5.1 Communication & Homeostasis

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5.1.1 THE NEED FOR HOMEOSTASIS

The Need for Communication Systems in Organisms

- Animals and plants need to be able to respond to changes in their **internal and external environment** and to coordinate the activities of their different organs
- In order to **function** properly and **efficiently**, organisms have different **control and communication systems** that ensure their **internal conditions** are kept relatively **constant**
- Physiological control systems maintain the internal environment within **restricted limits** through a process known as **homeostasis**
- Homeostasis is **critically important** for organisms as it ensures the maintenance of **optimal conditions** for **enzyme action** and **cell function**
- Examples of **physiological factors** that are **controlled** by **homeostasis** in **mammals** include:
  - Core body temperature
  - Metabolic waste (eg. carbon dioxide and urea)
  - Blood pH
  - Concentration of glucose in the blood
  - Water potential of the blood
  - Concentration of respiratory gases (carbon dioxide and oxygen) in the blood
- Homeostatic mechanisms in mammals require **information** to be **transferred** between **different parts of the body**
- There are **two communication systems** in **mammals** that do this:
  - The nervous system
  - The endocrine system

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The nervous system

- The human nervous system consists of:
    - **The central nervous system** (CNS) – the brain and the spinal cord
    - **The peripheral nervous system** (PNS) – all of the nerves in the body
- It allows us to make sense of our surroundings and respond to them and **coordinate and regulate body functions**
- Information is sent through the nervous system as **nerve impulses** – electrical signals that pass along nerve cells known as **neurones**
- A bundle of neurones is known as a nerve
- Neurones **coordinate** the activities of **sensory receptors** (eg. those in the eye), **decision-making centres in the central nervous system**, and **effectors** such as muscles and glands

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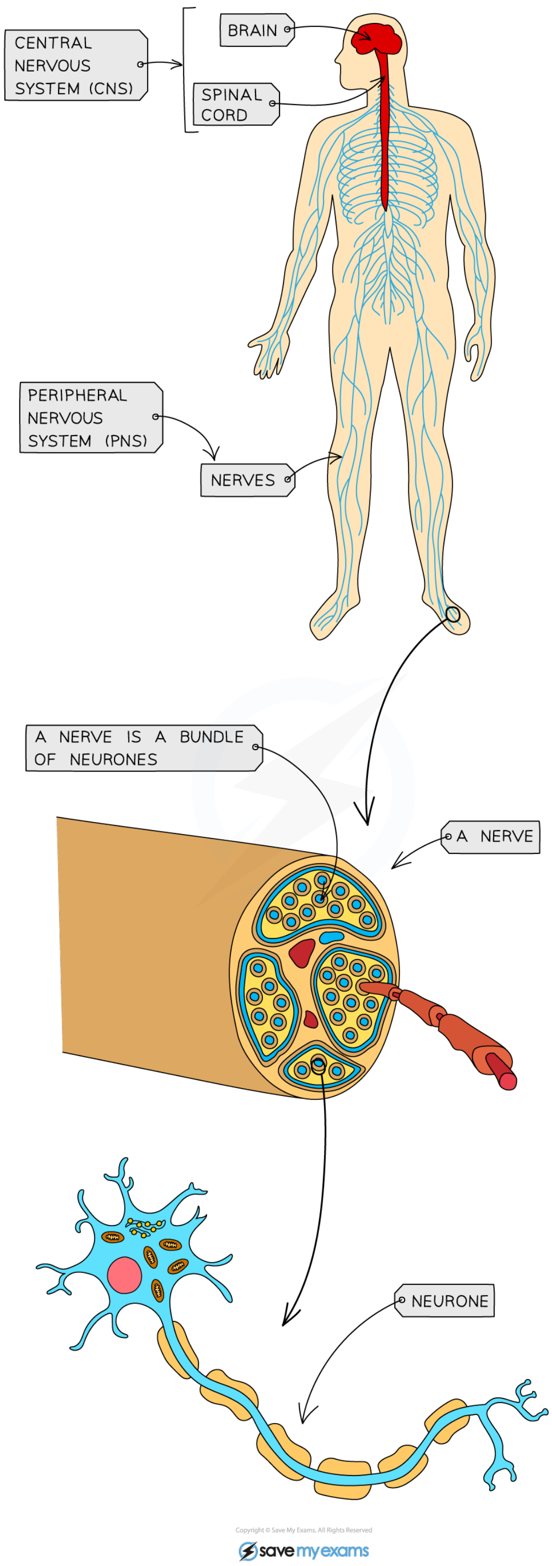

