CO-ORDINATION

All organisms have the ability to detect and respond to changes in the external and internal environment. Plants and animals have developed control systems that receive stimuli, process them and initiate appropriate responses.

CONCEPT OF RESPONSE AND RECEPTION IN PLANTS

Coordination and control in plants is carried out by hormones. Plants lack the nervous system and information is carried by hormones especially ***auxins.***

Plants do not move from one place to another. Their response involves growth movements of part of the plant and turgor changes within cells. Parts of the plant move towards or away from a stimulus due to changes in auxins concentration in the parts concerned.

PLANT RESPONSES

1. Tactic responses (taxes)

A taxis is the movement of a freely motile organism, or a freely motile part of an organism, in response to a directional stimulus. The direction of the response is related to that of the stimulus. Taxes occur in both plants and animals. In plants, it is common in lower plants such as green algae, antherozooids (sperm) of mosses, liverworts and ferns are attracted to chemicals produced by the archegonium.

Examples of taxis

- Unicellular organisms e.g. Euglena swim towards light hence positively tactic (phototactic)
- Earth worms, wood lice and cockroaches move away from light hence negative phototactic.
- Sperms swim towards the chemical produced by the ovum hence positively chemotactic.
- White blood cell moves towards harmful bacteria in the body hence positively chemotactic.

2. Nastic response

This is the movement of part of the plant in response to a non-directional stimulus. Nastic responses involve changes in turgidity and growth to some extent. This can be observed in the folding of the leaves of the sensitive plant (*Mimosa pudica)* when touched (thigmonasty). The touching of the plant causes water to be quickly withdrawn from the leaf cells into the pulvinus cells which have large air spaces, therefore causing the leaf or petiole to collapse due to change in turgidity.

Nastic response are named depending on the type of stimulus i.e. Photonastic if the stimulus is light, hydronasty if the stimulus is water and thigmonastic if the stimulus is touch.

Characteristics of a nastic response

- It involves changes of turgidity of plant cells.
- It is a rapid response.
- It occurs in any part of a plant.
- The response is not related to the direction of the stimulus.
- It is induced by non-directional stimulus.

Examples of nastic responses

- Opening and closing of flowers in response to light e.g. morning glory.
- Sudden folding of the sensitive plant's (*Mimosa pudica*) leaves in response to touch.
- Closure of leaves of insectivorous plants e.g. butter walt and pitcher plant when the insect lands on the leaf. Such plants are found in nitrogen deficient soils.

3. Tropic response (tropism)

Tropism is a growth movement of part of the plant organ in response to an external unidirectional stimulus. Growth movement towards a stimulus is referred to as ***positive tropism*** while growth movement away from a stimulus is referred to as ***negative tropism***.

Characteristics of a tropic response

- It involves growth.
- It is a slow response.
- It occurs at the shoots and root tips.
- It is related to the direction of stimulus.
- It is induced by directional stimulus.

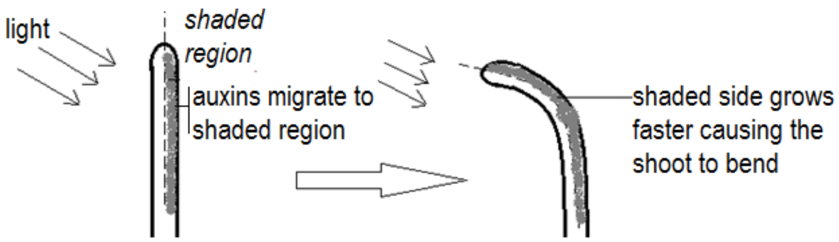
Examples of tropisms

Example of tropism (response)	Stimulus
1. Hydrotropism	Water
2. Thigmotropism / haptotropism	Touch
3. Chemotropism	Chemicals
4. Geotropism	Gravity
5. Phototropism	Light

Phototropism:

This is the growth movement of part of the plant in response to unidirectional light. Plant shoots are positively phototropic that is, they grow towards the direction of light while the roots are negatively phototropic (they grow away from the direction of light).

The shoot apex detects a light stimulus. When a shoot apex is exposed to a unilateral source of light causes ***auxins***, which are plant growth hormones produced at the shoot apex to migrate to the shaded side. The higher concentration of auxins on the shaded side causes faster growth than on the illuminated side, hence the shoot curves towards the source of light.



Importance of phototropism

- The shoot grows towards light hence the leaves are able to absorb light to carry out photosynthesis.
- Roots grow away from light into the ground from which water and mineral salts are absorbed and also provide support.

Assignment:

1. *Compare tropisms and nastic responses.*
2. *Explain what you understand by the terms irritability, stimulus and response.*
3. *a) Distinguish between a tactic and a tropic response.*
   b) Explain the survival values of tactic and tropic responses.
   c) What type of response would you expect in roots of a plant that are subjected to dry conditions on one side of the soil while the other side is moist?
4. *a) Name three plant hormones.*
   b) In which parts of a seedling are hormones produced?

Photoperiodism

The relative length of day and night varies with the time of the year and is called the photoperiod. The response of a plant to changes in day length or night length is called Photoperiodism. One of the most studied examples is flowering.

Photoperiodic control of flowering

Plants whose flowering is triggered by the photoperiod are often placed into three basic categories:

1) **Long day plants (LDP):** These only flower when the period of daylight exceeds a critical minimum length. Examples of LDP include clover, barley, lettuce and wheat.
2) **Short day plants (SDP):** These only flower when the period of day light is shorter than a critical maximum length. Examples include tobacco and straw berries.
3) **Day neutral plants:** These plants flower regardless of the length of day light. Examples include cucumber, carrot, tomato and garden peas.

Characteristics of long day plants

- They require long days and short nights to flower.
- They flower only when the light period exceeds the critical length of the day (12 hours).
- Short nights are more essential than the length of the day. Thus they are commonly known as short night plants.
- They flower even when the short night is interrupted by flashes of light and do not need an interrupted short night. They also show flowering even when the long day is interrupted by short dark periods.
- They flower during summer when the days are longer than the night, like wheat.

Characteristics of short day plants

- They require short days and long nights for them to flower.
- They flower only when day length become shorter than the critical day length.
- They need an uninterrupted period of darkness.
- They do not flower if given short days and long nights interrupted by flashes of light. On the contrary, if the short days are interrupted by intervals of darkness but left with an interrupted long night they flower.
- Such plants flower during autumn and winter.

Characteristics of day neutral plants

- They are independent of day length.
- They flower after a period of vegetative growth regardless of the photoperiod.

Phytochrome and the detection of night length

Photoperiodism requires a mechanism for detecting the length of darkness. One of the important ways in which light exerts its influence on living organisms is through variations in day length (photoperiod).

The pigment that is responsible for this is ***Phytochrome.*** Phytochrome exists in two inter-convertible forms:

i) Phytochrome 660 (P_R) which absorbs red light.

ii) Phytochrome 730 (P_{FR}) which absorbs light in the far-red region of the spectrum.

Phytochrome is synthesized in its P_R (P_{660}) form. Absorption or exposure to the appropriate light wavelength causes the conversion of one form into the other form within a second.

P_R is converted into P_{FR} when exposed to red light, and that P_{FR} is converted back into P_R when exposed to far-red light or when in darkness.

$$P_{660} \underset{\text{far-red light}}{\overset{\text{red light}}{\rightleftharpoons}} P_{730}$$

During day, there is more P_{FR} than P_R bacause sunlight has a higher proportion of red light than far-red light. P_{FR} form is the physiologically active form, but converts slowly to the more stable, but inactive, P_R form during the darkness of night.

$$P_{660} \underset{\text{darkness (slow conversion)}}{\overset{\text{day light}}{\rightleftharpoons}} P_{730}$$

Therefore the relative amounts of the two forms of phytochrome controls flowering in short-day and long-day plants. ***Accumulation of Pfr stimulate flowering in long-day plants, whereas in short-day plants, Pfr inhibits flowering***. (Note that P_R does not have any effect on flowering). Phytochrome is distributed throughout the plant in minute quantities, being most concentrated in growing tips.

The physiological processes affected by light through the phytochromic effects include;

- Germination of small seeds
- Elongation of internodes
- Chlorophyll development
- Leaf expansion
- Control of flowering in long day and short day plants.
- Leaf fall.

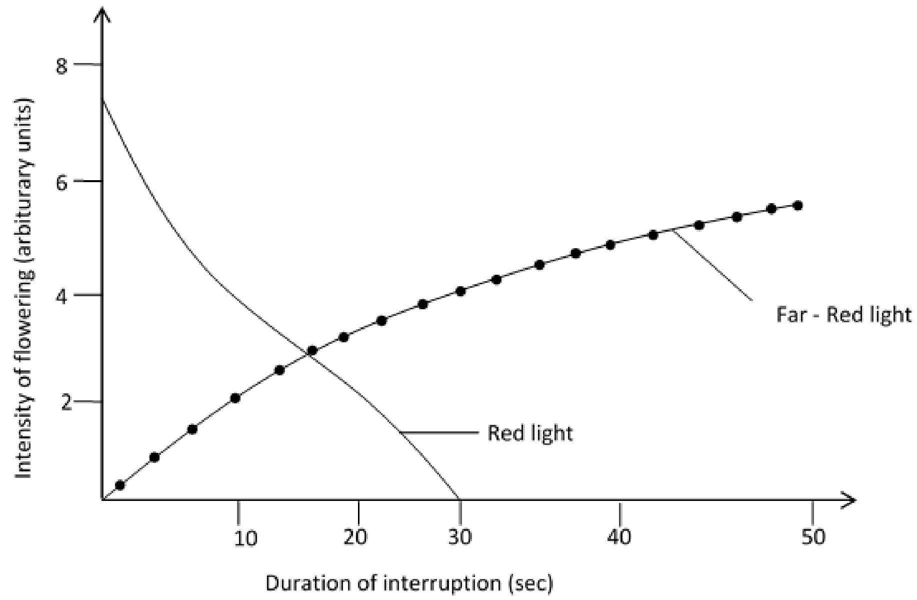
Role of florigen hormones in flowering

These are hormones that control flowering in long day plants. The light stimulus is detected by the leaves. In some cases even a single leaf needs to be subjected to the appropriate stimulus to induce flowering. A high concentration of Phytochrome far red is required for inducing the leaves to produce florigen hormone that travels through the phloem to the buds to cause flowering.

Note: Vernalisation is the exposure of seeds/plant to low temperature requirements for the initiation of germination/flowering.

Typical examination question:

1. **The figure below shows the effect of red light and far red light interruption of the night period on flowering of a plant.**



a) What is the effect of interruption of light period by each type of light?
   i) Red light
   ii) Far red light

b) Suggest the type of plant that would exhibit responses to light treatment as shown in figure above.

c) How can the knowledge of the effect of red light and far red light and far red light on flowering be utilized in the commercial growing of flowers?

Note:

If the whole plant is covered with light proof material except the leaves, flowering occurs proving that the point of perception is in the leaves. Flowering has been induced to occur in short day plants kept in long days by keeping one of the leaves in short days i.e. covering it with light proof material for a period longer than critical point of light.

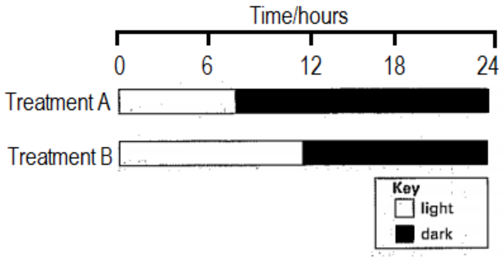
Possible solution:

a) *i) The interruption by red light lowers the intensity of flowering. The longer the duration of interruption, the lower the intensity of flowering up to duration of 30s when no flowering occurs. This is because it leads to accumulation of P_{FR}, which inhibits flowering.*
   ii) The interruption by far-red light increases the intensity of flowering. The longer the duration of interruption, the higher the intensity of flowering up to a maximum of 50s when no further increase in the intensity of flowering is achieved. This is because of conversion of P_{FR} to P_R, thus stimulating flowering.

b) *Short day plant.*

c) *Plants can be induced to flower at the required time by interruption of dark period by far red light or red light at the right time and duration.*

2. ***Two groups of short day plants were each subjected to one of two different treatments of light and dark periods as shown in the diagram.***



a) Which treatment would you expect to trigger a flowering response? Give a reason for your answer.

b) In a second series of treatments, two groups of short day plants were each subjected to long dark periods, as in treatment A, interrupted by a short period of light.

One group was exposed to a short period of far-red light.
What flowering response would you expect for each group? Give a reason for your answer in terms of phytochrome conversions.
   i) Red light interruption
   ii) Far red interruption

PLANT HORMONES

1. Indole Ascetic Acid (IAA)

Auxins are a group of plant growth hormones responsible for processes like growth, root formation and apical dominance. Auxins produced in plants include the ***Indoleacetic acid (IAA).***

Auxins are produced in small amounts in seeds, germinating embryos, buds, leaves and apices of roots, shoots and buds.

Effects of auxins on plant growth

- Promote elongation of young leaves.
- High auxin concentration stimulates the growth of the shoot but inhibits the growth of the root.
- They cause tropisms.
- They promote formation and growth of adventitious roots.
- They retard lateral buds in shoots.
- They promote apical dominance.

Commercial applications and uses of synthetic auxins

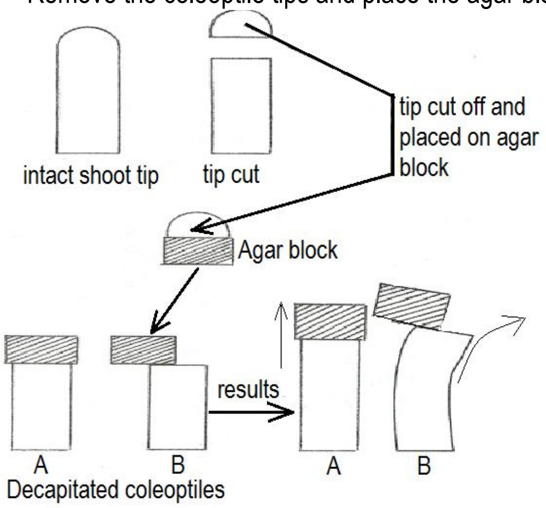
- Auxins are used to initiate rooting in stem cuttings.
- They are used to inhibit leaf fall when the leaf matures.
- They inhibit fruit fall, leaf fall and flower fall (abscission) by maintaining the structure of cell walls.
- They inhibit the development of lateral buds hence reducing branching in plants. Removal of the apical buds therefore leads to branching.
- Synthetic auxins kill broad leaf plants by disrupting their growth hence used as selective weed-killers.
- Synthetic auxins stimulate fruit growth and parthenocarpic fruit development. Parthenocarpy is fruit development without fertilization.

Experiment to show the effect of unequal distribution of auxins and to show that auxins are diffusible

Apparatus/Material: Maize seedlings with coleoptiles, agar block (gelatinous substance through which auxins diffuse) and razor blade.

Procedure:

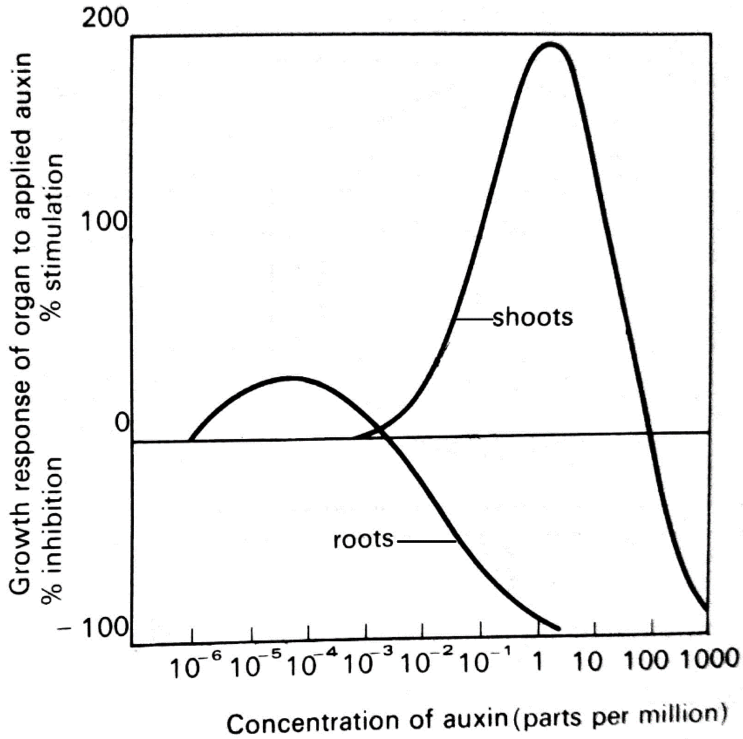
- Two maize seedlings with coleoptiles at least 2cm long are exposed to light for at least 4 hours.
- Cut the coleoptiles tips and transfer each on to an agar block and leave them for 24 hours.
- Remove the coleoptile tips and place the agar blocks on fresh decapitated shoot tips as shown below.



Observation:
Shoot A grew straight upright while shoot B grew bending away from the side with agar block.

Explanation:
Auxins diffused from the coleoptile tips into the agar block. Thus auxins are evenly distributed on the agar block.
In shoot A- Auxins diffuse from the agar block into the decapitated shoot. All sides receive same concentrations of auxins. Cell elongation occurred and growth took place evenly with the shoot growing up right.
In shoot B- Auxins diffused on one side of the shoot. I.e. the side covered with agar block. There was faster cell elongation and hence faster growth on the side compared to the uncovered side. This resulted to the growth curvature observed.

Graph showing the effect of auxins concentration on the growth of roots and shoots.



Observations:

Very low concentrations of auxins do not stimulate shoot growth. However, an increase in the amount of auxins brings about a rapid increase in the rate of growth of the shoot. If the amount of auxin in the shoot continues to increase, there comes a stage where the growth rate begins to slow down until at very high auxin concentration where growth is inhibited.

Roots are stimulated and inhibited by much lower concentrations of auxins than the shoots. Concentration of auxins which stimulate shoot growth inhibit root growth.

Very low concentrations of auxins stimulate root growth and high concentrations inhibit root growth.

Higher concentration of auxins stimulates growth of the shoot but inhibits growth of the root.

2. Gibberellins

They are produced by plants in varying amounts in seeds and young leaves and roots.

- They promote cell elongation of plant stems.
- They promote germination of seeds.
- Application of synthetic gibberellins to genetically dwarf plants causes bolting hence making dwarf plants grow taller.
- End dormancy of buds.
- They also induce flowering in some plants.
- They remove the need for cold treatment in vernalization.

3. Abscisc acid (ABA)

It's made in leaves, stems, fruits and seeds. It has the following effects:

- Inhibits growth.
- Promotes bud and seed dormancy.
- Promotes abscission and leaf senescence.

Commercially, ABA is sprayed on tree crops to regulate fruit drop at the end of the season.

4. Cytokinins

Cytokinins are most abundant where rapid cell division is occurring, particularly in fruits and seeds where they are associated with embryo growth. They have the following effects:

- They increase the rate of cell division (in the presence of auxins).
- They stimulate bud development.
- Promote leaf growth and fruit growth.
- Promote apical dominancy.
- Promote stomatal opening.
- Break dormancy

Commercially they prolong the life of fresh leaf crops such as cabbages by delaying leaf senescence as well as keeping flowers fresh.

5. Ethene (ethylene)

It's made by almost all plant organs. It is a product of plant metabolism. It has the following effects:

- Inhibits stem growth and root growth.
- Promotes flowering e.g. in pine apples.
- Ripens fruits.

