunny area to a dim room you cannot see much because our cones stop functioning in low intensity light and the rod pigments have become bleached. In dim light, retinal and opsin gradually combine again, forming rhodopsin – this is **dark adaptation.** Until rhodopsin is reformed, no more action potentials can be created in the bipolar cells so no more stimuli can be detected. This takes a few minutes. The brighter the light, the more rhodopsin molecules break down and the longer it takes for them to reform.

Dark

1. Na+ diffuses through open cation channels into outer segment
2. Na+ move down concentration gradient into inner segment
3. Na+ is actively pumped out of cell using ATP and ion pumps
4. Membrane slightly depolarised -40mV
5. Inhibitory neurotransmitter (glutamate) released from rod cells and binds to bipolar cell, preventing it from depolarising.

Light

1. Light energy breaks rhodopsin à opsin + retinal
2. Opsin binds to membrane of outer segment
3. Na+ cation channels close
4. Na+ still actively pumped out but cannot diffuse into outer segment
5. Inside of cell is more negative – membrane hyperpolarised (-90mV)
6. No inhibitory neurotransmitter (glutamate) is released
7. Cation channels in bipolar cell open and membrane is depolarised, generating an action potential in the neurone of the optic nerve à brain

Controlling pupil size

The iris is the coloured part of the eye surrounding the pupil and it controls the pupil size. Light passes through the pupil on its way to the retina. In bright light, the pupil is small (contracted) to limit the amount of light passing

through to prevent damage to rods and cones. In dim light the pupil is large (dilated) to allow more light to reach the retina.

When **bright light** hits the retina, it is detected by photoreceptors which send nerve impulses along the optic nerve to the CNS of the brain along a sensory neurone. This causes action potentials to be sent along parasympathetic **motor neurones** to the muscles in the iris. **Circular muscles contract** and **radial muscles relax**, making the iris wider and the pupil narrower (pupil constricts).

In dim light, the circular muscles relax and the radial muscles contract to widen the pupil – the opposite reaction.

The radial muscles are controlled by sympathetic reflex
The circular muscles are controlled by parasympathetic reflex

Reflex arcs

Nerve impulses follow routes/pathways through the nervous system, these reflex arcs are responsible for our reflexes and they are controlled by the autonomic nervous system. Reflexes are fast and help to avoid damage to the body.

1. Receptors detect stimulus and generate nerve impulse
2. Sensory neurones conduct nerve impulse to CNS along sensory pathway
3. Sensory neurones enter spine
4. Sensory neurone synapses with relay neurone
5. Relay neurone synapses with motor neurone which leaves spine
6. Motor neurone carries impulse to effector producing a response

If there is a relay neurone involved, the reflex can be overridden by the brain.

Habituation

Learning is when organisms modify their behaviour as a result of experience. One of the simplest types of learning is **habituation**, defined as a decrease in the intensity of a response when the same

stimulus is given repeatedly. For example humans show habituation when hearing a loud bang repeatedly.

Snails withdraw their body when it is touched on the shell. This response helps avoid damage by predators. If it is touched repeatedly and nothing unpleasant happens, it stops withdrawing its body. This is useful because it avoids energy being wasted on an unnecessary action and enables the snail to stay fully active.

How is habituation achieved?

With repeated stimulation, calcium ion channels become less responsive:

1. Less calcium ions cross presynaptic membrane into presynaptic neurone
2. Fewer synaptic vesicles fuse with presynaptic membrane
3. Less neurotransmitter released into synaptic cleft
4. Less sodium ion channels on posysynaptic membrane open
5. Less sodium ions flow into postsynaptic membrane
6. Less or no action potential is triggered in postsynaptic motor neurone

For example, sea slugs have less neurones than humans so their neurobiology is simpler than that of humans. They also have large accessible neurones so those involved in behaviours can be identified. The sea slug breathes through a gill in a cavity on the upper side of its body and water is expelled through a siphon tube. If the siphon is touched, the gill is withdrawn into the cavity – a protective reflex. Sea slugs are habituated to waves which stimulate the siphon. After a few minutes of repeated stimulation, the siphon no longer withdraws. Habituation allows animals to ignore unimportant stimuli so that limited sensory, attention and memory can be concentrated in more threatening or rewarding stimuli.

Practical – investigating habituation in pond snails:

1. Collect pond snails of the same species and place them in the same tank and leave for a few days to acclimatise
2. Place a snail in a dish and leave to rest for 5 minutes until active
3. Using a small implement, gently touch the snail between the tentacles. The snail will withdraw and then slowly extend again.
4. Repeat the stimulus several times, with set intervals of less than one minute. Record the time for the tentacle to be returned to its fully extended position
5. Plot a graph of time against number of stimuli given

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