The human nervous system

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The endocrine system

- A **hormone** is a **chemical substance** produced by an **endocrine gland** and carried by the **blood**
    - They are chemicals which **transmit information from one part of the organism to another** and bring about a **change**
    - They **alter** the **activity** of one or more specific **target organs**
- Hormones are used to control functions that **do not need instant responses**
- The endocrine glands that produce hormones in animals are known collectively as the **endocrine system**
    - A **gland** is a **group of cells** that produces and releases one or more substances (a process known as **secretion**)

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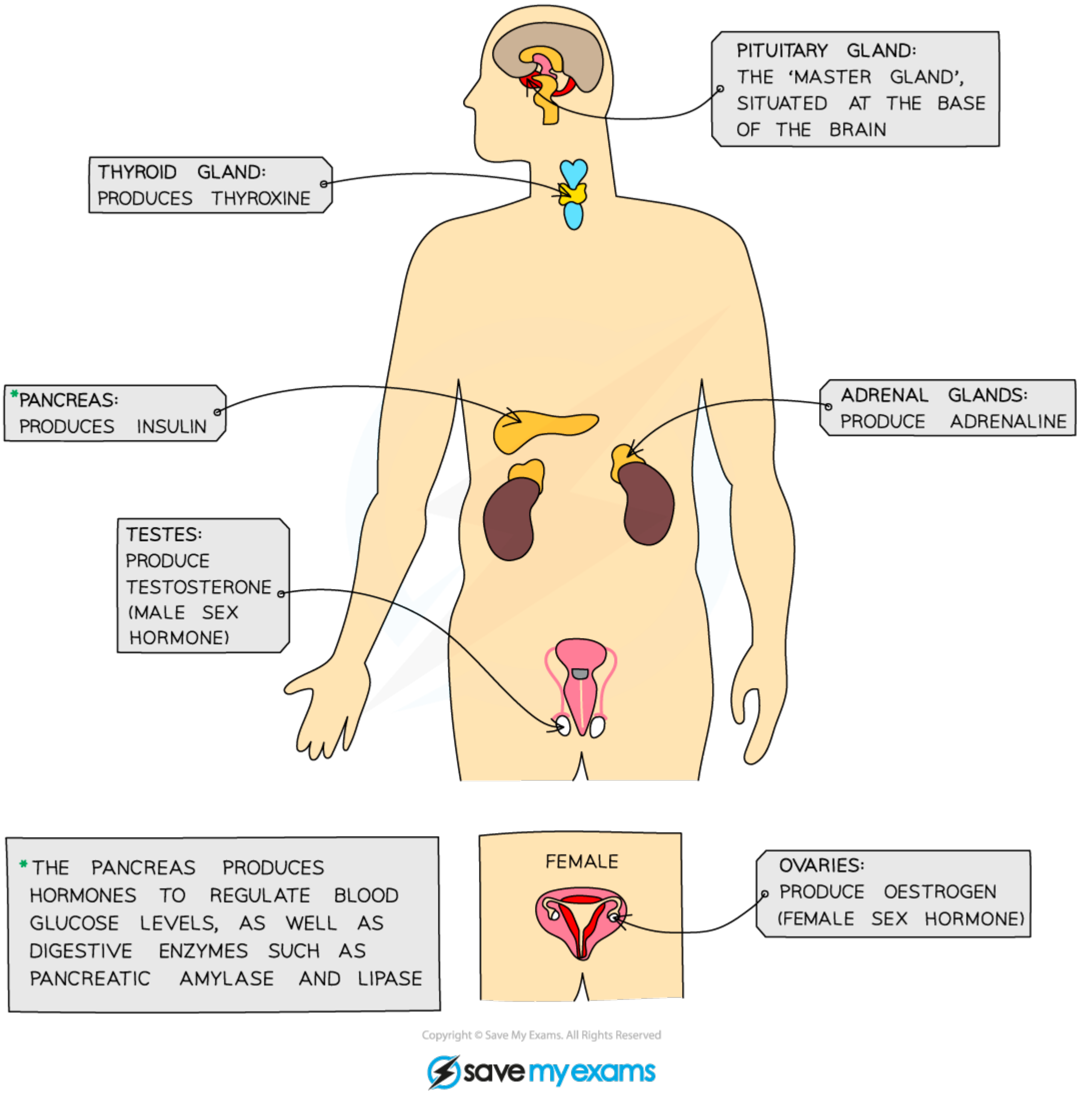