Commercially it induces flowering in pine apple and stimulates ripening of tomatoes and citrus fruits.

Note:

Synergism is where the combined effect of growth substances is much greater than the sum of their separate effects.

Antagonism is where the two substances have opposite effects on the same process, one promoting and the other inhibiting.

Examples of synergism are:

- The effect of gibberellins on elongation of stems, petioles, leaves is dependent on the presence of auxins.
- Cytokinins promote cell division only in presence of auxins.

HORMONAL COORDINATION IN ANIMALS

Animals unlike plants have two different but related systems of coordination; the nervous and endocrine system. The nervous system is fast acting, its effects are localized and it involves electrical and chemical transmission whereas the endocrine system is slower in acting, its effects are adverse and it relies on chemical transmission through the circulatory system.

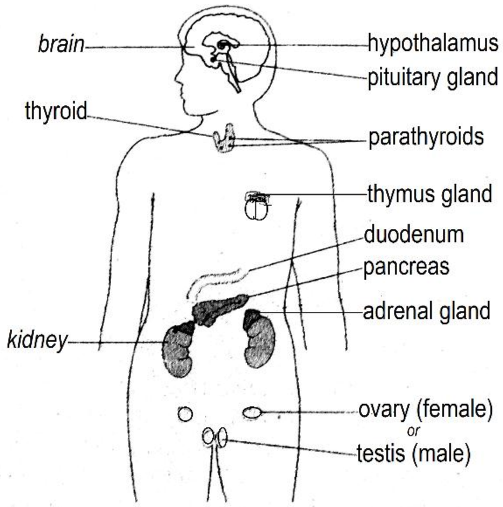
THE ENDOCRINE SYSTEM

This is the endocrine system of glands that secrete chemical substances called hormones.

This system is under the control of ***pituitary gland*** which is therefore known as the **MASTER GLAND** in the body because it controls the activities of all the glands in the body through the hormones it secretes.

*A hormone is a specific chemical substance produced by glands and is transported to a **target organ** to regulate physiological activities in the body.*

In animals, two types of glands are recognized: exocrine glands which convey their secretions to the site of action by special ducts, and endocrine glands, which lack ducts and transport their secretions instead by the blood.
Endocrine glands are stimulated to secrete hormones either by impulses from motor nerves or by hormones from other glands. The endocrine system is linked to the nervous system by the hypothalamus which exerts a major control over the pituitary gland of the endocrine system.
The positions of the major endocrine organs in humans are shown below:



Mechanisms controlling the release of hormones

1) The presence of a specific metabolite in the blood for example glucose in the blood causes the release of insulin from the islets of the Langerhans of the pancreas which lowers the glucose level.
2) The presence of another hormone in blood. Such hormones are called stimulating hormones and most of them are produced by the anterior pituitary gland like thyroid stimulating hormone.
3) Stimulation by neurons from the autonomic nervous system like adrenaline and noradrenaline are released from the cells of the adrenal medulla by the arrival of the nerve impulse in situations of anxiety and danger.

The cascade effect

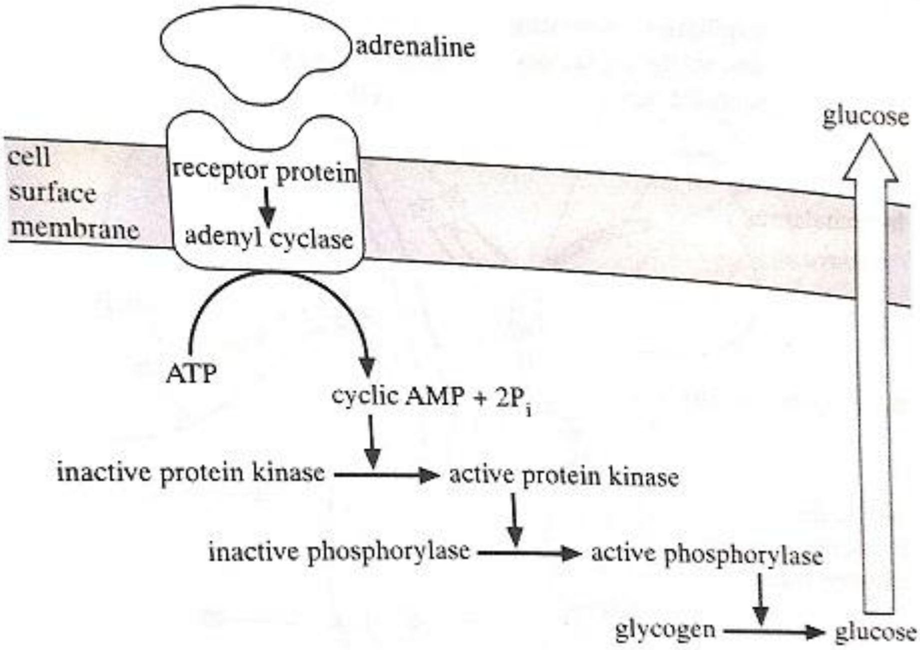
This is the release of hormones by the presence of another circulating hormone usually under the control of the hypothalamus and pituitary gland. The cascade effect is significant because it enables the effect of the release of a small amount of initial hormone to become amplified (magnified) at each stage in the pathway.
An example of the cascade effect in the control of the conversion of glucose to glycogen as a result of the release of adrenocorticotrophic releasing factor. (***Fig 17.47 BS page 601)***

Effects of hormones on target cells

Hormones are very specific and only exert their effects on target cells which possess the particular protein receptors that recognize the hormone. Non target cells lack these receptors and therefore do not respond to the circulating hormone. Once attached to a receptor, the hormone may exert its effect in a number of ways. Three of the most important are through effects on:

1) **The cell membrane:**
   Insulin exerts one of the effects by increasing the uptake of glucose into cells. It binds with a receptor site and alters the permeability of the membrane to glucose. Adrenaline works on smooth muscle cells by opening or closing ion channels for sodium or potassium ions or both, changing membrane potentials and either stimulating or inhibiting contraction as a result.
2) **Enzymes located in the cell membrane** (second messenger mechanism):
   Adrenaline and many peptide hormones bind to receptor sites on the cell membrane but cannot enter the cells themselves. Instead they cause the release of a 'second messenger' which triggers a series of enzyme-controlled reactions. These eventually bring about the hormonal response. In many cases this second messenger is the nucleotide cyclic AMP (cyclic adenosine monophosphate).

An example is how adrenaline causes the release of glucose from a liver cell. The activation of membrane bound adenyl cyclase produces cyclic AMP which activates enzyme systems leading to the breakdown of glycogen to glucose. Glucose then diffuses out of the cell into the bloodstream. At each stage in the process an amplification occurs because only a few molecules of adenyl cyclase are needed to activate many molecules of protein kinase, and so on. This is the cascade effect.



3) Genes:

Steroid hormones (sex hormones and other hormones secreted by the adrenal cortex) pass through the cell surface membrane and bond to a receptor protein in the cytoplasm. The complex formed passes to the cell nucleus where the hormones exert a direct effect upon the chromosomes by switching on genes and stimulating transcription. The messenger RNA enters the cytoplasm and is translated into new proteins, such as enzymes, which carry out a particular function. For example, the hormone thyroxine passes through the surface membrane and binds directly to receptor proteins in the chromosomes, switching on certain genes,

Typical examination question:

1. a) What are target cells?

They are cells that respond to specific hormones.

b) Explain any two mechanisms by which hormones bring about cellular response in target cells.

- *The hormone binds onto its receptor in the cell membrane forming a hormone-receptor complex which activates a G-protein in the membrane.*
  The G-protein activates adenylcyclase which catalyzes conversion of ATP to cAMP. The cAMP activates a specific enzyme that catalyzes reactions which end with activation of another enzyme.
  The enzyme produced brings about change in the structure or function of the cell.
- *Some hormones pass through the cell membrane and bind with specific receptor protein in the cytoplasm to form a hormone-receptor complex.*
  The receptor then carries it into the nucleus where it then activates specific genes in a specific section of DNA triggering synthesis of mRNA which initiates enzyme synthesis in the cytoplasm bringing change in the function of the target cell.

c) Explain how a very small amount of hormone is able to exert a large effect on a target cell.

By use of a two messenger system where a very small amount of hormone can lead to the synthesis of a comparatively large amount of cyclic AMP which in turn evoke a correspondingly large response - the cascade effect.

THE ENDOCRINE GLANDS

1. The hypothalamus

It performs the following functions:

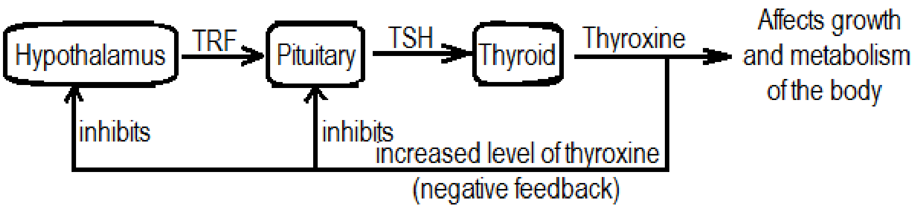
- It regulates activities such as thirst, sleep and temperature control.

- It monitors the level of hormones and other chemicals in blood passing through it.
- It controls the functioning of the anterior pituitary gland.
- It produces antidiuretic hormone and oxytocin which are stored in the posterior pituitary gland.

The hypothalamus is the link between the nervous and endocrine systems.
By monitoring the level of hormones in the blood, the hypothalamus is able to exercise homeostatic control of them. For example, the control of thyroxine production by the thyroid gland is achieved by this means:

i) The hypothalamus produces thyrotrophin releasing factors (TRF) which passes to the pituitary along blood vessels.
ii) TRF stimulates the anterior pituitary gland to produce thyroid stimulating hormone (TSH).
iii) TSH stimulates the thyroid gland to produce thyroxine.
iv) As the level of thyroxine builds up in the blood it suppresses TRF production from the hypothalamus and TSH production by the anterior pituitary gland. By this form of negative feedback the levels of thyroxine in the blood is maintained at a constant level.

Homeostatic control of thyroxine production



2. The pituitary gland

The pituitary gland is called a Master gland because it produces a number of hormones many of which influence the activity of other endocrine glands.
It's connected to the brain by the pituitary stalk. The two lobes of the pituitary gland are the anterior and posterior pituitary lobes.

Anterior pituitary:

It produces and secretes six hormones. Most have other endocrine glands as their target organs. These hormones called trophic hormones, stimulate the activity of their respective endocrine glands. The only non-trophic hormone is growth hormone which directly affects body tissues in general. The secretion of the six hormones is triggered off by specific chemical substances from the hypothalamus called releasing factors.
The hormones secreted include;

Hypothalamus hormone	Anterior pituitary hormones	Function
Growth hormone releasing factor	Growth hormones	• Promotes growth of skeletal muscles. • Control protein synthesis and general body metabolism.
Thyrotrophin releasing factors	Thyroid stimulating hormones (Thyrophic hormones)	• Stimulates growth of thyroid glands. • Stimulates the Thyroid gland to secrete thyroxine hormone
Adrenocorticotrophic releasing factor (C.R.F)	Adrenocorticotrophic hormone	• Regulates growth of adrenal cortex
Prolactin releasing factor (P.R.F)	Prolactin hormones (Luteotrophin)	• Induces milk production in pregnant women. • Maintains progesterone production in corpus luteum.
Luteinizing hormone releasing factor	Luteinizing hormone	• Causes the release of ovum from the ovary. • Stimulates ovary to produce progesterone or corpus luteum.
Follicle stimulating factors	Follicle stimulating hormones	• Initiates cyclic changes in ovary causing development of the graafian follicle. • Stimulates the secretion of oestrogen in the ovary. • Initiates sperm formation in the testis.

Posterior pituitary lobe:

The posterior lobe communicates to the hypothalamus by means of nerve fibres. It does not synthesize any hormone but stores two hormones i.e. antidiuretic hormone (ADH) or vasopressin and oxytocin.
Antidiuretic hormone is released in response to fall in the water content of the plasma and leads to an increase in the permeability to water of the distal convoluted tubule and collecting ducts of the nephron so that water is retained in the blood plasma. It also rises the blood pressure by constricting arterioles.
Oxytocin causes the contraction of uterine walls during birth. It also causes the release of milk from the nipples.

3. Thyroid glands

It produces 3 hormones i.e. Triiodothyronin, thyroxine and calcitonin hormones.

Triiodothyronin and thyroxin hormones are chemically and functionally similar (both contain iodine), however thyroxin contain 4 iodine molecules while triiodothyronin contain 3 iodine molecules.

They both regulate the growth and development of cells and regulate the metabolic rate. They also help in the oxidation of glucose by the cells. This has an effect of increasing the heat production thus these hormones are produced when an animal is exposed to extreme coldness, emotional stress and hunger.

The overall function is to increase the rate of metabolism thus thyroxin work in conjunction with adrenaline and insulin.

In conditions of low iodine levels, triiodothyronin is produced instead of thyroxin in order to maximize the use of limited iodine. If the thyroid gland is unable to make adequate supply of this hormone, it results into under activity of the gland.

Abnormalities of thyroid gland

1) Hypothyroidism (under activity):

In young ones, it brings about sluggishness, physical and mental retardation. In adults, it results in mental and physical sluggishness, reduced metabolic rates, reduced heart beat rates, lowered body temperature and obesity (over weight). Such a condition is called myxoedema. This results into a swelling of the neck called Goitre. Hypothyroidism is caused by insufficient supply of thyroid stimulating hormones and can be cured by taking in thyroxin orally.

2) Hyperthyroidism (over activity):

It leads to increased metabolic rates, increased heart beat rate and ventilation rate, raised body temperature, nervousness i.e. restless. It brings about wasting of muscles where one fails to grow fat.

Extreme cases of hypothyroidism results into heart failure. The main cause of over activity is a blood protein that stimulates thyroid gland to produce triiodothyronin and thyroxin.

Role of calcitonin and parathormone in Ca^{2+} regulation

Calcitonin is concerned with calcium ion regulation in conjunction with parathormone secreted by the parathyroid gland. **Calcitonin (**secreted by the thyroid gland) lowers levels of calcium ion concentration in blood while **Parathormone** (secreted by the parathyroid gland) rises the level of the Calcium ions.

When the concentration of calcium ions rises to high levels in blood, the thyroid gland secretes calcitonin hormone which lowers the calcium ions in the blood stream by:

- Stimulating greater calcium ion loss through the kidneys. Over production causes excess calcium ions to be removed from the kidney causing kidney stones.
- Reducing calcium ion absorption in the gut.
- Increasing calcium ion storage in the bones.

When the concentration of calcium ions in the blood reduces significantly, the parathyroid gland secretes parathormone which rises the level of calcium ions in 3 ways:

- Increases calcium ion absorption from the gut.
- Increases calcium ion reabsorption by the kidney at the expense of phosphate ions.
- Causes release of calcium ion from the bones into the blood stream. Over production of parathormone leads to excess removal of calcium ions from bones making them brittle and reliable to fracture.

Under production of these hormones results into low levels of calcium ions in blood leading to nervous disorder and uncontrolled contraction of muscles.

4. Adrenal glands

They are of two parts, i.e.

- Adrenal cortex: consisting of the outer region of the gland.
- Adrenal medulla: consisting of the inner region of the gland.

Adrenal cortex

All the hormones produced by the cortex are steroid hormones formed from cholesterol. Hormones from this cortex are collectively called corticoids and are of two types:

- Gluco-corticoids which is concerned with glucose metabolism.
- Mineral corticoid that is concerned with mineral metabolism.

i) Gluco-corticoids:

Such hormones include cortisol hormone which is produced in response to stressful situation like pain, stroke, emotion and extreme cold infection.

The hypothalamus stimulates the anterior pituitary gland to secrete the adrenocorticotropic hormone (corticotrophin). Corticotrophin stimulates the adrenal cortex to synthesize and secrete cortisol hormone. When stress is prolonged, the size of adrenal glands increase. Cortisol fight stress in the following ways:

- Inhibits glycogenesis (stops formation of glycogen).
- Rises the blood sugar level by inhibiting insulin and hence lead to the formation of glucose (glucogenesis).
- Increases the uptake of amino acids by the liver. These are deaminated to form more glucose.

ii) Mineral corticoids:

This is a group of hormones including Aldosterone which regulate water retained in the body. It does this by controlling the distribution of Na^+ and other minerals in the tissues. Aldosterone increases the re-absorption of Na^+ and Cl^- ions by the kidney and K^+ lost in urine.

The reduction of Na^+ concentration in the total blood volume causes special kidney cells to produce renin which activates the plasma proteins and angiotensin that stimulates the release of aldosterone from adrenal cortex. This causes the kidney to conserve both water and sodium ions.

Angiotensin also creates a sensation of thirst that drives the organism to drink water thus helping to restore the blood volume.

Over production of aldosterone often results into excessive Na^+ retention by tissues, high blood pressure and headache. Retention of sodium ions in the body leads to a fall in potassium ions level in the blood leading to muscle weakness.

Under production of aldosterone leads to the fall in the amount of sodium ions in blood.

Adrenal medulla

It produces adrenalin and noradrenalin hormones.

Both are important in preparing organisms for emergence or action. The cells producing them are modified neurons of sympathetic nerve system. Therefore, they act as a link between the nervous and endocrine system. They are sometimes known as 'fight or flight' hormones as they prepare an organism to either take off or face the enemy.

The effect of both hormones is to prepare a body for danger and to fasten its response to stimulus. In some cases adrenaline dilates blood vessels while noradrenaline constricts them. This explains why blood vessels around the gut constrict while those supplying the muscles, lungs and liver dilates.

Effects of adrenalin and noradrenalin in the body

Effect	Function
Bronchioles dilates	Air is more easily inhaled and more oxygen is made available for the production of energy by glucose oxidation.
Glycogen in the liver is converted to glucose	Increases blood sugar level making glucose available for respiration.
Heart beat rate increases and the volume of blood pumped per beat increase.	Increases the rate at which glucose and oxygen are distributed to tissues.
Blood is diverted from digestive and reproductive system to vital organs e.g. liver, lungs and muscles.	Blood rich in oxygen and glucose is diverted from tissues with low energy need to those with high energy need.
Peristalsis and digestion inhibited.	Inhibition of the process diverts blood to muscles, liver and lungs that need more energy.
Sensory perception increases.	It produces rapid reaction to stimulus.
Increased mental awareness.	To allow quick response to stimuli.
Pupil of the eye dilates.	Increases the range of vision and perception of visual stimulus.
Erector muscles of hair contract, hairs on skin stand.	Gives an impression of increased body size to scare the enemy.

PANCREAS

It is an exocrine as well as endocrine gland with special cells called islets of Langerhans. Within them are the beta cells which produce insulin and alpha cells which secret glucagon hormones.

Glucagon increases blood sugar levels by stimulating the breakdown of glycogen to glucose and its release from the liver cells.

Insulin reduces the blood sugar levels by stimulating the conversion of glucose to glycogen in the process called glycogenesis.

Insufficient levels of insulin in blood leads to disorders called ***diabetes mellitus***. As a result, the blood sugar levels rises to dangerous levels causing blindness and kidney failure.

In case the kidney is unable to reabsorb all glucose passing through it, it results into the symptom of the presence of glucose in urine. Treatment involves administering insulin.