The major endocrine glands in the body

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The importance of homeostasis

- Homeostatic mechanisms help organisms to keep their internal body conditions within restricted limits
- Three key factors that need to be controlled include:
    - **Temperature** (thermoregulation is explained in more detail later)
    - **pH**
    - **Blood glucose concentration**
- A stable core temperature and blood pH are vital for **enzyme activity**
    - If the temperature or pH of the tissue fluid surrounding cells is too high or too low it can negatively affect the rate of important enzyme-controlled reactions

pH

- All enzymes have an **optimum pH** or a pH at which they operate best
- Enzymes are **denatured** at extremes of pH
    - **Hydrogen and ionic bonds** hold the tertiary structure of the protein (ie. the enzyme) together
    - Below and above the optimum pH of an enzyme, solutions with an excess of H^+ ions (acidic solutions) and OH^- ions (alkaline solutions) can cause these **bonds** to **break**
    - This **alters the shape of the active site**, which means enzyme-substrate complexes form less easily
    - Eventually, enzyme-substrate complexes can no longer form at all
    - At this point, **complete denaturation** of the enzyme has occurred
- Where an enzyme functions can be an indicator of its optimal environment:
    - Eg. **pepsin** is found in the stomach, an acidic environment at pH 2 (due to the presence of **hydrochloric acid** in the stomach's gastric juice)
    - Pepsin's optimum pH, not surprisingly, is pH 2

Blood glucose concentration

- Another key factor that must be controlled within mammals is the concentration of glucose in the blood
- The amount of glucose present in the blood affects the **water potential** of the blood and the **availability of respiratory substrate** for cells
- The normal glucose concentration for human blood is roughly 90mg per $100cm^3$
- A sufficient amount of circulating glucose is essential for **cellular respiration**
    - Brain cells can become rapidly damaged or die if they do not receive a sufficient supply of glucose
- Alternatively, if the blood glucose concentration is too high then it will have a dramatic effect on the **water potential** of the blood

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Stomata

- Plants also carry out **homeostasis** – just like animals they need to maintain a **constant internal environment**
    - For example, mesophyll cells in leaves require a **constant supply of carbon dioxide** for **photosynthesis**
- **Stomata** (specifically the **guard cells**) control the diffusion of gases in and out of leaves
    - This means stomata **control the entry of carbon dioxide** into leaves

Response of guard cells & stomata table

Environmental stimuli causing stomata to open	Environmental stimuli causing stomata to close
Increasing light intensity	Darkness
Low carbon dioxide concentrations in the air spaces within the leaf	High carbon dioxide concentrations in the air spaces within the leaf
	Low humidity
	High temperature
	Water stress — when the supply of water from the roots is limited and/or there are high rates of transpiration

- Regulation of stomatal aperture balances the need for carbon dioxide uptake by diffusion, with the need to minimise water loss by transpiration

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Advantages & disadvantages of stomatal opening & closure table

	Stomata open during the day	Stomata closed during the day
Advantage	Leaves gain carbon dioxide for photosynthesis	Water is retained inside the leaf, which is important in times of water stress
Disadvantage	Leaves lose large amounts of water by transpiration	Supply of carbon dioxide decreases so the rate of photosynthesis decreases

Exam Tip

A stoma is actually the aperture (hole) between two guard cells, but the term is often used to refer to the whole unit (the two guard cells and the hole between them).

Don't forget – stoma (singular) refers to one of these units, whereas stomata (plural) refers to many!