Summary of endocrine glands and their functions

Gland	Hormone	Function
Pituitary gland		
Thyroid gland	Tri-iodothyroxine Iodine Calcitonin	Regulates growth and development by affecting metabolism.
Parathyroid	Parathormone	Raise calcium levels as it lowers phosphate levels
Adrenal gland i) Adrenal cortex ii) Adrenal medulla	Cortisol hormone	Helps in combating stress by rising blood sugar levels and pressure.
	Aldosterone	Increases reabsorption of Na^+ by kidney tubules.
	Adrenaline and noradrenaline	They prepare the body for fright or fight/emergency or stressful situations.
Pancreas	Insulin	Lowers blood sugar levels
	Glucagon	Increases blood sugar levels
Duodenum	Secretin	Stimulates secretion of minerals and pancreatic juice by pancreas. Stimulates the secretion of bile by the liver into the gall bladder.
	Cholecystokinin	Causes contraction of gall bladder to release bile. Stimulates the pancreas to release its enzymes.
Ovary	Oestrogen	Stimulates the pituitary gland to produce luteinizing hormone. Causes repair of uterine lining after menstruation.
	Progesterone	Causes the uterus lining to be maintained in readiness for the embryo to be implanted. Inhibits production of FSH and luteinizing hormone thus inhibiting ovulation and maintaining pregnancy.
Testis	Testosterone	Produces male sex secondary characteristics.
Placenta	Progesterone	Maintains pregnancy after corpus luteum has degenerated.
	Chorionic gonadotrophin hormone	Maintains the presence of corpus luteum in the ovary.
Kidney	Renin	Activates plasma proteins and angiotensin.
Stomach walls	Gastrin	Initiates secretion of gastric juice.

INSECT HORMONES

Most invertebrate hormones are nerve secretory hormones. In insects their important in controlling ecdysis/molting. The process involves two hormones; ecdysin and juvenile/neotenin hormones.

In holometabolous (complete metamorphosis), all moults require ecdysin hormones. If however a high concentration of juvenile hormone is present the larva moults to another larva stage. As growth proceeds, the level of juvenile decreases. At less levels of juvenile, the larva moults to give rise to pupa. In absence of juvenile hormone, ecdysin causes the pupa to molt to an adult.

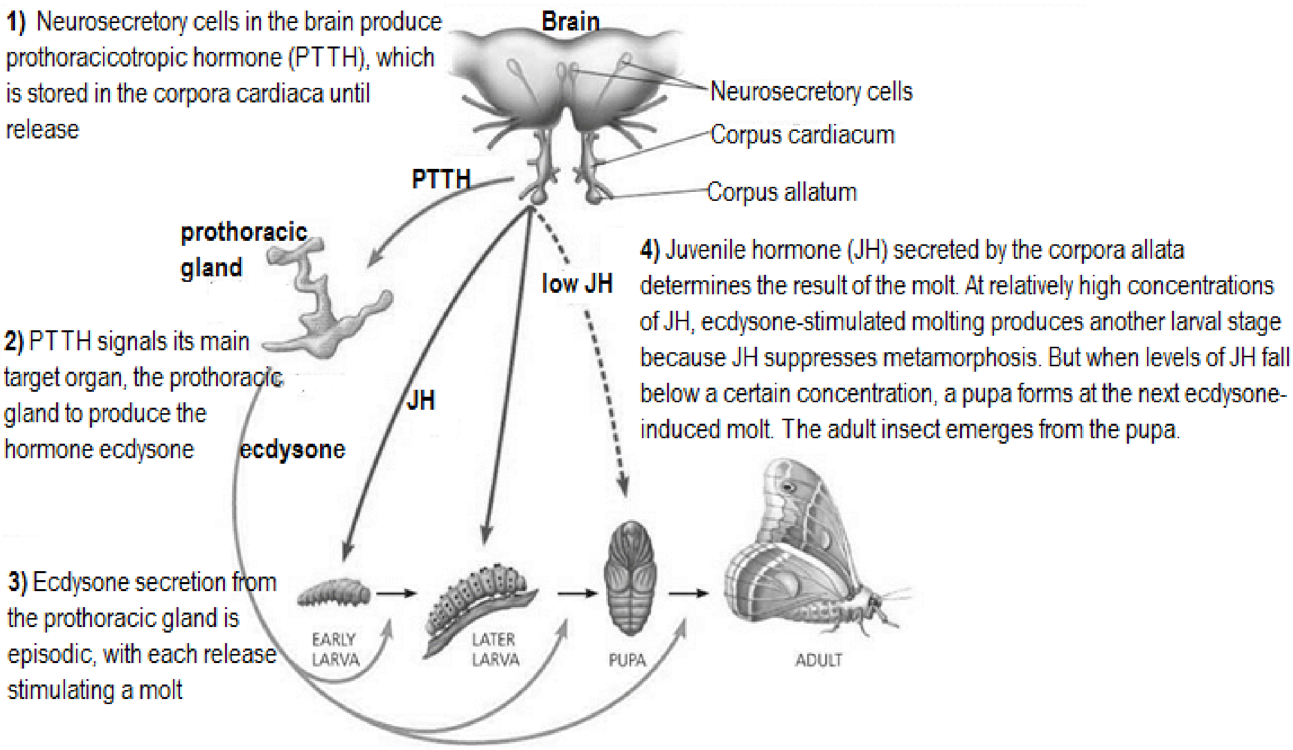
Production of two hormones is controlled by the insect brain as follows:

The brain produces a hormone prothoracic-trophic hormone which passes to a pair of bodies called corpora cardiaca which lies next to the brain where it's stored. In response to external stimulus like day length, temperature and food supply, the brain sends impulses to corpora cardiaca to release the formed prothoracic trophic hormones.

Juvenile/neotenin is produced by the region behind the brain called corpora allatum. The production of the juvenile hormone decreases as the insect develops and resumes in adults because it is important in the production of eggs in female insects stimulation of the male accessory glands to produce seminal fluid in male adult insects.

Therefore the main role of JH in immature insects is to inhibit the genes that promote development of adult characteristics, causing the insect to remain as nymph or larva.

In adult insects, the neurosecretory cells of the brain release a brain hormone that reactivates the corpora allatum, stimulating the production of juvenile hormone.



Other hormone-like substances

Pheromones:

These are chemicals capable of acting like hormones outside the body of the secreting individual to impact the behaviour of the receiving individuals.

They include alarm pheromones, food trail pheromones, sex pheromones, and many others that affect behavior or physiology. Some species like female silk moth produce sweet smell that attract male sex moth.

Pheromones attract individuals from far distance thus these pheromones are used to control population of the same species. Ants, termites and bees all produce chemicals which aid others in their social groups to go for food resource.

Prostaglandins:

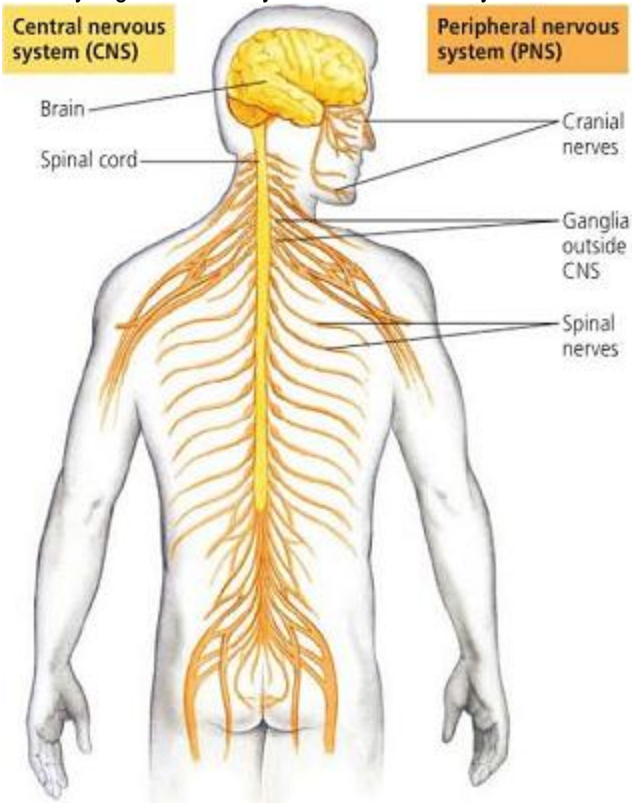
They are produced throughout the body and are found in the semen. They bring about contraction of smooth muscles, contraction of the uterus to push the sperm up to the oviduct.

Endorphins:

They act in such a way that they reduce pain, induce thyroxin activities, influence hibernation, lower ventilation and cardiac rate. They act by attaching on the receptor sites on the cells of the human brain.

NERVOUS COORDINATION IN ANIMALS

This is a system of nerve cells and sensory organs that carry out co-ordination by transfer of impulses.



The nervous system consists of;

Receptors: These are the organs that detect ***stimuli*** to which the animals respond. E.g. sensory endings in the skin, nose, tongue, eyes and ears.

Impulses: these are electrical transmissions or chemical stimuli sent from the receptors to the coordinating center. The coordinating center interprets the impulses before a response is made.

Effectors: These are organs that respond to the stimuli and carry out the response.

The central nervous system (CNS): This interprets and determines the nature of the response. The CNS consists of the brain and spinal cord.

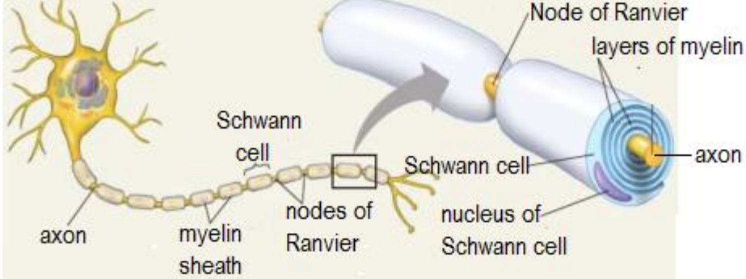
Peripheral nervous system: This consists of the vast network of spinal and cranial nerves linking the body to the brain and spinal cord.

Functions of the nervous system

1. It receives impulses from all sensory organs of the body.
2. It stores information.
3. It correlates various stimuli from different sensory organs.
4. It sends messages to all parts of the body making them function accordingly.
5. It's involved in temperature regulation.

STRUCTURE AND FUNCTIONS OF THE NEURONE

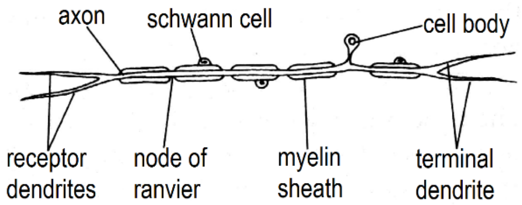
A neurone is made up of a small mass of cytoplasm, a nucleus in a structure called the cell body, branching cytoplasmic filaments called dendrites and a single long fiber called axon.



There are three types of neurones i.e. Sensory neurone, Motor neurone and Relay neurone

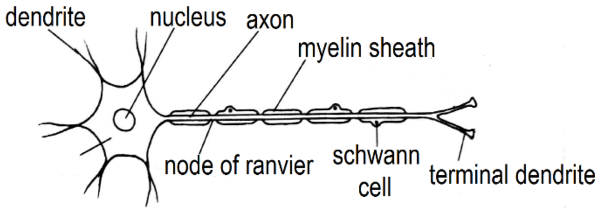
Sensory neurone

Sensory neurones are cells that transmit impulses from the receptor cells to the central nervous system.



Motor neurone

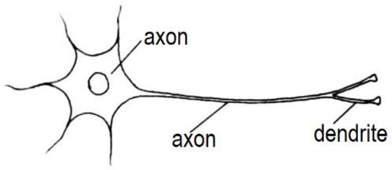
This is a neurone that transmits impulses from the central nervous system to the effector organs such as muscles and glands, where a response is made. The muscles respond by contracting while glands respond by secreting substances.



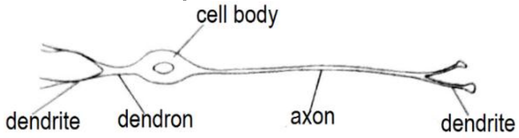
Relay neurone

This is a neuron located in the central nervous system and transmits impulses from the sensory neurone to the motor neurone. The axon extends towards the motor neurone. It is also referred to as an intermediate neurone. A relay neurone is either unipolar, bipolar or multipolar.

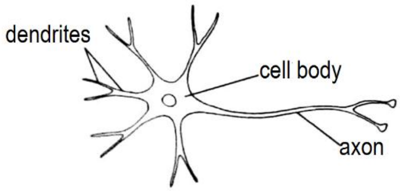
Unipolar neurone:



Bipolar neurone:



Multipolar neurone:



Functions of the parts of a neurone

Cell body: This consists of a nucleus surrounded by a mass of cytoplasm. The nucleus controls all activities of the neuron.
Axon: Transmits impulses over long distances in the body. Each axon is filled with cytoplasm called axoplasm.
Myelin sheath: This is a fatty material that covers the axon. The myelin sheath is secreted by cells called ***Schwann cells***. The myelin sheath insulates the axon and speeds up the transmission of impulses.
Dendrites: These are hair-like structures surrounding the cell body. They conduct incoming signals.
Node of Ranvier: This is the space on the axon between two adjacent myelin sheaths. It speeds up nervous transmission.
Dendron: It is a branch through which impulses are transmitted to the body.
Schwann cell; this is a cell which secretes the myelin sheath.
Nissl's granules; these are groups of ribosomes responsible for protein synthesis.

Differences between motor and sensory neurons

Motor neuron	Sensory neuron
Has a long axon.	Has a short axon.
It has a cell body at the terminal end of the axon.	Has a cell body located on the axon branch.
It has a short dendrons.	It has a long dendron.
It carries impulses from the central nervous system to the effector organ.	It carries impulses from the receptor cells to the central nervous system.
It has several dendrons.	It has one dendron.
Terminal dendrites connect with effector organ.	Terminal dendrites connect to relay neurones.

How the motor neurone is suited for functioning

- The nucleus is **relatively large** to coordinate the metabolic activities all over the large cytoplasm of the cell.
- There are very many rows of rough endoplasmic reticula (**Nissl's granules**) for massive production of proteins and neurotransmitters.
- The dendrites are **numerously branched** to increase the surface area for synapting with several other neurones.
- Axon is **long** to carry impulses to the target parts.
- The axon membrane is wrapped with a myelin sheath for electrical **insulation.**
- The axon membrane is wrapped with a **thick** myelin sheath for **protection** against damage.
- The axon membrane is wrapped with a myelin sheath at intervals around the axon which **increases speed** of impulse transmission through salutatory conduction.

THE FUNCTIONING OF NEURONES

Neurones are electrically excitable cells i.e. they can change their membrane potential and are capable of transmitting electrical nerve impulses. The impulses are due to events in their cell membrane.

Polarization of the neuron's membrane:

Cell membranes surround neurons just as any other cell in the body has a membrane. When a neuron is not stimulated — it's just sitting with no impulse to carry or transmit — its membrane is **polarized**. Being polarized means that the electrical charge on the outside of the membrane is positive while the electrical charge on the inside of the membrane is negative. **The outside of the cell contains excess sodium ions (Na+); the inside of the cell contains excess potassium ions (K**+).

You're probably wondering: ***How can the charge inside the cell be negative if the cell contains positive ions?*** Good question. The answer is that in addition to the K+, negatively charged protein and nucleic acid molecules also inhabit the cell; therefore, the inside is negative as compared to the outside.

Then, if cell membranes allow ions to cross, **how does the Na+ stay outside and the K+ stay inside**? If this thought crossed your mind, you deserve a huge gold star! The answer is that the Na+ and K+ do, in fact, move back and forth across the membrane. However, Mother Nature thought of everything. There are Na+/K+ pumps on the membrane that pump the Na+ back outside and the K+ back inside. The charge of an ion inhibits membrane permeability (that is, makes it difficult for other things to cross the membrane).

Resting potential

This *gives the neuron a break.* When the neuron is inactive and polarized, it's said to be at its resting potential. It remains this way until a stimulus comes along.

Action potential

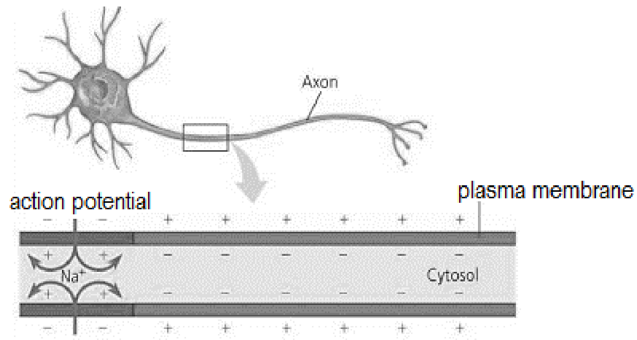
This begins when sodium ions move into the inside the membrane**.**

When a stimulus reaches a resting neuron, the gated ion channels on the resting neuron's membrane open suddenly and allow the Na+ that was on the outside of the membrane to go rushing into the cell. As this happens, the neuron goes from being polarized to being depolarized.

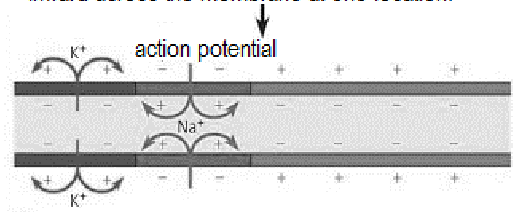
Remember that when the neuron was polarized, the outside of the membrane was positive, and the inside of the membrane was negative. Well, after more positive ions go charging inside the membrane, the inside becomes positive, as well; polarization is removed and the **threshold** is reached.

Each neuron has a threshold level — ***the point at which there's no turning back***. After the stimulus goes above the threshold level, more gated ion channels open and allow more Na+ inside the cell. This causes complete depolarization of the neuron and an action potential is created. In this state, the neuron continues to open Na+ channels all along the membrane. When this occurs, it's an ***all-or-nothing*** phenomenon. "***All-or-nothing"*** *means that if a stimulus doesn't exceed the threshold level to cause* ***all*** *the gates to open, no action potential results*; however, after the threshold is crossed, there's no turning back: Complete depolarization occurs and the impulse will be transmitted.

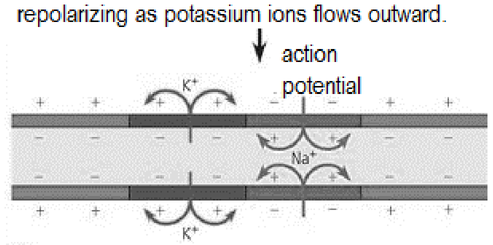
When an impulse travels down an axon covered by a myelin sheath, the impulse must move between the uninsulated gaps called nodes of Ranvier that exist between each Schwann cell – *this is referred to as the* ***saltatory effect.***



1. An action potential is generated as sodium ions flow inward across the membrane at one location.



2. The depolarization of the action potential spreads to the neighbouring region of the membrane, reinitiating the action potential there. To the left of this region, the membrane is repolarizing as potassium ions flows outward.



3. The depolarization-repolarization process is repeated in the next region of the membrane. In this way, local currents of ions across the plasma membrane cause the action potential to be propagated along the length of the axon.

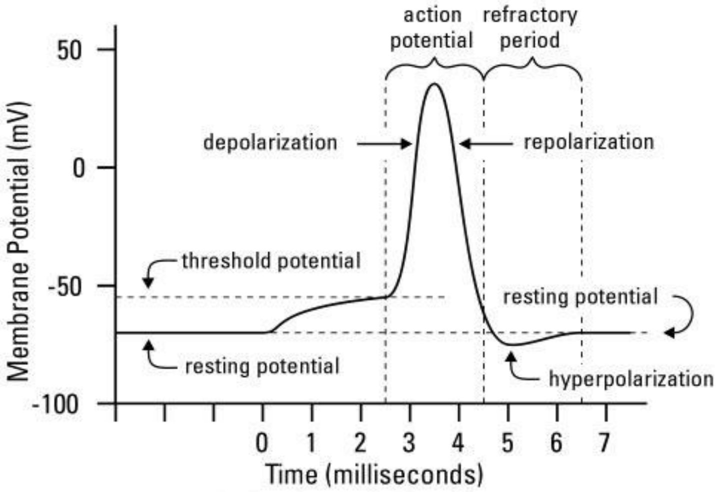
Repolarization

Potassium ions move outside, and sodium ions stay inside the membrane. After the inside of the cell becomes flooded with Na^+, the gated ion channels on the inside of the membrane open to allow the K^+ to move to the outside of the membrane. With K^+ moving to the outside, the membrane's repolarization restores electrical balance, although it's opposite of the initial polarized membrane that had Na^+ on the outside and K+ on the inside. Just after the K+ gates open, the Na+ gates close; otherwise, the membrane couldn't repolarize.

Hyperpolarization

More potassium ions are on the outside than there are sodium ions on the inside. When the K^+ gates finally close, the neuron has slightly more K^+ on the outside than it has Na+ on the inside. This causes the membrane potential to drop slightly lower than the resting potential, and the membrane is said to be hyperpolarized because it has a very low membrane potential. (Because when the membrane's potential is lower, it has more room to "grow."). This period doesn't last long, though (well, none of these steps take long!). After the impulse has traveled through the neuron, the action potential is over, and the cell membrane returns to normal (that is, the resting potential).

A graph showing the changes in membrane potential inside a neuron



Therefore in summary: The membrane is more permeable to outward diffusion of K^+ than inward diffusion of Na^+. This will leave a surplus negative charges inside and positive charges outside hence resting potential.

When an impulse is passing, the membrane suddenly become permeable to Na^+ and they diffuse into the axon rapidly and reverse the resting potential by making the inside positive and leaving the outside negative hence an action potential which is propagated along the axon as a current of propagation.

As sodium ions enter the axon, potassium ions leave to the outside and this restores the negative charges inside. The sodium ions are later expelled from the inside by Na-K pump and return the potassium ions hence restoring the distribution of ions as they normally exist when an axon is at rest.

Refractory period

This puts everything back to normal. Potassium returns inside, sodium returns outside.

The refractory period is when the Na+ and K+ are returned to their original sides: Na+ on the outside and K+ on the inside. While the neuron is busy returning everything to normal, ***it doesn't respond to any incoming stimuli***. After the Na+/K+ pumps return the ions to their rightful side of the neuron's cell membrane, the neuron is back to its normal polarized state and stays in the resting potential until another impulse comes along.

WORKED OUT EXAMINATION QUESTIONS

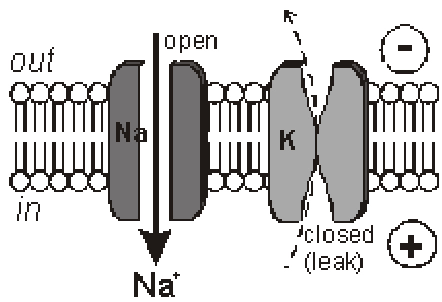
a) State the 'All-or-nothing law' in the transmission of nerve impulses.

It states that if the strength of the stimulus is below certain threshold intensity, no action potential is evoked. If however the stimulus is above the threshold, a full sized potential is evoked and remain the same however-much intensity the stimulus becomes.

b) Describe how a nerve impulse is initiated and propagated in a neurone

Depolarization:

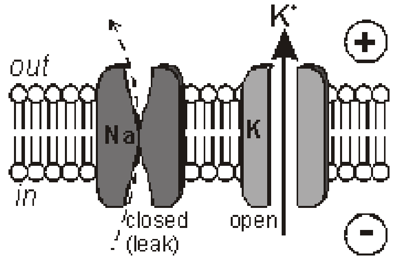
- A stimulus from sensory cell or another neurone can cause the membrane potential of a target neurone to change a little.
- The voltage-gated ion channels can detect this change, and when stimulated past threshold (about –30mV in humans), the sodium channels open for 0.5ms.
- This causes Na^+ to rush in, making the inside of the cell more positive.
- This phase is referred to as a **depolarization** since the normal voltage polarity (negative inside) is reversed (becomes positive inside).



Repolarization:

- The region of positive charge causes nearby voltage gated sodium channels to close.

- Just after the sodium channels close, the potassium channels open wide for 0.5ms, causing potassium ions to rush out, making the inside more negative again, so the charge across the membrane is brought back to its resting potential.
- This is called **repolarization.** As the polarity becomes restored, there is a slight 'overshoot' in the movement of potassium ions (called **hyperpolarization**).
- This process continues as a chain-reaction along the axon in one direction.
- The influx of sodium depolarizes the axon, and the outflow of potassium **repolarizes** the axon.
- The resting membrane potential is restored by the Na-K pump.



c) What is meant by a resting potential?

A resting potential is a negative potential difference existing across a membrane of an axon when the outside of the membrane is more positive while the inside of the membrane is more negative or membrane is polarized, when there exists no stimulus**.**

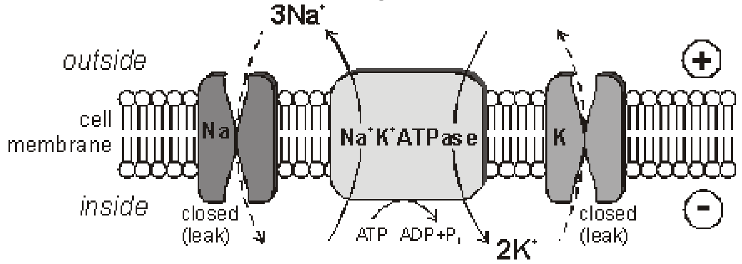
d) Explain how a resting potential is maintained across the membrane of a resting axon.

It is maintained by the activity of sodium-potassium pump mechanism**;** which actively pumps 3 sodium ions outside**;** the membrane and two potassium ions inside the membrane**;** The membrane remain permeable to potassium ions but impermeable to sodium ions**;** and outward flow of negative ions such as chloride ions, potassium ions freely diffuse outside the membrane while the negative ions are retained**;** inside the membrane causing the inside of the membrane more negative and outside of the membrane more positive**;**

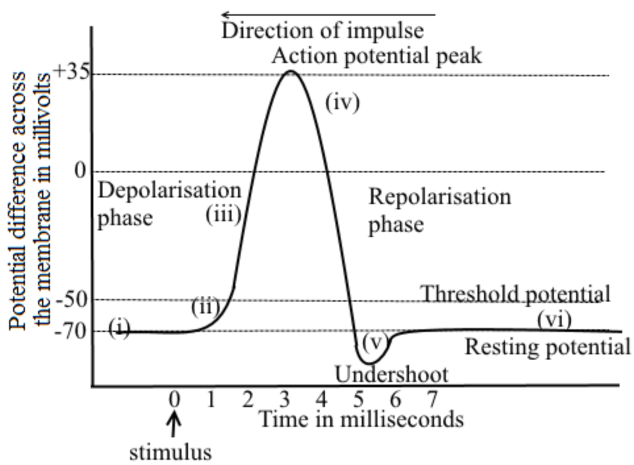
e) Explain how the resting membrane potential is created

The protein pump called the sodium-potassium pump in all animal cell membranes actively pumps **simultaneously** 3 Na^+ out of the cell and 2 K^+ in, causing a higher concentration of Na^+ outside the membrane than in the cytoplasm, and more K^+ in the cytoplasm than outside thus creating a chemical gradient.

Although Na^+ and K^+ later leak by diffusion along their gradients, the axon membrane is more permeable to potassium ions which therefore leak out of the cytoplasm faster than the sodium ions leak in because most of the potassium gates are open while most of those of sodium are closed, resulting in a potential difference (difference in charge) between the negative inside of the neurone and the positive outside, called the **resting membrane potential.**



Changes in potential difference across a neuron membrane during the passage of an impulse



Note: Nerve impulses can only travel in one direction. Action potential can only depolarize the membrane in front while the membrane behind is recovering from refractory period (previous action potential)

Resting membrane potential

At (i): Both the voltage-gated sodium and potassium channels are closed. The membrane's resting potential is maintained by the Na+/K+ pump and the permeability of the membrane which permits facilitated diffusion of more K+ ions out and less Na+ ions into the inside.

At (ii): A stimulus triggers the opening of some sodium voltage-gated channels. When the influx of Na+ ions exceeds threshold potential, more sodium voltage-gated channels open

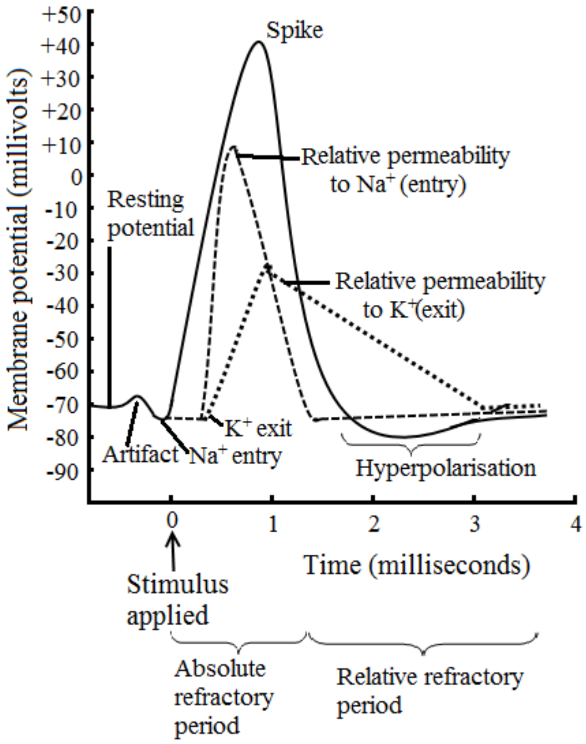
Depolarization phase of the action potential at (iii): The activation gates of the voltage-gated sodium channels open. There is influx of Na+ ions into the axon as the cell becomes more positive inside. The voltage-gated potassium channels remain closed.

Repolarization phase of the action potential at (iv): Inactivation gates close voltage-gated sodium channels. Voltage-gated potassium channels open and K+ ions diffuse out of the cell. The loss of positive K+ ions cause the inside of the cell to become more negative than the outside.

Hyperpolarization / Undershoot at (v): Both gates of the voltage-gated sodium channels are closed. The voltage-gated potassium channels remain open because their gates close slowly. Within one or two milliseconds, voltage-gated channels close.

Re-establishing resting potential at (vi): The resting potential is re-established by the Na+/K+ pump and facilitated diffusion through ion channels.

Axon membrane permeability to Na^+ and K^+



Comparison of membrane permeability to Na^+ and K^+

Similarities: ***Axon membrane permeability***: is **constant** from 0ms to about 0.3ms and 3ms to 3.5ms**; increases** from about 0.3ms to 0.5ms**; equivalent** at about 1ms**; decreases** between 1ms and 1.3ms;	
Differences:	
Axon permeability to Na+	**Axon permeability to K+**
Increases rapidly from 0.3ms to about 0.5ms	Increases gradually from 0.3ms to about 0.5ms
Attains much higher peak	Attains much lower peak
Constant from about 1.5ms to 3ms	Decreases from about 1.5ms to 3.5ms

Neurone excitability during and after an impulse

Refractory period: Represents a time during which the membrane cannot be depolarised again.

- Occurs during repolarization and hyperpolarization.
- Membrane is impermeable to Na^+ ions / sodium ion channels are closed.
- Sodium ions cannot enter axon.
- K^+ ions move out as membrane is more permeable to K^+ ions.
- Membrane becomes more negative than resting potential.

Nerve impulses can only travel in one direction.

- Action potential can only depolarize the membrane in front.
- Membrane behind is recovering from refractory period (previous action potential)

Refractory period limits frequency with which neurones can transmit impulses

- **Absolute refractory period:** is when it is not possible to elicit another action potential despite the size of the stimulus. Na+ channels are recovering and no matter what stimulus is applied, they cannot activate to allow Na+ in and depolarize the membrane to the threshold of an action potential.
- **Relative refractory period**: is when it is more difficult to elicit an action potential, but still possible if a greater stimulus is used than is needed at rest.

In relative refractory period some of the Na+ channels have re-opened but the threshold is higher than normal making it more difficult for the activated Na+ channels to raise the membrane potential to the threshold of excitation.

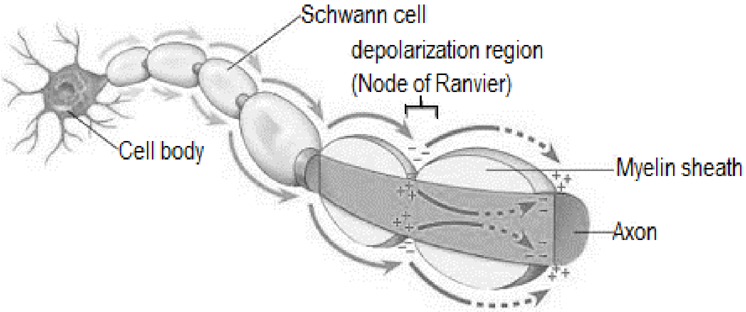
Importance of refractory period

- Determines the maximum frequency at which an axon can transmit an impulse.
- Ensures separation of action potential and specify the stimulus causing the excitation.
- Prevents spreading of action potential and makes it flow in one direction.

Factors that affect nerve conduction speed

1) **Axon diameter:**
Impulses are faster in an axon with larger diameter because longitudinal resistance of axoplasm decreases with increasing diameter of axon, which increases the length of the membrane influenced by local circuit as the distance between adjacent depolarization increases; causing increased conduction velocity.
Small cells or cells with large surface area to volume ratio or ion leakage weakens membrane.
Myelin sheath stops ion leakage; therefore large diameter only important for unmyelinated neurons.
2) **Temperature:**
Homoiotherms with steady body temperature have faster impulse propagation than poikilotherms which have fluctuating body temperature.
3) **Myelination and saltatory conduction:**
Myelination speeds up conduction. In a myelinated neuron, the conduction velocity is directly proportional to the fiber diameter. Schwann cells prevent diffusion of ions; flow of current occurs only between adjacent nodes of Ranvier. Therefore, depolarization only at nodes of Ranvier because action potential 'jumps' from node to node.

Transmission of an impulse along a myelinated neuron

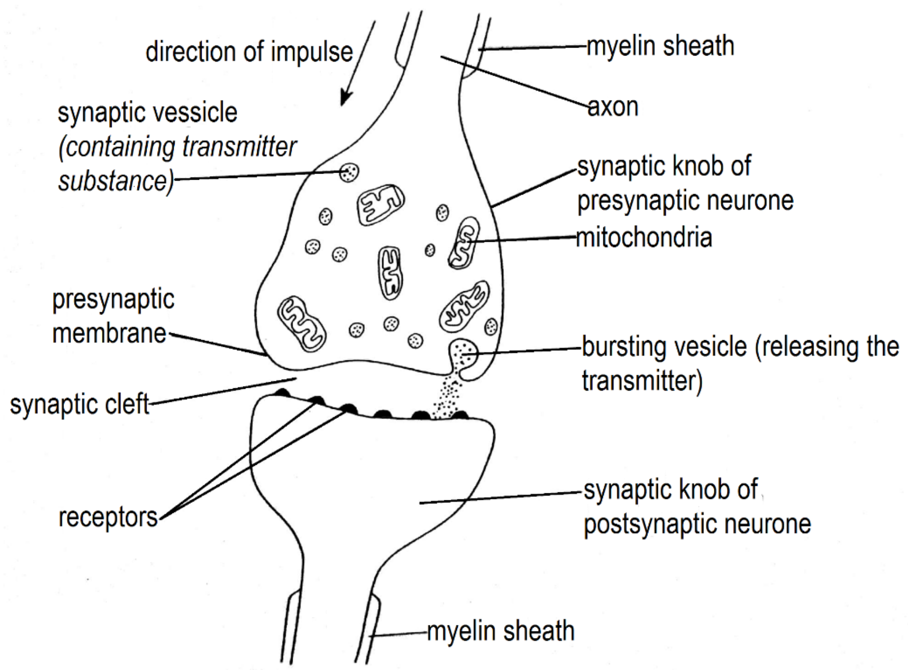


Note: Properties of nerves and nerve impulses are based on stimulation, the all or nothing law, transmission speed, and myelin sheath and axon diameter

SYNAPSE

This is the point where the axon of one neuron meets and joins with the dendrite or cell body of another neuron. This allows information to cross from one neuron to another neuron.

Structure of the synapse



Synapses can be:

Inhibitory i.e. neurotransmitter opens Cl^- ion or K+ ion-gated channels in the post-synaptic membrane, causing hyperpolarization which makes it difficult to generate an action potential

Excitatory i.e. neurotransmitter opens Na+ channels to cause depolarization in the post-synaptic membrane.

Transmission of the impulse across a synapse

When an impulse arrives on the presynaptic knob, the calcium ion channels in the presynaptic membrane are opened. Calcium ions from the synaptic cleft enter the knob and cause the vesicles to move close to the presynaptic membrane.

When these vesicles reach the membrane, they discharge/release the transmitter substances through the membrane to the cleft.

The released neurotransmitter substances then diffuse across the synaptic cleft attaches to specific receptor sites on the postsynaptic membrane.

What follows depends on whether the synapse is either excitatory or inhibitory.

At excitatory synapse, the reception of neurotransmitter substance (acetyl choline) on the receptor sites changes their configuration such that the membrane channels in them are opened up thus allowing sodium ions to diffuse into the postsynaptic membrane.

The potential difference of the membrane therefore changes and an **excitatory postsynaptic potential (EPSP**) results. This fills up until the threshold is reached which results into an action potential being fired in the post synaptic neuron. At that point the impulse has crossed the synapse.

At an inhibitory synapse, release of transmitter substances (noradrenaline) into the synaptic cleft leads to the opening up of chloride ion channels in the post synaptic membrane resulting into chloride ions entering and potassium ions leaving.

As a result, the interior of the post synaptic membrane becomes more negative. This is known as **inhibitory postsynaptic potential (IPSP)** and makes it difficult to generate an action potential in the post-synaptic cell.

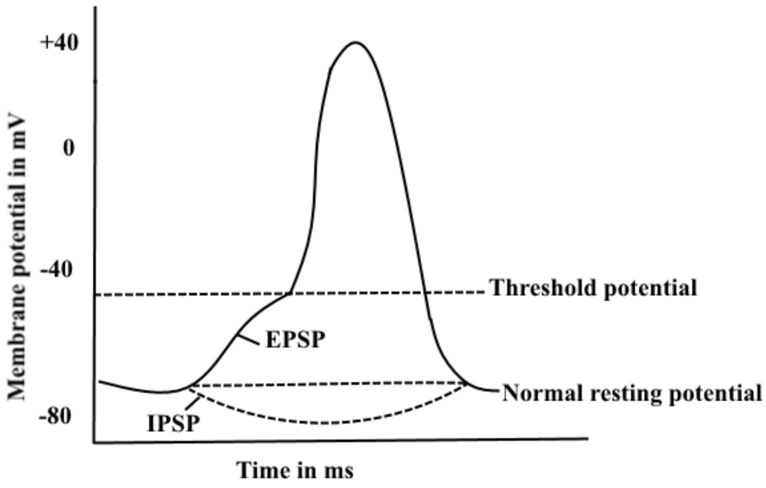
Note:

After neurotransmitter substance has performed its function, it does not stay because if it was to stay it would continue to stimulate the post synaptic neuron.