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5.1.2 THE PRINCIPLES OF HOMEOSTASIS

The Principles of Homeostasis

- The majority of homeostatic control mechanisms in organisms use **negative feedback** to maintain **homeostatic balance** (i.e. to keep certain physiological factors, such as internal temperature or blood glucose concentration, **within certain limits**)
- Negative feedback control loops involve:
  - A **receptor** (or sensor) – to **detect** a **stimulus** that is involved with a condition / physiological factor
  - A **coordination system** (nervous system and endocrine system) – to **transfer information** between different parts of the body
  - An **effector** (muscles and glands) – to **carry out a response**
- The outcome of a negative feedback loop:
  - The factor/stimulus is **continuously monitored**
  - If there is an **increase** in the factor, the body responds to make the factor **decrease**
  - If there is a **decrease** in the factor, the body responds to make the factor **increase**

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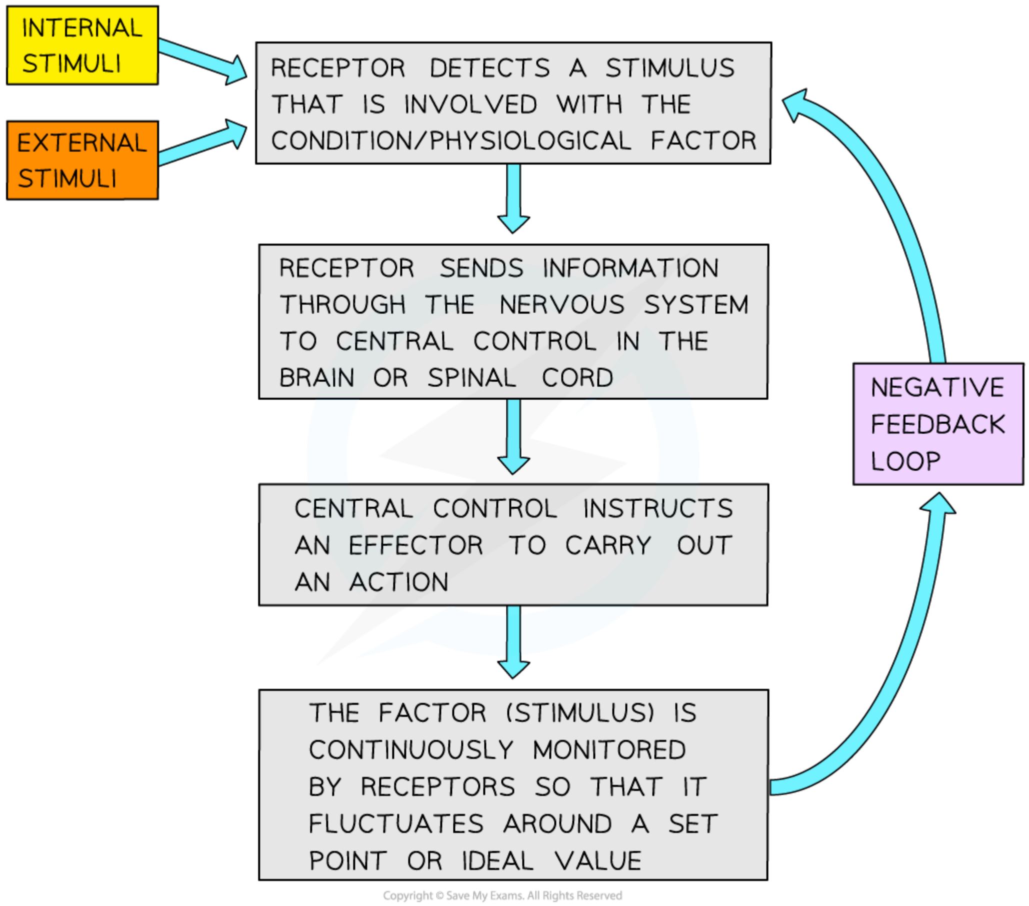