Acetyl choline is normally hydrolyzed by an enzyme, acetyl cholinesterase to choline and acetyl. These two products then diffuse back and re-enter the presynaptic knob and combine back to form the transmitter substance which is packed into vesicles ready for reuse.

Because this process is energy demanding, it explains why the synaptic knob has many mitochondria.

Graph showing membrane potential changes during synaptic transmission



Action of drugs and poison

The fact that transmission of impulse is as a result of chemicals, it provides explanations that drugs and poisons have an effect on the synapse:

Cocaine blocks reuptake of neurotransmitter e.g. **dopamine**

Curare blocks action of **acetylcholine** by binding to receptors on the post synaptic membrane.

Organophosphate insecticides and nerve gases block **acetylcholinesterase**, thus acetylcholine remains active for longer periods.

Being an antagonist of **acetylcholine-receptors** and **adrenaline-receptors** on membrane of muscle cells in heart, **curare** in small doses is used as a general muscle relaxant in patients undergoing major surgery.

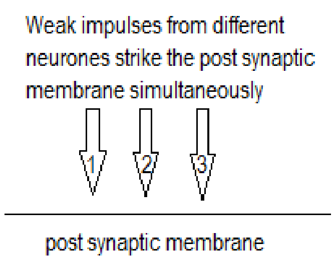
Curare is commonly applied on tips of hunting arrows to paralyze animals.

Other terms used in impulse transmission

1. **Summation:** This is a phenomena used to describe how the depolarizing effect of several excitatory post synaptic potential is additive. There are two types i.e.

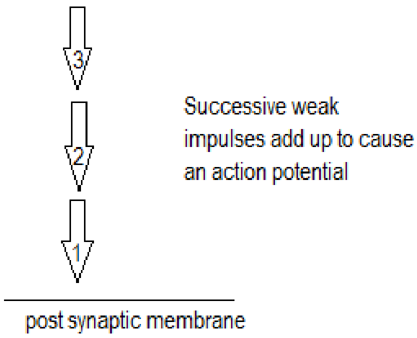
   Spatial summation:
   This is the addition of transmitter substances from two synaptic knobs so that it can be enough to excite the post synaptic membrane.

   Spatial summation

   Temporal summation:
   This involves the facilitation process i.e. the first impulse transmission is insufficient to trigger off an impulse in the post synaptic membrane but cause an effect, therefore the second faster stimulation will add to the former and generate an impulse at the post synaptic membrane. The rapid repeated release of transmitter substance from several synaptic vesicles by the same synaptic knob as a result of an intense stimulus produces individual excitatory post synaptic potentials (epsp) which are so close together that they summate and give rise to an action potential in the post synaptic membrane.

   Temporal summation

2. **Accommodation:**

If a synapse has had a persistent high frequency impulse for a long time than usual, the post synaptic nerve cell may fail to respond and impulses are no longer generated. This means supply of transmitter substance is exhausted and its re-synthesis can't keep pace with the rate at which the impulse are reaching the synapse therefore the synapse is said to be fatigued or accommodate.

Functions of the synapse

- They transmit information between neurones.
- They filter out low frequency impulses.
- They act as valves to ensure that impulses pass across them in one direction only.
- They also act as junctions allowing impulses to be divided up along many neurones or merge into one.
- To protect effectors from damage by overstimulation.
- Synapses may be involved in memory and the learning process.

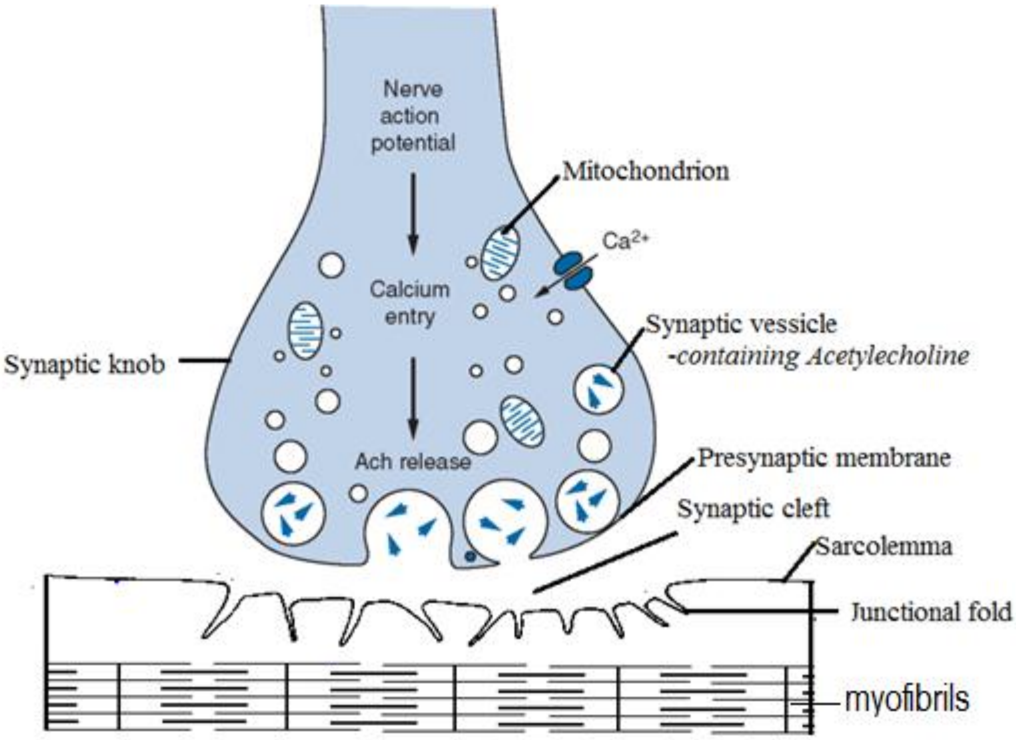
Disadvantages of synapse

- Slows down the speed of transmission.
- Are highly prone to drugs and fatigue which may inhibit impulse transmission.

Neuromuscular junction

This is a single synapse or junction made between one motor neuron and one muscle fiber

Structure of a neuromuscular junction



Functioning of the neuromuscular junction

Arrival of an action potential at the synaptic terminal of motor neuron causes the influx of Ca^{2+} ions from the extracellular fluid into the presynaptic neuron's cytosol followed by exocytosis of synaptic vesicles containing acetylcholine.

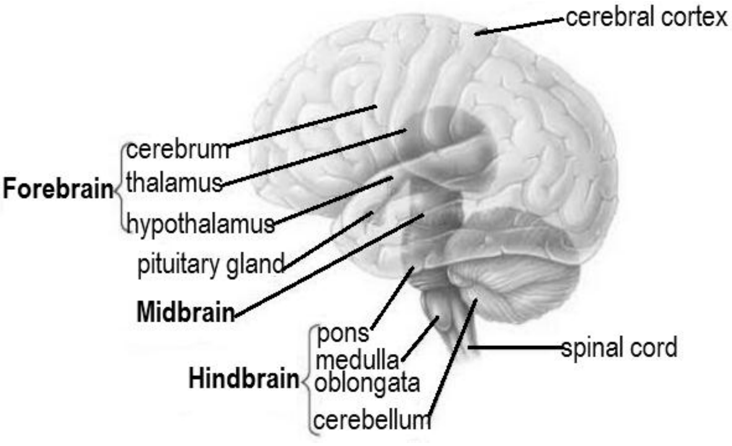
A**cetylcholine** diffuses across the synaptic cleft of neuromuscular junction to depolarize the sarcolemma and trigger an action potential that brings about contraction and relaxation of the muscle.

THE CENTRAL NERVOUS SYSTEM

This is made up of the brain and spinal cord and it coordinates all the neutral functions.

THE BRAIN

The brain is covered and protected externally by the skull (cranium) and internally by membranes called meninges. It is made up of three distinct areas namely the forebrain, midbrain and hindbrain.



Functions of the parts of the brain

1. **The fore brain**

It consists of:

i) The cerebrum (cerebral hemisphere):

It consists of right and left cerebral hemispheres which are interconnected by the corpus callosum. It is covered by a thin layer of cerebral cortex.

The right hemisphere sends and receives impulses from the left side of the body while the left hemisphere receives impulses from the right side of the body.

It coordinates learning, memory, reasoning, conscience and personality. It is responsible for intelligence.

ii) Thalamus: It transmits impulses of sensations received from sense organs to the cerebral cortex.

iii) Hypothalamus:

It controls activities of the pituitary gland.

It also coordinates and controls the autonomous nervous system.

2. **The mid brain**

It relays audio and visual information.

It is also responsible for movement of the head and the trunk.

3. **Hind brain:** It is made up of:

i) Cerebellum: It is responsible for balance and muscular coordination.

ii) Medulla oblongata: It controls heartbeat, blood pressure, breathing rate, coughing and sneezing.

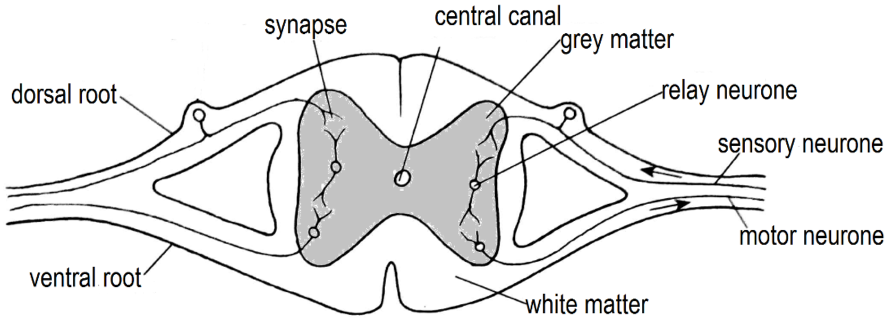
Functions of the brain

- It receives impulses from all receptors and sends back impulses to the effectors.
- It integrates and coordinates all activities in the body such that the body works efficiently.
- It stores information.
- It is involved in cranial reflex actions but it does not initiate them.

THE SPINAL CORD

This is part of the central nervous system that runs from the brain through to the tail and protected by the vertebral column.

Transverse section through the spinal cord



Functions of the spinal cord

- It connects the peripheral nervous system to the brain.
- It is a center for simple spinal reflex actions.
- Receives impulses from receptors.
- Interprets messages especially in reflex arc.
- Sends impulses to the effectors.

THE PERIPHERAL NERVOUS SYSTEM

It is made up of neurones that link the brain and spinal cord to muscles and organs such as the eyes and ears.

It is divided into autonomic nervous system and somatic nervous system. The autonomic nervous system is responsible for the ***involuntary*** control of internal organs, blood vessels, smooth muscles and cardiac muscles.

The somatic nervous system is responsible for the ***voluntary*** control of skin, bones, joints and skeletal muscles.

Voluntary and involuntary actions

A voluntary action *is one initiated consciously under the direct control of the brain i.e. they are actions one does at will e.g. dancing, laughing, stealing, etc.* These actions are performed consciously by an animal. In such actions the animal chooses to do or not to do something.

Involuntary actions *are the ones that occur without conscious thoughts e.g. breathing, etc.*

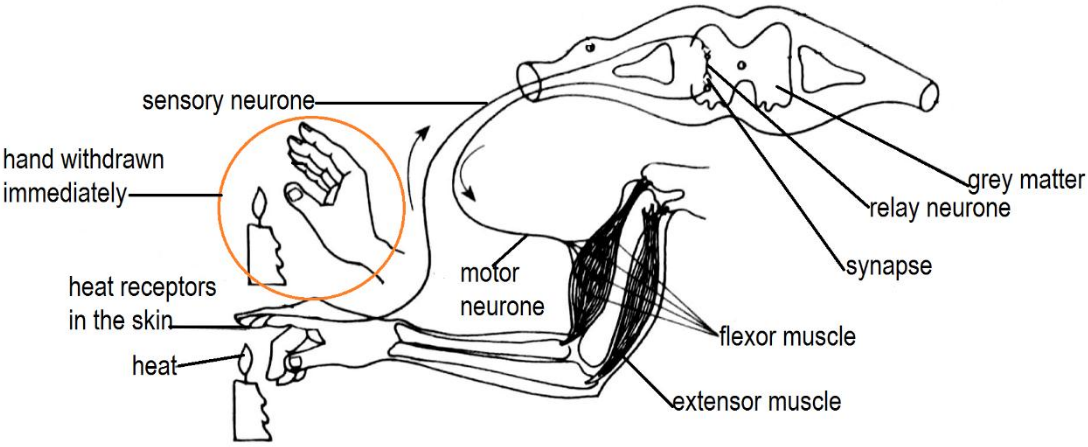
THE REFLEX ACTION

A reflex action is an automatic (involuntary) response to a particular stimuli. Reflex actions take place without the awareness of the individual. A reflex action occurs as a result of impulses travelling along neurons in a path called a ***reflex arc***. A reflex action can either be **simple** or **conditioned reflex**

Simple reflex action

This is an involuntary quick response to a stimulus without conscious thought. It is also known as an ***instinctive reflex*** which does not have to be learnt. They include sneezing, coughing, salivating, the knee jerk and removal of a hand from a hot flame. For instance, when one steps on a sharp object, the knee jerk enables the removal of the foot thus avoiding further injury.

Reflex arc of a hand being withdrawn from a hot flame



The stimulus is perceived by the receptors, which change it into nervous impulse (transduction). The impulse travels along the sensory neurone to the spinal cord. In the grey matter of the spinal cord, the sensory neurone makes synaptic connections to the relay neurone and impulses move from the sensory neurone to the relay neurone across synapses. The relay neurone in turn transmits the impulse to the motor neurone across a synapse. The impulse then moves from the spinal cord to the effector muscles through the motor neurone. The impulse causes the muscles to contract or relax depending on the stimulus.

Characteristics of a simple reflex action

- ✓ It occurs rapidly i.e. the action occurs very fast.
- ✓ It is inborn (innate) but not learnt.
- ✓ It is coordinated by either the brain or spinal cord but usually initiated by spinal cord.
- ✓ It occurs without one's will.
- ✓ It is a repeated response to a similar stimulus.
- ✓ Three neurons are involved.

Examples of simple reflex actions

1) Blinking when a foreign body falls on the eye.
2) Withdraw of the arm when someone accidentally touches a hot body.
3) Sneezing.
4) Knee jerk i.e. a relaxed leg gives a forward kick when tapped slightly below the patella.
5) With draw of the foot from a sharp object.

How a hand is withdrawn from a hot object (an example of a simple reflex action)

When one accidentally touches a hot body using a finger, the receptors in the finger receive the stimulus and change it into nervous impulses that travel along the sensory neurone to the spinal cord and then cross the synapse.

The impulse is then handed over to the relay neurone in the spinal cord (grey matter) and then cross another synapse.

The relay neurone in turn hands over the impulse to the motor neuron.

The motor neuron then carries the impulse from the spinal cord to the effector muscles of the hand. This causes the muscles to contract and the hand is removed from the hot body.

At the same time, the original message is sent to the brain which then interprets it as pain or heat.

Note; these processes occur rapidly in the body without the awareness of the individual

Importance of simple reflex actions to animals

- They help animals to avoid danger.
- They control activities in the body, which we do not have conscious control over.
- They form a basis of some animals' behaviour, e.g. amoeba.

Conditioned reflex action

This is the type of reflex action which involves learning. Organisms learn to respond to strange or meaningless stimuli by associating it with other meaningful/familiar stimuli, e.g. ***the Ivan Pavlov's experiment.***

A scientist called Ivan Pavlov performed an experiment to demonstrate a conditioned reflex action in a dog.

In his experiment he noticed that the sight or smell of food triggers off salivation reflex in a dog.

When Pavlov gave his dog food, the taste made the dog salivate. He later modified the experiment by ringing a bell each time he fed the dog. The two unrelated stimuli, that is sound and taste, were sensed simultaneously.

After several presentations of the two stimuli, he discovered that the dog salivated when the bell was rang even without the presentation of food. The dog had learned to associate the ringing of the bell to food, to a point whereby ringing the bell alone caused salivation.

Characteristics of a conditioned reflex action

- It is a temporary reflex
- It involves learning
- It is coordinated in the brain
- It involves more than one stimuli
- It involves association of stimuli
- It is reinforced by repetition
- Responses are involuntary

Similarities between simple and conditioned reflex actions

- They both involve the central nervous system particularly the brain.
- Both are autonomic responses
- Both are associated with a stimulus.
- Both involve neurons for the transmission of impulses

Differences between simple and conditioned reflexes

Conditioned reflex action	Simple reflex action
Stimulus and responses are not directly related	Stimulus and response are related
More than one stimulus is required to cause a response	Only one stimulus is needed to cause a response
It involves learning	No learning but in born
Takes time	Takes a very short time
It is coordinated in the brain only	Co-ordinated in either the brain or spinal cord
Responses occur as a result of repetition and practice.	Responses occur instantly after a stimulus.
Is an inborn, automatic response	Is a learned, automatic response
It is always constant	Can be reinforced through rewards or punishment.

Similarities between the nervous and endocrine system

- Both are affected by change in stimulus.
- Both cause a response.
- They provide a means of co-ordination in the body.
- Both systems transmit messages.

Differences:

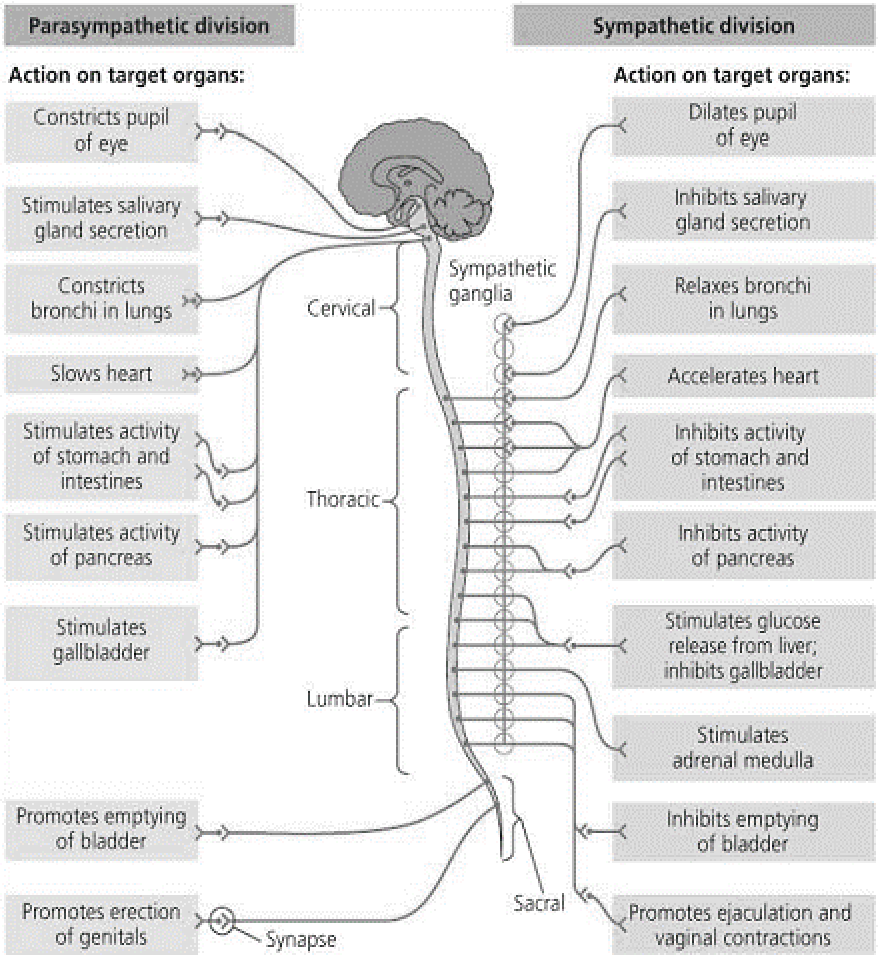
Nervous system	Endocrine system
Nerve impulses are electrical	Impulses are chemical
Responses are fast as the impulses are carried fast.	Responses are slow but long lasting.
Impulses go along nerve fibres.	Hormones are carried in blood.
This effect is more localized (specific).	Effect is wide spread in the whole body.
Stimulus arises from any part of the body where sensory receptors are located.	Stimulus arises from specific places only e.g. endocrine glands.

AUTONOMIC NERVOUS SYSTEM

This is subdivided into two parts all controlling involuntary activities. These are the sympathetic nervous system and parasympathetic nervous system.

Most pathways in each division consist of preganglionic neurons (having cell bodies in the CNS) and postganglionic neurons (having cell bodies in ganglia in the PNS).

The parasympathetic and sympathetic divisions of the autonomic nervous system



SENSE ORGANS (RECEPTOR ORGANS)

A receptor is a cell or tissue which can transform an impulse into action potential in neurones. It informs the CNS of external and internal changes.

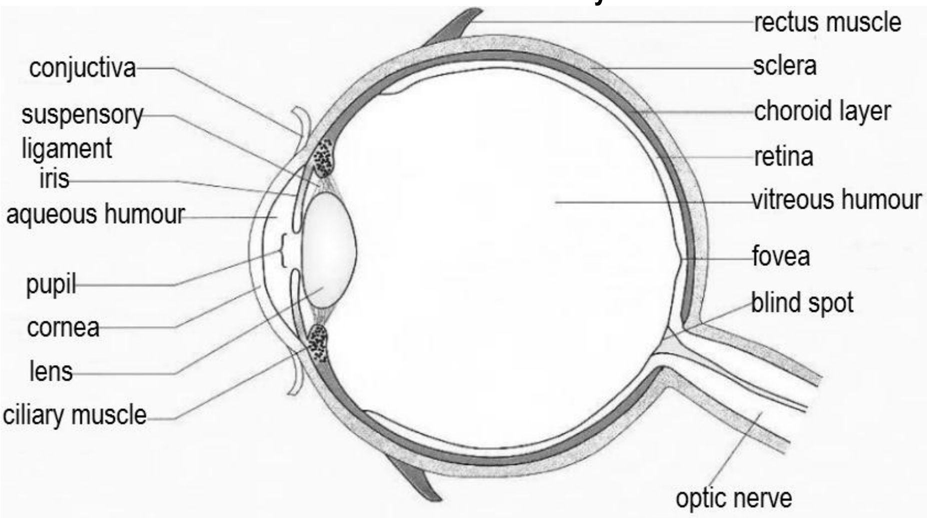
Characteristics (properties) of receptor cells

1) **Transduction**: Receptor cells are capable of changing physical stimuli into an electrical impulse.
2) **Sensitivity**: Receptor cells are able to detect the slightest change in their environment (stimulus).
3) **Adaptation:** If a stimulus is maintained, receptor cells are able to adapt to it so that the stimulus no longer causes an impulse, however strong it is. For example, the inability to hear a clock's ticking in a room after prolonged exposure to its ticking. Receptors however vary in the speed with which they become adapted, thus phasic receptors are those which adapt rapidly while tonic receptors are those which adapt slowly. Adaptation is advantageous in the following ways:
   - It provides animals with precise information about changes in the environment.
   - It enables the nervous system ignore unchanging environmental conditions and concentrate on monitoring those of survival value.
   - It prevents overloading of the nervous system with irrelevant information which reduces energy wastage.
4) **Inhibition:** Receptor cells can be stopped from firing impulses by special synaptic connections. As a result, certain impulses are transmitted only when required.
5) **Precision:** Receptors are able to transmit the information precisely without alteration.
6) Receptors are sensitive to low intensity stimulation. E.g. in some insects, tactile receptors can respond to airborne sounds when stimulated just 3.6 nm. In rod cells of human eyes, high sensitivity results from retinal convergence.
7) They are specialized in structure and position.

Therefore receptors have the following properties: *transforms energy to action potentials; Specialized in structure and function; Creates generator potentials; Has a threshold value of stimulation; Becomes adapted; Sensitive to low intensity stimulation*

THE HUMAN EYE

Structure of the human eye



The globe of the human eye, or eyeball, consists of the **sclera**, a tough white outer layer of connective tissue, and a thin, pigmented inner layer called the **choroid**. At the front of the eye, the sclera becomes the transparent **cornea** which lets light into the eye and acts as a fixed lens. Also at the front of the eye, the choroid forms the doughnut-shaped iris, which gives the eye it colour.

By changing size, the **iris** regulates the amount of light entering the pupil, the hole in the center of the iris. Just inside the choroid, the **retina** forms the innermost layer of the eyeball and contains layers of neurons and photoreceptors.

Functions of different parts

Sclera: It maintains the shape of the eyeball and protects the inner layer of the eye.

Conjunctiva: It is a thin and transparent layer over the cornea and is continuous with skin over the eye. It protects the cornea.

Choroid layer: It's a pigment layer present beneath the sclera and contains numerous blood vessels that nourish the retina. The pigmentation prevents unnecessary reflection within the eye.

Ciliary muscle: They are collected in the ciliary body and they are set of smooth muscles controlled by the autonomic nervous system.

They alter the shape of the lens. Their contraction results into the spherical shape of the lens and the relaxation results in the flattening of the lens.

Suspensory ligaments: These are thread-like ligaments that attach the ciliary body to lens hence holding the lens in position.

The aqueous humour:

- It is a solution of sugar, salts and proteins.
- The aqueous humor is a watery fluid which maintains the shape of the eye.
- It also refracts light into the pupil and the lens.

The vitreous humour:

- It is a jelly-like substance that fills the inner cavity of the eye.
- It is transparent and maintains the shape of the eye.
- It refracts light to the retina.

The ciliary body: This contains ciliary muscles, which control the size of the lens during viewing nearby or distant objects.

The lens.

- It is transparent and held by suspensory ligaments.
- It refracts light to make an image on the retina.

The iris

- This is made up of an opaque tissue the center of which is a hole called pupil that allows in light to form an image on the retina.
- The contraction of the muscles of the iris increases the size of the pupil and relaxation decreases the size of the pupil.
- It is therefore responsible for controlling the amount of light entering the eye.

The retina: This is a layer containing photoreceptor cells (light sensitive cells). It is where the image is formed in the eye.

The blind spot: This is a region where the nerve fibers leave the eye to enter the optic nerve. It has no light sensitive cells. When an image falls on this point, it is not taken to the brain thus blind spot.

The fovea: This is a small depression in the center of the retina. It has only cones in a high concentration. It is therefore a region on the retina that contains the largest number of sensory cells. Due to this, it produces the most accurate images in the eye.

Eye lids: These protect the eye and remove any foreign bodies that enter it. Regular blinking enables the spread of the fluid all over the exposed surface of the eye.
Eye lashes: They prevent dust particles and other objects from entering the eye.

Working of the eye

The camera and the eye work on the basic principles which include;

i) Control the amount of light entering the structure.
ii) Focuses the images of the external world by the lens system
iii) Registering images on sensitive surface
iv) Processing a captured image to produce a pattern which can be seen.

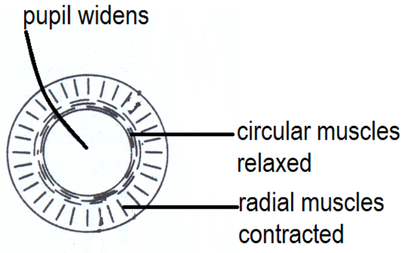
All the working principles of the eye and the camera are the same only that the lens of the human eye does not move forward or backward like that of the camera but it adjusts the distance of focus by undergoing changing of its shape.

Control of light amount entering the eye

The iris controls the amount of light entering the eye. It is made up of circular and radial muscles. This is done to protect the retina from damage by bright light and the wide size of the pupil during dim light allows in enough light of low intensity.

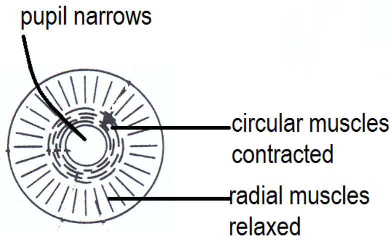
Control of amount of light entering the eye in dim light

- In dim light, radial muscles contract,
- Circular muscles relax,
- Pupil widens and more light is admitted into the eye.



Control of amount of light entering the eye in bright light

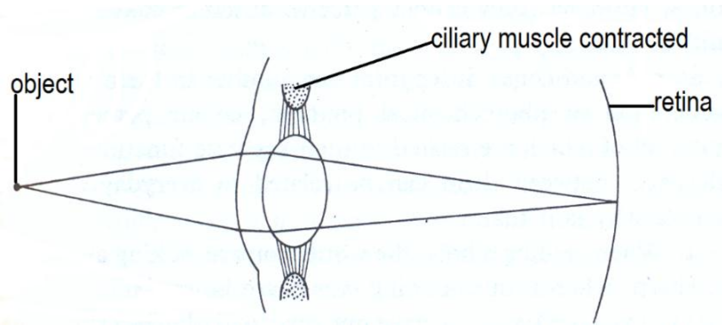
- Circular muscles of the iris contract,
- Radial muscles relax,
- Pupil becomes smaller and narrower hence less light is admitted into the eye.



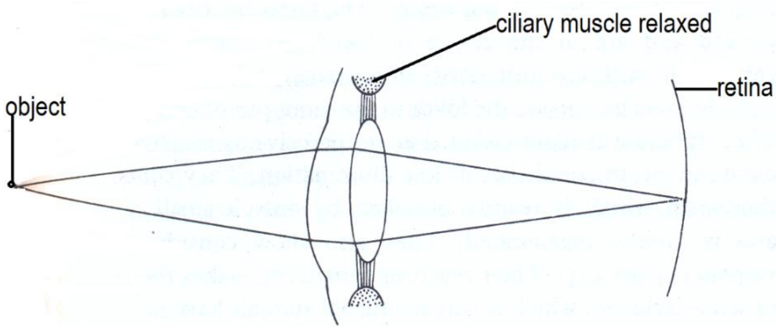
Accommodation of the eye

Accommodation is the ability of the eye to change the focal length of the lens when viewing distant or nearby objects.

Accommodation for a nearby object:
When looking at a nearby object, the ciliary muscles in the ciliary body contract, the suspensory ligaments slacken. This makes the lens short and thick. This increases the ability of the lens to refract light and reduces the focal length of the lens for the nearby object to be seen clearly.



Accommodation for a distant object:
When viewing a distant object, the ciliary muscles in the ciliary body relax. This causes tension in the suspensory ligaments. The suspensory ligaments pull the lens apart making the lens thin and long. This makes the lens to refract less and increase the focal length of the lens.



Summary of accommodation

Nearby object	Distant object
Diverging light rays from a nearby object are refracted by cornea.	Parallel light rays from a distant object are refracted by the cornea.
Ciliary muscles in the ciliary body contract.	Ciliary muscles in the ciliary body relax.
Suspensory ligament slacken.	Suspensory ligaments develop tension.
The lens become short and thick.	The lens becomes thin and long.
The focal length of the lens decreases	The focal length of the lens increases.
Light rays are refracted to the retina.	Light rays are refracted to the retina.

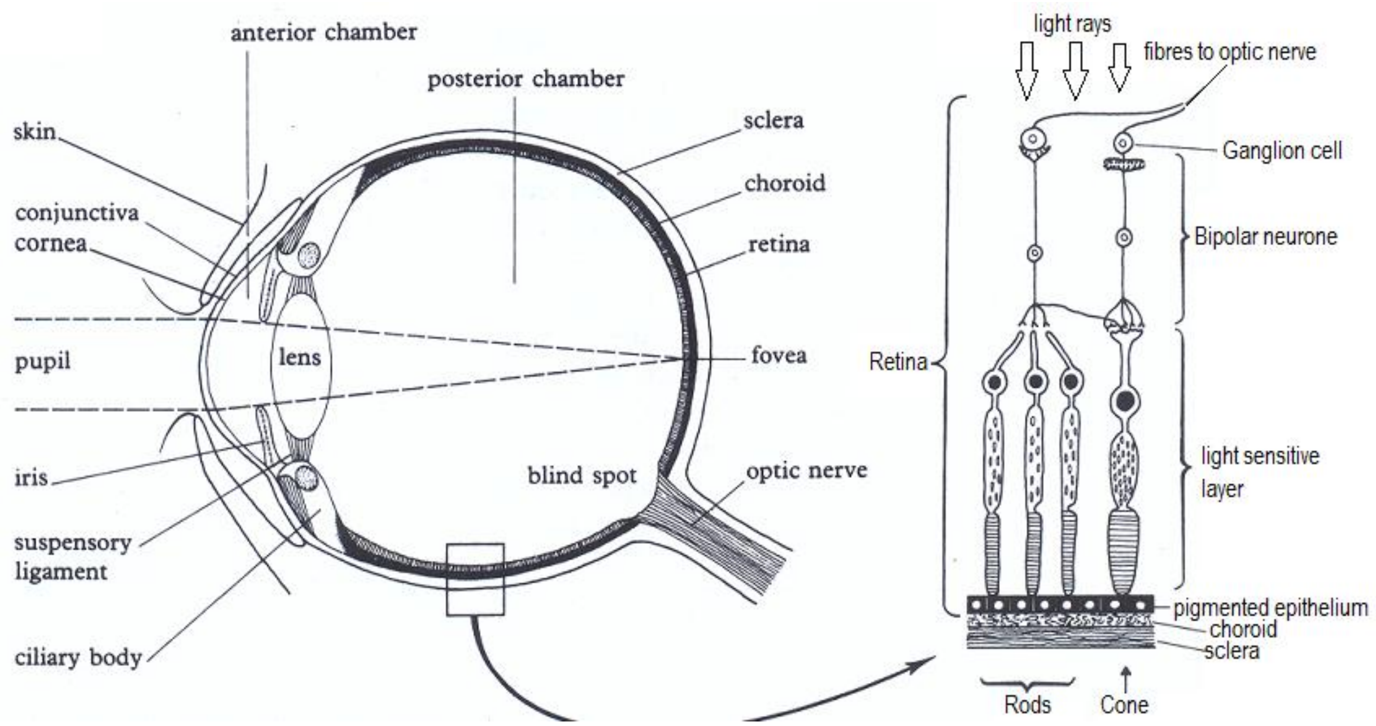
THE RETINA

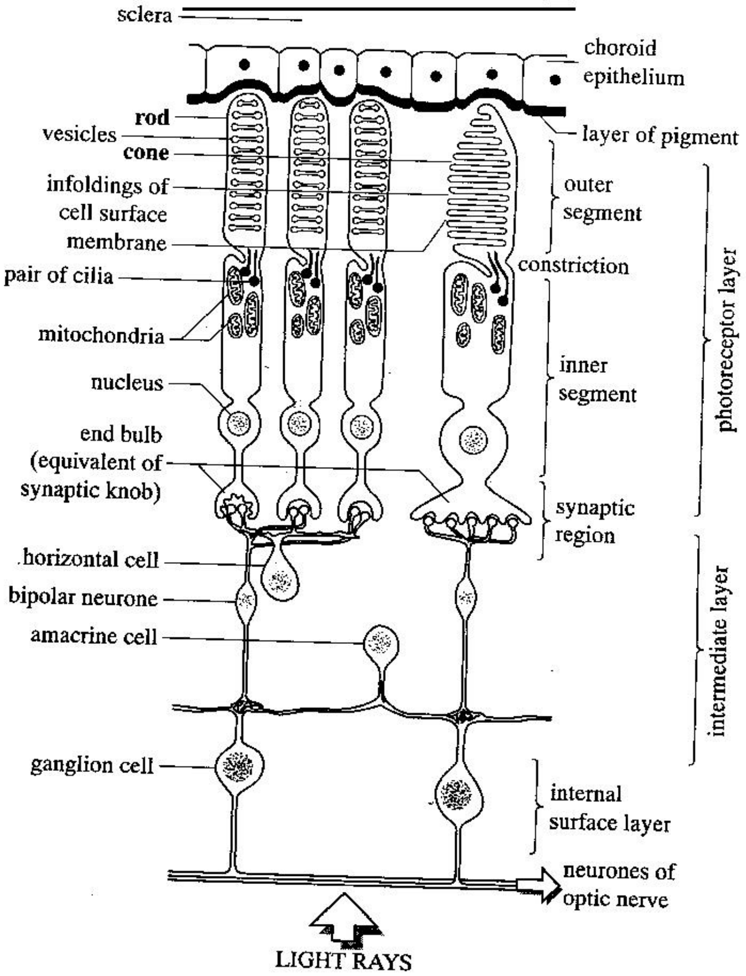
The human retina contains **rods** and **cones,** two types of photoreceptors that differ in shape and in function.
Rods are more sensitive to light but do not distinguish colours; they enable us to see at night, but only in black and white.
Cones provide colour vision, but, being less sensitive, contribute very little to night vision. There are 3 types of cones. Each has a different sensitivity across the visible spectrum, proving an optimal response to red, green, or blue light.
The relative numbers of rods and cones in the retina varies among different animals, correlating to some degree with the extent to which an animal is active at night.
The distribution of rods and cones varies across the human retina. Overall, the human retina contains about 125 million rods and about 6 million cones.
The fovea, the centre of the visual field, has no rods, but has a very high density of cones – about 150,000 cones per square millimeter. The ratio of rods to cones increases with distance from the fovea, with the peripheral regions having only rods. In day light, you achieve your sharpest vision by looking directly at an object, such light shines on the tightly packed cones in your fovea. At night, looking directly at a dimly lit object is ineffective, since the rods-the more sensitive light receptors are found outside the fovea. Thus, for example, you see a dim star best by focusing on a point just to one side of it.

Structure of the human retina

The retina is composed of 3 layers of cells containing a characteristic type of cells, i.e.

i) **Photoreceptor layer (outermost layer):** This contains the photosensitive cells, the rods and cones partially embedded in the microvilli of pigment epithelium cells of the choroid.
ii) **Intermediate layer:** This contains bipolar neuron with synapses connecting the photoreceptor layer to the third layer. Horizontal and Amacrine cells are found in this layer and enable lateral inhibition to occur.
iii) **Inter surface layer:** This contains ganglion cells with dendrites in contact with bipolar neuron and axons of the optic nerves.





Horizontal cells and ***amacrine cells*** function in neural pathways that integrate visual information before it is sent to the brain.