A negative feedback control loop

The control of negative feedback

- Negative feedback loops help maintain a normal range or balance within an organism
  - They **reduce the initial effect of the stimulus**
- **Receptors** detect any deviations from the normal range (stimuli) which results in a **corrective mechanism** to return the factor back to its normal range
- In a negative feedback loop there are usually **two corrective mechanisms:**
  - One for when the factor becomes **too low**
  - One for when the factor becomes **too high**
- The corrective mechanisms may involve the **nervous system** or the **endocrine system**
- The **magnitude** of the correction required to bring a factor back within its normal range is monitored and **regulated** by negative feedback
  - As the factor gets closer to its normal value the level of correction reduces

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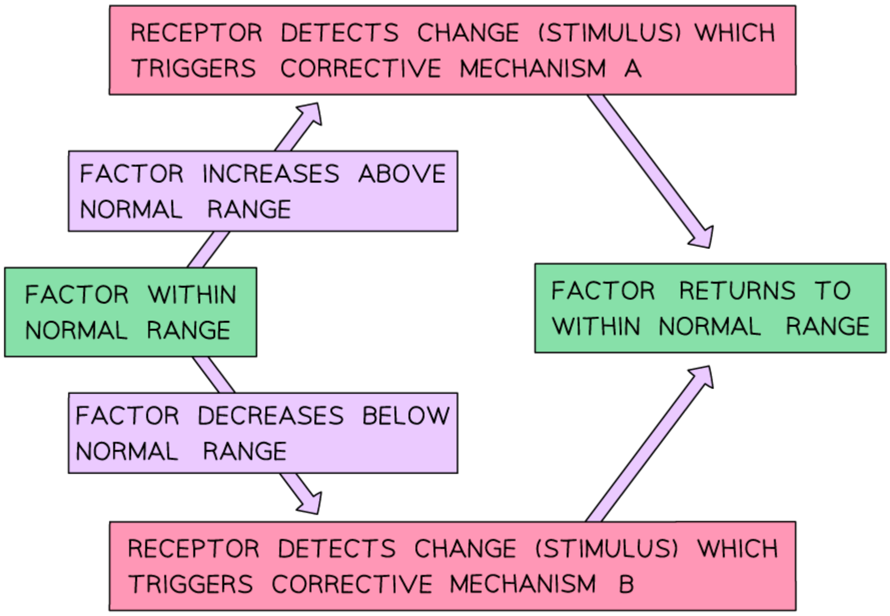

Two corrective mechanisms are involved in the negative feedback loop

Positive feedback

- In **positive** feedback loops, the original stimulus produces a response that causes the factor to deviate even more from the normal range
    - They **enhance the effect of the original stimulus**

Positive feedback loop in bone repair

- The repair of broken bones is carried out via a positive feedback loop involving special cells called osteoblasts and osteoclasts
- The osteoblasts secrete a hormone called osteocalcin
    - Osteocalcin is a **protein**
- They secrete the osteocalcin in an **inactive** form
- The osteoclasts secrete acid which lowers the pH and the **acidic conditions** cause the inactive form of the protein osteocalcin to change into the active form of osteocalcin
    - The low pH alters the hydrogen and ionic bonds in the protein which changes the tertiary structure
- The active form of osteocalcin binds to a receptor on beta (β) cells in the pancreas which stimulates them to release insulin
- Osteoblast cells possess **insulin receptors** which when stimulated causes them to release more inactive osteocalcin
- The osteoblast cells **enhance the effect of the original stimulus** (insulin) – positive feedback