Signals from rods and cones can follow several different pathways in the retina. Some information passes directly from photoreceptors to bipolar cells to ganglion cells. In other cases, horizontal cells carry signals from one rod or cone to other photoreceptors and to several bipolar cells. When an illuminated rod or cone stimulates a horizontal cell, the horizontal cell inhibits more distant photoreceptors and bipolar cells that are not illuminated. The result is that the light spot appears lighter and the dark surroundings even darker. This form of integration, called ***lateral inhibition****, sharpens edges and enhances contrast in the image. Amacrine cells distribute some information from one bipolar cell to several ganglion cells. Lateral inhibition is repeated by the interactions of the amacrine cells with the ganglion cells and occurs at all levels of visual processing in the brain.*

A single ganglion cell receives information from an array of rods and cones, each of which responds to light coming from a particular location. Together, the rods or cones that feed information to one ganglion cell define a receptive field-the part of the visual field to which the ganglion can respond. The fewer rods or cones that supply a single ganglion cell, the smaller the receptive field. A smaller receptive field results in a sharper image, because the information as to where light struck the retina is more precise. The ganglion cells of the fovea have very small receptive fields, so visual acuity (sharpness) in the fovea is high.

The structure and composition of cones and rods

Rods and cones have an essentially similar structure and their photosensitive pigments are attached to the outer surface of the membrane in the outer segment. They have four similar regions where structure and function are shown below;

i) Outer segment:

This is the photosensitive region where light energy is converted into a generator potential. The entire outer segment is composed of flattened membranous vesicles containing the photosensitive pigments.

ii) Constriction:

The outer segment is almost separated from the inner segment by an in folding of the outer membrane. The two regions remain in contact by cytoplasm and pair of cilia which pass between the two.

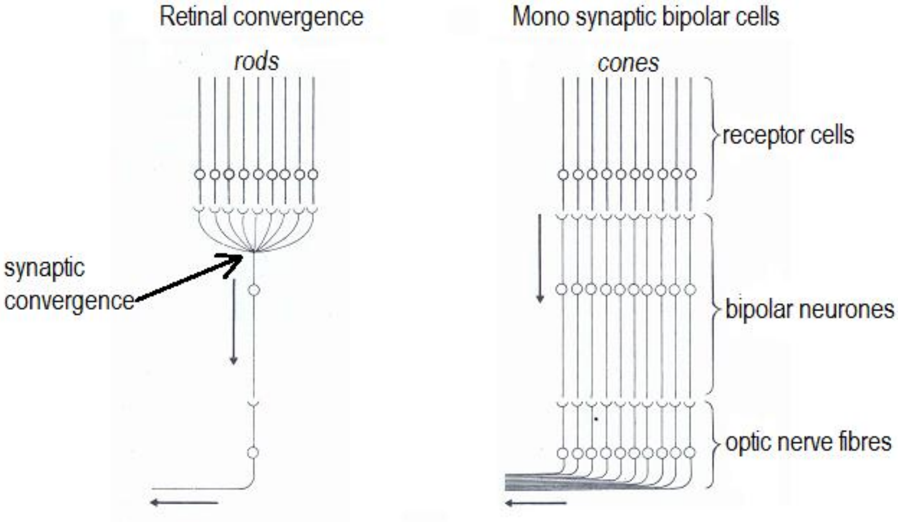
iii) Internal/inner segment:

This is an actively metabolic region. It's packed with mitochondria producing energy for visual processes and polysomes for synthesis of proteins involved in the production of membranous vesicles and visual pigments. The nucleus is located in this region.

iv) Synaptic region:

Here the cells form synapses with bipolar cells. Different bipolar cells may have synapses with several rods; this is called **synaptic convergence** and it increases visual sensitivity.

Mono synaptic bipolar cells link one cone to one ganglion cell and this gives the cone greater visual acuity than the rods.

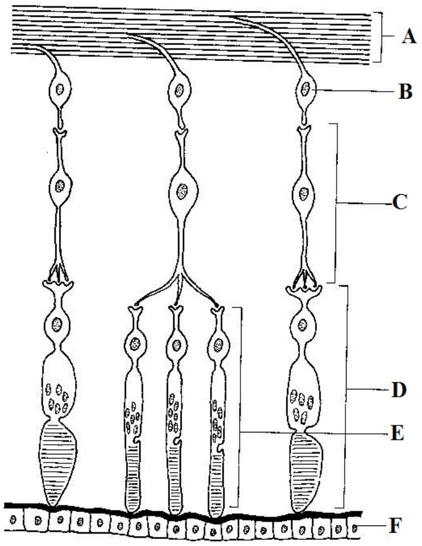


The high visual acuity in the cones is also because they are highly packed at fovea with direct connection to the optical nerves.

Visual acuity is the amount of detail that can be seen (image sharpness). Although there are far more rods than cones, we use cones most of the time because they have fine discrimination and can resolve colours. This is because one cone cell synapses to one bipolar cell which in turn synapses onto one ganglion cell as the information is relayed to the visual cortex. The more densely-packed the cone cells, the better the visual acuity. In the fovea of human eyes there are 160 000 cones per mm^2, while hawks have 1 million cones per mm^2, so they really do have far better acuity.

Differences between rods and cones

Rods	Cones
Photochemical pigment is readily regenerated when bleached.	Pigment take long to be regenerated once bleached.
Poor colour vision	High ability of recognizing colours.
Have retinal convergence.	Lack retinal convergence.
The photosensitive pigment is rhodopsin.	The photosensitive pigment is iodopsin.
Outer segment is rod shaped	Outer segment is cone shaped
Greater numbers (about 10^9 cells per eye)	Fewer numbers (about 10^6 cells per eye).
Distributed more at the periphery of the retina (absent at fovea), so used for peripheral vision.	Concentrated in the fovea, so can only detect images in centre of retina.
Sensitive to low light intensity – can detect a single photon of light, so are used for night vision.	Not sensitive to low light intensity – need bright light, so only work in the day.
Only 1 type, so only give monochromatic vision.	3 types (red green and blue), so are responsible for colour vision.
Many rods usually connected to one bipolar cell, so poor acuity (i.e. rods are not good at resolving fine detail).	Each cone usually connected to one bipolar cell, so good acuity (i.e. cones are used for resolving fine detail such as reading).



WORKED OUT EXAMINATION QUESTIONS

(a) (i) Name the structures labelled A to F

A – Optic nerve fibres; B - ganglion cell; C – bipolar neurone;

D – cone cell; E – rod cell; F – choroid epithelium / layer [pigment epithelium / layer] ;

(b) What is the significance of the fact that:

(i) Several cells of type labelled E connect to one cell in layer C?

Retinal convergence increases the eye's sensitivity. Light which activates one rod cell (cell E) may be insufficient to generate an action potential in the bipolar neuron (cell C) connected to it yet several rods when hit by light simultaneously may activate action potential the bipolar neuron (cell C) due to summation of generator potentials. Impulse propagation to the CNS results in image formation.

(ii) One cell of type labeled D connects to one cell in layer C?

It improves visual acuity / precision / resolving power of the eye because light from two objects close together stimulate two cones (cell D), the brain receives two impulses and interprets this as two separate objects rather than when different impulses summate into a single message received by the brain]

MECHANISM OF PHOTORECEPTION

Light reception in the rods

Each rod or cone in the vertebrate retina contains visual pigments that consist of a light absorbing molecule called **retinal** (a derivative of vitamin A) bound to a membrane protein called an **opsin.** The opsin present in rods, when combined with retinal, makes up the visual pigment **rhodopsin.**

Absorption of light by rhodopsin shifts one bond in a retinal from a *cis* to a *trans* arrangement, converting the molecule from an angled shape to a straight shape.

This change in configuration destabilizes and activates rhodopsin. Because it changes the color of rhodopsin from purple to yellow, light activation of rhodopsin is called "bleaching."

When this potential difference is large enough, it results into an impulse being generated into an optic nerve leading to the brain.

Rhodopsin returns to its inactive state when enzymes convert retinal back to the *cis* form for it to be stimulated again (dark adaptation). In very bright light, however, rhodopsin remains bleached, and the response in the rods becomes saturated. If the amount of light entering eyes decreases abruptly, the bleached rods do not regain full responsiveness for some time. This is why you are temporarily blinded if you pass abruptly from the bright sunshine into a dark place.

Rods are more sensitive than the cones because:

i) Their pigment is readily broken down and regenerate faster than that of the cones. That's why they are mostly used for vision during conditions of low illumination or darkness.

ii) They show retinal convergence where separate rods add up or summate to build a generator potential upto a threshold.

Qn. How is a rod cell suited for photoreception?

Qn. How are rod cells suited for photoreception?

WORKED OUT EXAMINATION QUESTIONS

1) Suggest why convergence of rod cells in the retina of human eyes reduces the ability to read small print in dim light.

Light falling on groups of rods is transduced into an impulse in only one receptor neurone so the power of resolution is low

2) Suggest a chemical explanation of convergence

Only when many synaptic knobs release their neural transmitter simultaneously does its concentration reach a threshold at which depolarization of the post-synaptic membrane occurs.

3) Why should pilots waiting to fly at night not be exposed to bright lights?

Even a short exposure to bright light would cause the rhodopsin in the rods to break down so destroying the pilot's night vision.

4) Many nocturnal mammals like cats have a reflective layer – the tapetum lining the back of the eye rather than a pigmented layer. Suggest the value of this arrangement

Light will be reflected back off the tapetum so that it passes twice through the light-sensitive cells, thereby increasing the size of the generator potential developed in the cells

5) Explain why when sitting in a dimly lit room, objects often appear slightly fuzzy and colours are more difficult to distinguish.

Seeing objects using rod cells leads to lower visual acuity; rod cells are insensitive to colour

6) Explain why brightly coloured objects often appear grey in dim light

Only rods are stimulated by low-intensity (dim) light. Rods cannot distinguish between wavelengths / colours of light, therefore the object is perceived only in a mixture of black and white i.e. grey.

7) At night, it is easier to see a star in the sky by looking slightly to the side of it rather than directly at it. Suggest why this is so.

Light reaching the earth from a star is of low intensity. Looking directly at a star focuses light on to the fovea, where there are only cone cells. Cone cells respond only to bright light, so they are not stimulated by dim light from the star and it cannot be seen. Looking to one side of the star ensures that light from the star is focused to the periphery of the retina, where there are mostly rod cells. These are stimulated by low light intensity and therefore the star is seen.

8) What is the role of:

i) Horizontal cells? They cause lateral inhibition which increases sensitivity and visual acuity i.e. they inhibit (cancel out) equal intensity stimuli if received from two adjacent rods thereby increasing contrast between weakly stimulated and strongly stimulated areas. E.g. edges of objects stand out more clearly.

ii) Amacrine cells? After partial processing, they transmit information about changes in the level of illumination

9) **Explain the following phenomena:**

a) When a person moves from bright sunlight into a dimly-lit room; objects in the room cannot at first be seen but they gradually become visible.

In bright light, the circular muscles contract to narrow the pupil; and reduce on over-stimulation of the retinal cells by entry of light into the eye. In dim light, radial muscles contract to dilate the pupil slowly to allow entry of light; whose threshold at first is low to stimulate the rods for objects to be seen; but later improves to enable vision as the pupil dilates fully;

b) In the dimly-lit room, objects are only visible in black and white.

Rods which are sensitive to light of low intensity do not respond to light of various wavelengths; causing images to appear black and white;

c) Some nocturnal animals like cats close their pupils to a vertical slit and also squint in bright light

The retina of nocturnal animals is almost entirely composed of rods; with rhodopsin which is particularly sensitive to low levels of light and breaks down so rapidly in bright light; The slit pupil and squinted eyes reduce the amount of light entering the eye to enable rhodopsin form faster than it breaks down for vision to occur;

d) When trying to see a faint star in the sky, it is better to look slightly to one side of it rather than directly at it.

When you look directly at an object, its image forms on the retina's *Fovea centralis* (yellow spot) which is packed with cone cells yet these are only activated by bright light, hence can't see in dim light. Looking slightly away from a faint star moves the image off the fovea and onto parts of the retina that have more rod cells, which are more light-sensitive than the cones.

e) If both your eyes are open and you press the side of one of your eyeballs, you see double.

Pressing of eye ball distorts the eye position such that the two eyes are unable to look directly at an object in the same direction, hence the brain fails to blend together the images from the two eyes, causing double vision to be perceived

Colour perception in the cones

There are three different kinds of cone cell, each with a different form of opsin (they have the same retinal). These three forms of iodopsin are sensitive to different parts of the spectrum, so there are red cones (10%), green cones (45%) and blue cones (45%).

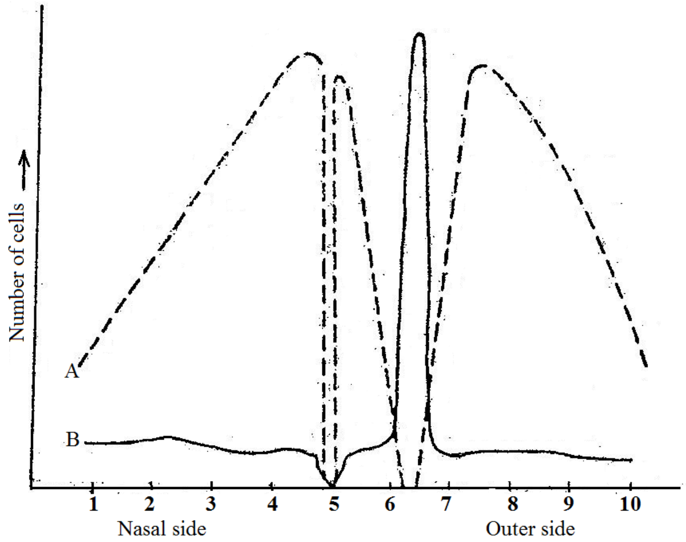
Trichromatic theory of colour vision:

It suggests that different colours are produced by the degree of stimulation of the different types of cone.

When viewing an object, the three types of cone are stimulated to various degrees depending on the wavelength of light the object reflects. By comparing the nerve impulses from the three kinds of cone, the brain can interpret any colour. For example, when the red/blue/green receptors are stimulated in the ratio of 10:86:15, the color of an object is interpreted by the brain to be blue. When the ratio is 13:14:86, the color is interpreted as green, and when it is 100:20:99 the color is yellow.

Question:

The figure below shows the number of receptor cells (types A and B) in the human retina along a horizontal line from the nasal side of the eye to the outer side. Distances are expressed in arbitrary units.



The table below shows the absorption of different wavelengths of light by three varieties of the light sensitive pigment **iodopsin** as suggested by the trichromatic theory of colour vision in man.

Light wavelength (nm)	Amount of light absorbed as a percentage of maximum		
	Red iodopsin	***Green iodopsin***	***Blue iodopsin***
660	5	0	0
600	75	15	0
570	100	15	0
550	85	85	0
530	60	100	10
500	35	75	30
460	0	20	75
430	0	0	100
400	0	0	30

a) From the graph;

i) With a reason in each case, identify the types of receptor cells represented by letters A and B

ii) Explain why there are no receptor cells at position 5

iii) What is the name of the region of the retina at position 6?

iv) Explain how position 6 is suited for functioning

b) From the table;

i) Plot a suitable graph to represent the data.

ii) Using the data in the table, comment on perception of the wavelength of light as colour.

c) From your knowledge of the retina explain why small objects close together can be more easily distinguished by cones than by rods.

Colour blindness

It is the inability to distinguish between colours. Red-green colour blindness is the commonest, although other forms of colour blindness are also possible, but are much rarer.

The red, green and blue opsin proteins are made by three different genes. The green and red genes are on the X chromosome, which means that males have only one copy of these genes (i.e. they're haploid for these genes). About 8% of males have a defect in one or other of these genes, leading to red-green colour blindness.

Binocular vision

Binocular vision occurs when the visual fields of both eyes overlap so that the fovea of both eyes are focused on the same object. It has several advantages over monocular vision and these include;

- Larger visual fields.
- Damage to one eye is compesated for by the other e.g. it cancels the effect of the blind spot and provides the basis of stereoscopic vision.

Stereosccopic vision depends upon the eyes simultaneously producing slight different retinal images which the brain resolve as one image.

Binocular and stereoscopic vision enables predator animals e.g. hawks and lions to accurately judge the distance to catch prey. Their eyes are set in front.

The animals with eyes on the sides of their head e.g. a rabbit (a common prey) rely on:

- The relative size of an object.
- The shadow it creates.
- The movement of it relative to distant non-moving objects, to judge distance because they have poor stereoscopic vision due to little overlapping of visual field results.

However, they have wide overall visual field, which is good for detecting movements.

Eye defects

An eye defect is a condition where the eye fails to focus an object well unless aided by external lenses. The common eye defects include:

Myopia results from eyeball being too long, so that the image is brought to a focus in front of the retina; this is corrected by a concave lens.

Hyperopia results from eyeball being too short, so that the image is brought to a focus behind the retina; this is corrected by a convex lens.

Astigmatism is the condition in which asymmetry of the cornea and or lens causes uneven refraction of light around 360 degrees of a circle, resulting in an image that is not sharply focused on the retina.

COMPOUND EYE

Arthropods have compound eyes and some have simple eyes.

Simple eyes consist of a single lens able to distinguish between light and dark, unable to produce an image.

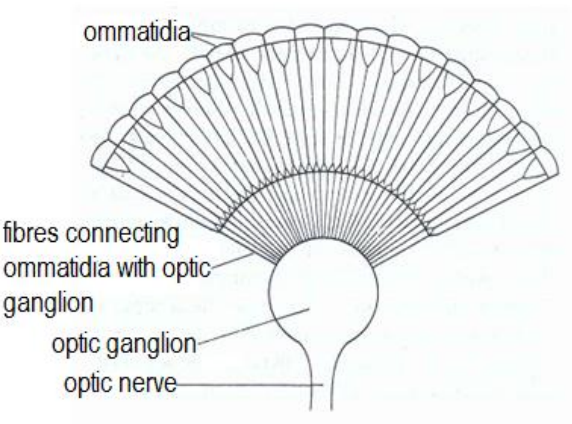
A compound eye consists of up to thousand light detectors called ommatidia, each with its own light focusing lens. Each ommatidium detects light from a tiny portion of the visual field.

A compound eye is very effective at detecting movement, an important adaptation for flying insects and small animals constantly threatened with predation.

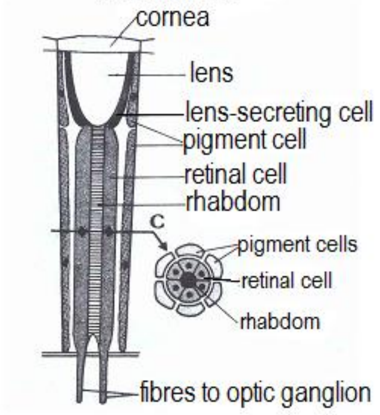
Whereas the human eye can only distinguish about 50 flashes of light per second, the compound eyes of some insects can detect flickering at a rate six times faster. If they slipped into a movie theatre, these insects could easily resolve each frame of the film being projected as a separate still image- this is termed as flicker fusion.

Insects have an excellent colour vision, and some (including bees) can see into the ultra-violet (UV) range of the electromagnetic spectrum. Because UV light is invisible to us, we miss seeing differences in the environment that bees and other insects detect.

Structure of the compound eye



Longitudinal section through an ommatidium



Note: C - *shows the cross section through ommatidium*

Functions of the parts

The ***lens*** converges light rays onto the tip of the rhabdom.

The ***pigment cells*** regulates the amount of light reaching the retinal cells. They also separate the ommatidium from its neighbor.

The ***rhabdom*** is the light sensitive part of the ommatidium where photochemical stimulation occurs leading to depolarization of the membrane of the retinal cells.