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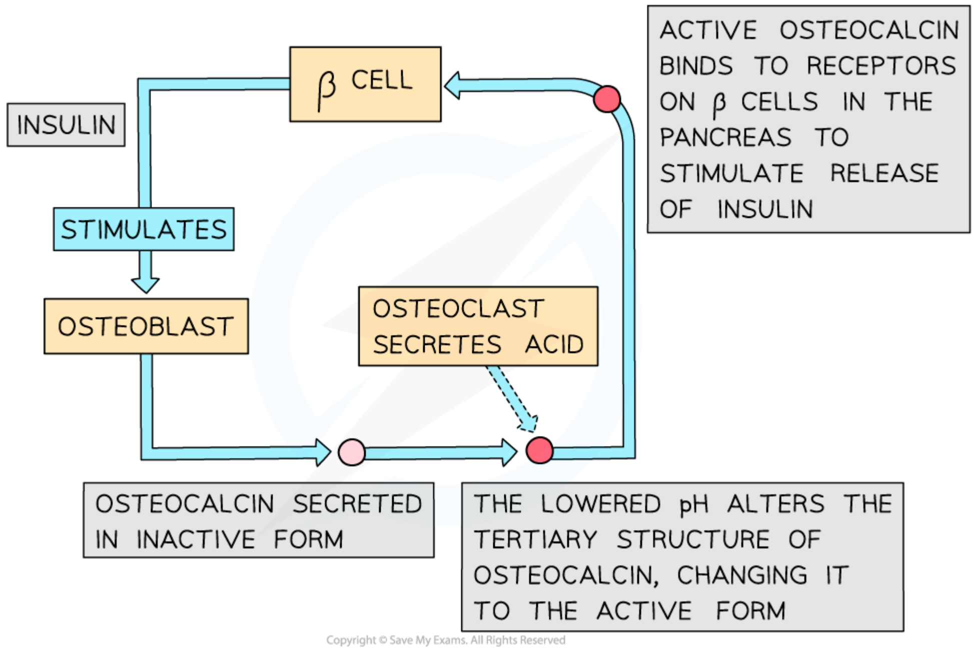

A positive feedback loop

Exam Tip

Learn the following definition for homeostasis:

Homeostasis is the regulation of the internal conditions of a cell or organism to maintain optimum conditions for function, in response to internal and external changes.

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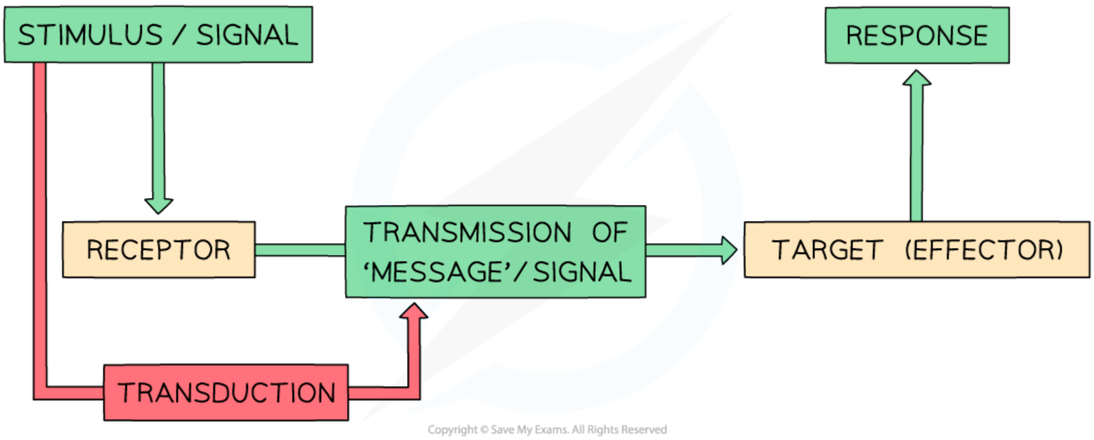
5.1.3 CELL SIGNALLING

Cell Signalling

- Cell signalling is the process by which cells communicate with each other
- Cell signalling is very important as it **allows multicellular organisms to control and coordinate their bodies and to respond to their environments**
- Cell signalling pathways coordinate the activities of cells, both between cells that are very close to each other and between cells that are large distances apart within the organism
- The basic stages of cell signalling are:
  - A **stimulus** is received by a **receptor cell**
  - The stimulus is converted to a **signal** (nearly always a chemical) that can be passed on – this process is known as **transduction**
  - The signal is transmitted to a **target cell** (**effector**) that can detect it (via receptors in its cell membrane)
  - An appropriate **response** is made



The basic stages of a cell signalling pathway

- In animals, cell signalling pathways can be categorised into **two types**, depending on **how far** the signal must travel:
  - **Paracrine signalling** (signalling between cells that are **close together**)
  - **Endocrine signalling** (signalling between cells that are **far apart**, which involves the signalling molecule being transported in the **circulatory system**)
- The signalling molecules produced by cells can belong to various chemical groups, including **proteins, glycoproteins, amino acids, lipids and phospholipids**
  - In **endocrine signalling**, however, the signalling molecules are always **hormones**

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Cell membranes

- **Transmission of messages** in cell signalling pathways requires **crossing barriers** such as **cell surface membranes**
- Cell surface membranes are therefore **very important** in signalling pathways as the membrane **controls** which molecules (including cell signalling molecules) can move between the internal and external environments of the cell
- Signalling molecules are usually **very small for easy transport** across cell membranes
- The receptor molecules **on or in the cell surface membrane** are **proteins** or **glycoproteins**
    - Some receptors, such as oestrogen receptors, may be present in the **cytoplasm** (in this case, because steroid hormones can diffuse through the cell membrane)
- The signalling molecule binds to the receptor molecule, causing **specific changes** in the receiving cell

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5.1.4 THERMOREGULATION

Thermoregulation in Ectotherms & Endotherms

- **Homeostatic mechanisms** help organisms to keep their internal body conditions **within restricted limits**
- **Temperature** is a key factor that needs to be controlled
  - For example, the human body maintains a core temperature of 36.8 ± 0.5 °C
  - Core temperatures of 35 °C or lower and 38 °C or higher indicate hypothermia or fever respectively
- A stable core temperature is vital for **enzyme activity**
  - If the temperature of the tissue fluid surrounding cells is too high or too low it can negatively affect the rate of important enzyme-controlled reactions
  - For example, human enzymes have evolved to function optimally at a core body temperature of about 37 °C, so that is their optimum temperature (the temperature at which they catalyse a reaction at the **maximum rate**)
- **Lower temperatures** either **prevent** reactions from proceeding or **slow them down**:
  - At lower temperatures molecules move relatively **slowly**
  - As a result, there is a **lower frequency of successful collisions** between substrate molecules and active site of enzyme so less frequent enzyme-substrate complex formation occurs
  - The substrate and enzymes collide with **less energy**, making it less likely for bonds to be formed or broken (stopping the reaction from occurring)
- **Higher temperatures speed up reactions**:
  - Molecules move more **quickly** due to having greater **kinetic energy**
  - There is a **higher frequency of successful collisions** between substrate molecules and the active sites of enzymes
  - More frequent enzyme-substrate complex formation occurs as a result
  - Substrates and enzymes collide with **more energy**, making it more likely for bonds to be formed or broken (allowing the reaction to occur)
- However, as temperatures continue to increase, the rate at which an enzyme catalyses a reaction **drops sharply**, as the enzyme begins to **denature**:
  - **Bonds** (eg. hydrogen bonds) holding the enzyme molecule in its precise shape start to **break**
  - This causes the **tertiary structure** of the protein (ie. the enzyme) to **change**
  - This permanently **damages** the **active site**, preventing the **substrate** from **binding**
  - **Denaturation** has occurred if the substrate can no longer bind

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Thermoregulation

- Thermoregulation is the **control of internal (core) body temperature**
- With regards to the process of thermoregulation, animals can be split into two groups:
    - **Endotherms**
    - **Ectotherms**
- Endotherms are animals that possess **physiological mechanisms to control their internal body temperature** (they can maintain their body temperatures using heat generated within their body tissues)
    - Examples include **mammals** and **birds**
- Ectotherms are animals that rely on **behavioural adaptations to ensure their internal body temperature does not get too high or low** (they regulate their body temperatures by absorbing heat from their environment)
    - Examples include **all other animals** (e.g. reptiles and amphibians)

Thermoregulation in endotherms

- Endothermic animals detect external temperatures via **peripheral receptors** (thermoreceptors found in the skin and mucous membranes)
    - There are receptors for both heat and cold
    - These communicate with the **hypothalamus** to bring about a **physiological response** to changing external temperatures
- The hypothalamus also helps to regulate body temperature by **monitoring the temperature of the blood flowing through it** and **initiating homeostatic responses** when it gets too high or too low
- Endotherms display a variety of **cooling** mechanisms, including:
    - **Vasodilation of skin capillaries**
    - **Sweating**
    - **Flattening of hairs**
- They also display a variety of **warming** mechanisms, including:
    - **Vasoconstriction of skin capillaries**
    - **Boosting metabolic rate**
    - **Shivering**
    - **Erection of hairs**
- Human skin contains a variety of **structures** that are involved in processes that can **increase** or **reduce heat loss** to the environment