The ommatidia would serve the same function as the rods and cones of the vertebrate eye but they are much larger and this brings about the reduced visual acuity in arthropods.

Differences between compound eye and mammalian eye

Compound eye	Mammalian eye
No rods and cones.	Rods and cones are present.
Consists of many repeated units able to function on their own - ommatidia.	The whole eye functions as a single unit.
Lens is crystalline and very elastic.	Lens is membranous and elastic.
Has a rhabdom.	No rhabdom.
No muscles attached to it i.e. it's immovable.	Has muscles attached to it and is very movable.
Has no eye lids and isn't protected at all.	Has eyelids for external protection.
Has a fixed focus (no accommodation).	Has adjustable focus (accommodation is possible).
Overlap image is greater.	Overlap image is small.
Detect light parallel to its longitudinal access.	Detects light reaching it at all angles.
Has poor resolving ability and poor visual acuity.	Good resolving ability and greater visual acuity.
Shows near sightedness.	Can see both near and far objects.

Similarities:

- Both contain pigmented cells.
- Both have the cornea.
- Both possess convex lens.
- Both have nerve fibres to the brain.
- There is overlap of image in both.

Question:

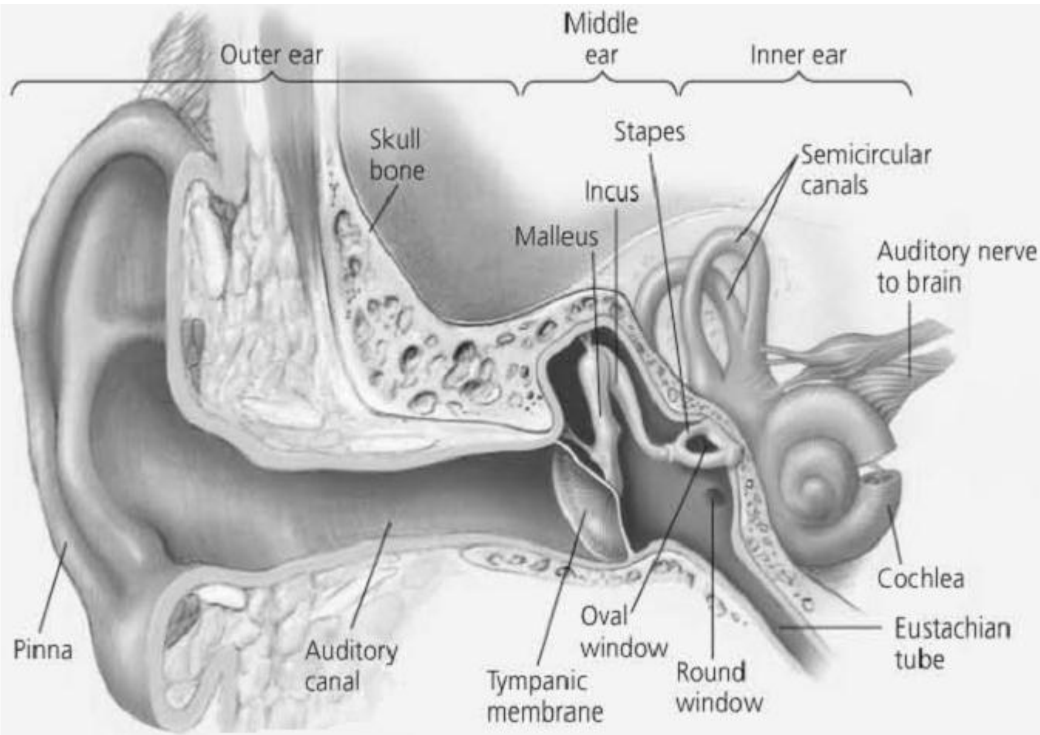
Why do insects generally have very low visual acuity compared with the vertebrates?
How have insects overcome the above problem?

THE MAMMALIAN EAR

The ear has **mechanoreceptors** (receptors that detect physical transformation) associated with sound, gravity and displacement. The ear performs three basic functions i.e. detection of:

1) Sound (hearing)
2) Head movements
3) Changes in gravity (balance or posture)

Structure of the ear



The ear is made up of three areas i.e. the outer ear, middle ear and inner ear.

1. **The outer ear:** This is the tube opening to the side of the head and inwards stopping at the eardrum. It consists of the pinna, auditory canal and the ear drum.

The outer projecting portion of the outer ear is known as the ***pinna (auricle)***. Its function is to receive and concentrate sound waves.

The ***auditory canal*** has hairs and wax that trap foreign bodies. It transmits sound waves to the eardrum (tympanum).

The ***ear drum*** is a thin membrane. The eardrum transmits sound waves to the middle ear.

2. **The middle ear:**

This is a cavity in the skull filled with air. It is comprised of three small bones called ***ossicles**, i.e. **hammer (malleus)**, **anvil (incus)** and **stapes (stirrup)***. They transmit sound vibrations from the eardrum to the ***oval window (fenestra ovalis)** that* transmits sound vibrations to the inner ear.

It communicates with the mouth cavity through the ***Eustachian tube*** (a slender canal that connects the middle ear to the pharynx). It equalizes the air pressure on the two sides of the eardrum.

3. **The inner ear:**

The inner ear is filled with a fluid and consists of mainly a coiled tube known as the cochlea. The cochlea has sensory ***auditory nerve*** that transmits impulses to the brain.

The ***semi-circular canals***, ***utriculus*** and ***sacculus*** form the ***vestibular apparatus***, which controls body balance and orientation.

The ***round window (fenestra rotunda)*** equalizes pressure in the cochlea.

The process of hearing in mammals

The pinna receives and concentrates the sound waves.

They are transmitted to the eardrum, which vibrates.

The vibrations of the eardrum are transmitted to the ossicles that vibrate and transmit the vibrations to the oval window at the entrance of the **vestibular canal** of the cochlea.

The **perilymph** (fluid in the vestibular canal) vibrates and causes **Reissner's membrane** to be displaced.

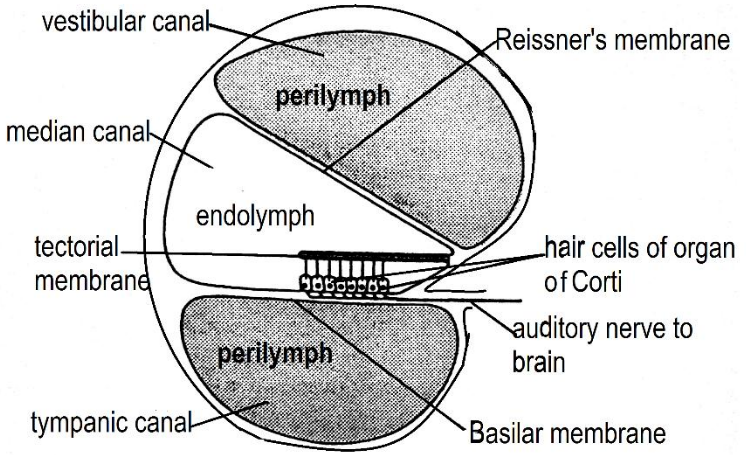
The displacement of Reissner's membrane causes the **endolymph** in the **median canal** to vibrate, which in turn causes the **basilar membrane** to vibrate.

The vibration of the basilar membrane stimulates sensory cells (in the **organ of Corti**), which generate impulses.

The impulses are transmitted by the auditory nerve to the brain, which interprets them into sounds.

The vibrations of the basilar membrane disturb the perilymph in the **tympanic canal**. The round window takes up these vibrations.

Transverse section of the cochlea



Qn: Explain why even though the head is not moved, the direction from which a sound comes may be determined?

Deafness

Deafness is the inability to hear. It may be brought about by a defect in the nerves or the conduction of waves.

Causes of deafness

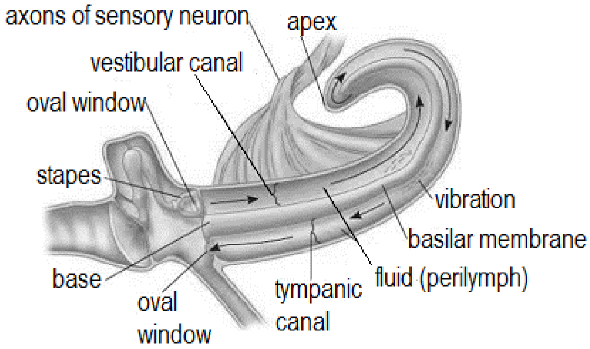
1) ***Accumulation and hardening of wax in the outer auditory canal*** that presses against the eardrum. This can be controlled by use of cotton buds to remove excess wax after the wax has been softened using warm water.
2) ***Blocking of the Eustachian tube*** as a result of accidents and certain infections such as the common cold, etc. This can be treated by use of antibiotics to kill the bacteria that caused the infection.
3) Some individuals are born with ***thick eardrums*** that do not easily vibrate. This can be solved by use of hearing aids.
4) ***Ruptured eardrum*** due to accidents and infections. Sometimes the eardrums heal on their own or a hearing aid can also be used.

5) Damage to the cochlea as a result of ***exposure to loud noise over a long period of time***. This can be prevented by keeping sound volume low because once the cells of organ of Corti in the cochlea are damaged, they cannot be repaired.
6) ***Fused ossicles*** due to infections that cause inflammation in the middle ear. Some individuals are born with fused ossicles. The ossicles do not hit each other when they vibrate. This can be treated by medication to kill the microorganisms that caused the infection or surgical operation to replace the ossicles.
7) ***Damage to the hearing centre of the brain*** also causes deafness.

Worked out question:

What prevents pressure waves from reverberating within the ear and causing prolonged sensation?

Once pressure waves travel through the vestibular canal, they pass around the apex (tip) of the cochlea. The waves then continue through the tympanic canal, dissipating as they strike the round window. This damping of sound waves resets the apparatus for the next vibrations that arrive.



Discrimination of sound intensity

The human brain is able to discriminate the sound quality in terms of pitch and intensity.

The pitch of sound (frequency) depends on its wave length.

High tones are as a result of sound of high frequency (short wave length) while low tones are as a result of sound of low frequency (long wave length).

The basilar membrane is about 2-5 times wider at the apex than at its base between the oval and round window. Sound of short wave length (high frequency) vibrates relatively a short portion of basilar membrane. Only the hair cells nearest the oval window will be stimulated. The impulses fired from these few cells and arriving at the brain are interpreted as a high pitched sound.

On the other hand, sound of a longer wave length (low frequency) causes a larger portion of the basilar membrane to vibrate, therefore the sensory hair cells that are stimulated further along this membrane are stimulated. The impulses fired from these cells when they reach the brain are interpreted as sound of low pitch.

In this way, the brain is therefore able to determine the pitch of each sound according to the source of impulse from the cochlea.

The role of the semi-circular canals and utriculus and sacculus in maintaining body balance

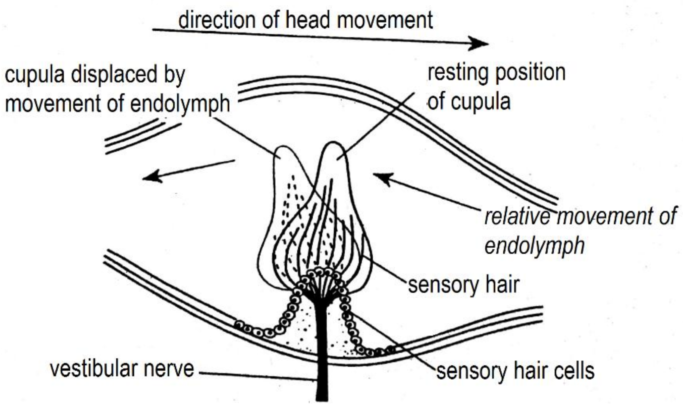
i) Semi-circular canals:

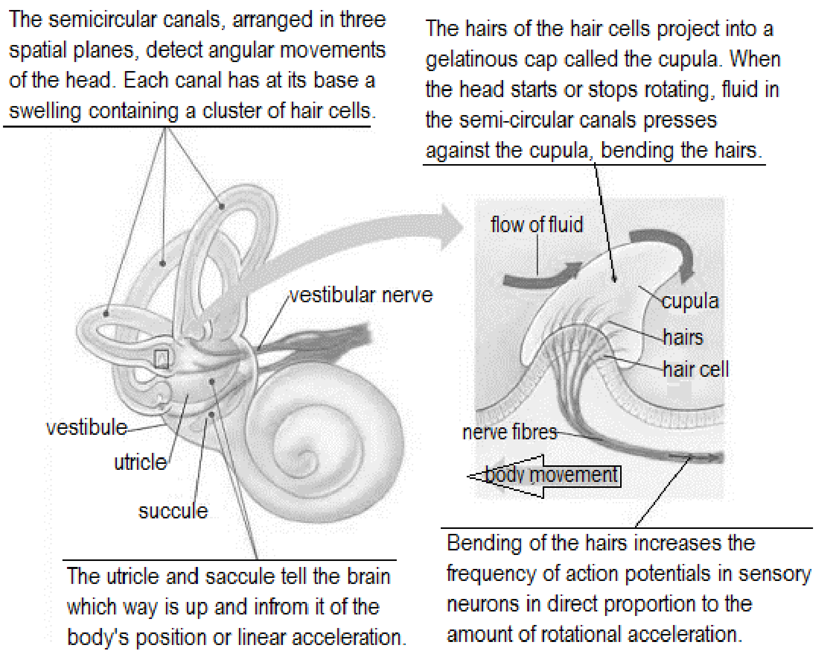
The semi-circular canals are important in in dynamic equilibrium. Each semi-circular canal terminates in a swelling known as the **ampulla**, which contains the **cupula** (dome-shaped, gelatinous structure). The cupula is in contact with sensory hairs.

The canals are filled with fluid and are three in number, arranged in three planes; vertical canals detect movement in upward direction, horizontal canals detect backward and forward motion while lateral canals detect sidewise movements of the head.

When the head moves, the endolymph in the ampulla of one of the canals moves in the opposite direction and deflects the cupula. This stimulates the **cristae** (sensory cells), which generate impulses. The impulses are transmitted by the **vestibular neurones** to the brain.

The pattern of impulses is interpreted by the brain which detects the direction and speed of movement and sends instructions to relevant organs that maintain dynamic balance.





ii) Utriculus and sacculus:

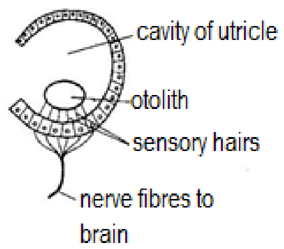
The utriculus and sacculus contain structures called **maculae** which maintain body posture (static equilibrium).

Each macula consists of a patch of sensory cells with the free ends embedded in the **otolith** (gelatinous granule of calcium carbonate). The otolith detects the position of the head with respect to the force of gravity. By varying the position of the head, the pull of gravity over the hairs on the otolith tilts them accordingly.

The different influences of the pull of gravity result in a pattern of impulses to the brain.

The impulses are interpreted thus providing information about the position of the head and accordingly sends instructions to relevant muscles to restore balance. When the head is upright, the otolith is positioned on top of the sensory cells and no stimulation occurs.

Utricle organ (macula) in section



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14) ***Damage to the hearing centre of the brain*** also causes deafness.

Echolocation in bats

Bats fly so swiftly at night without seeing but do not collide with obstacles on their way. This is done because they use sound orientation in the environment.

They are able to use echoes of the sound they produce to detect on their way, a phenomenon known as echolocation.

Bats produce sound of high frequency (short wave length) which are far beyond which man can perceive and use thus can't hear sounds used in echolocation.

Major advantages of sound of echolocation

1) The sound vibrations do not spread so wide and their echoes are so refined that they pin point the obstacle on which they are correctly reflected.
2) The echoes allow location of even small objects since these sounds have short wave lengths.

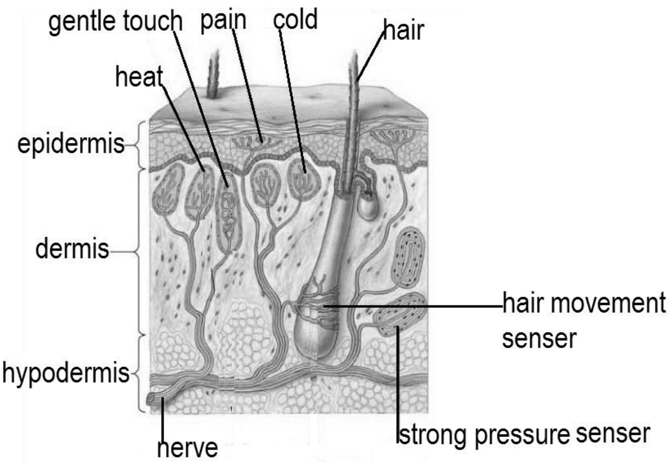
Differences between hearing in bats and man

Bat	Man
Depend on sound produced and deflected by object.	Depend mainly on sound produced by vibrating objects in the environment.
Have the ability to eliminate noise in their echoes.	Have the ability to discriminate between sounds.
Able to detect sounds of very high frequency.	Can perceive sounds of low frequency.

THE SKIN

The skin is a sense organ responsible for the senses of pain, touch, pressure and temperature. The skin has mechanoreceptors, pain receptors and thermo receptors.
Mechanoreceptors sense physical deformation caused by forms of mechanical energy such as pressure, touch, stretch and motion. The sense of touch relies on mechanoreceptors that are dendrites of sensory neurons. Touch receptors are often embedded in layers of the skin. Other receptors sense movement of hairs. For example, cats and many rodents have extremely sensitive mechanoreceptors at the base of their whiskers which help them to detect the size of the tunnel and also get information about nearby objects.
Pain receptors detect stimuli that reflect harmful conditions like extreme pressure and temperature hence triggering defensive reactions such as withdrawal from danger.
Thermo receptors in the skin and hypothalamus detect heat and cold. *(**Note:** in essence, we describe spicy foods as 'hot' because they activate the same sensory receptors as do hot things).*

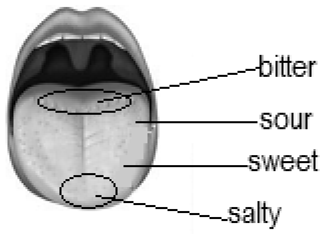
Structure of the skin as a sense organ showing the sense receptors



THE TONGUE

The tongue is a chemoreceptor organ for taste. It changes chemical stimuli in the mouth into nervous impulses. It contains chemo-receptors which carry out this function. The tongue contains taste buds, which contain the chemo-receptor cells. The tongue distinguishes between four different kinds of taste, i.e. *sweet, sour, salty and bitter.*
When a chemical is placed in the mouth, it dissolves in the moisture (saliva) in the buccal cavity. The dissolved chemicals then stimulate the taste buds in the different parts of the tongue depending on the type of taste. Impulses are then sent from the tongue through a sensory neuron to the brain and the brain interprets the type of taste.

Structure of the tongue showing the taste regions



THE NOSE

The nose is the receptor organ for smell. It is also made up of chemo-receptor cells and it is stimulated by chemicals in air. This helps the organism to respond to chemical stimuli at a distance. When air containing a chemical enters the nose, it dissolves in the moisture (mucus) in the nasal cavity. In this form, it stimulates the chemo-receptor cells in the nose. These cells send nervous impulses through a sensory neuron to the olfactory lobe of the brain where interpretation occurs.

"You will experience a painful sharpening from time to time, but this is required if you are to become a better pencil"