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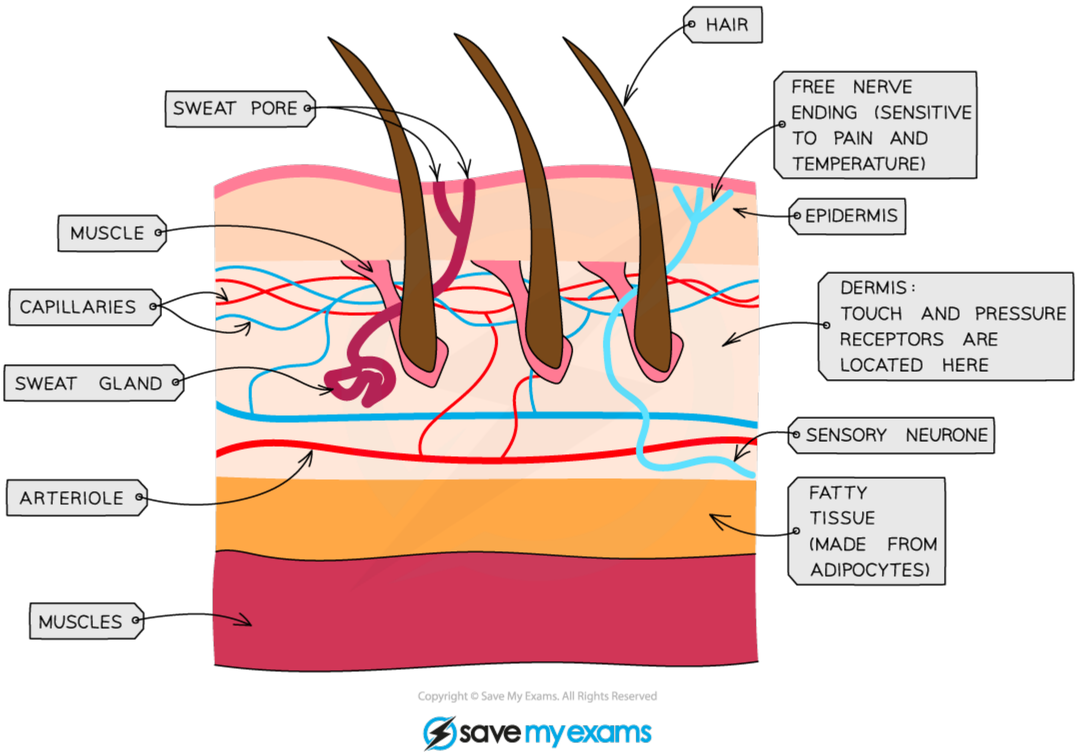

Structures in human skin involved in increasing or reducing heat loss

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Cooling mechanisms in endotherms

- **Vasodilation of skin capillaries**
    - Heat exchange (both during warming and cooling) occurs at the body's surface as this is where the blood comes into closest proximity to the environment
    - The warmer the environment, the less heat is lost from the blood at the body's surface
    - One way to increase heat loss is to supply the capillaries in the skin with a greater volume of blood, which then loses heat to the environment via radiation
    - Arterioles (small vessels that connect arteries to capillaries) have muscles in their walls that can relax or contract to allow more or less blood to flow through them
    - During vasodilation, these muscles relax, causing the arterioles near the skin to dilate and allowing more blood to flow through capillaries
    - This is why pale-skinned people go red when they are hot
- **Sweating**
    - Sweat is secreted by sweat glands
    - This cools the skin by evaporation which uses heat energy from the body to convert liquid water into water vapour
    - This means sweating is less effective as a cooling mechanism in humid environments, as humid air is less effective at evaporating water (due to a reduced concentration gradient)
- **Flattening of hairs**
    - The hair erector muscles (effectors) in the skin relax, causing hairs to lie flat
    - This stops them from forming an insulating layer by trapping air and allows air to circulate over skin and heat to leave by radiation

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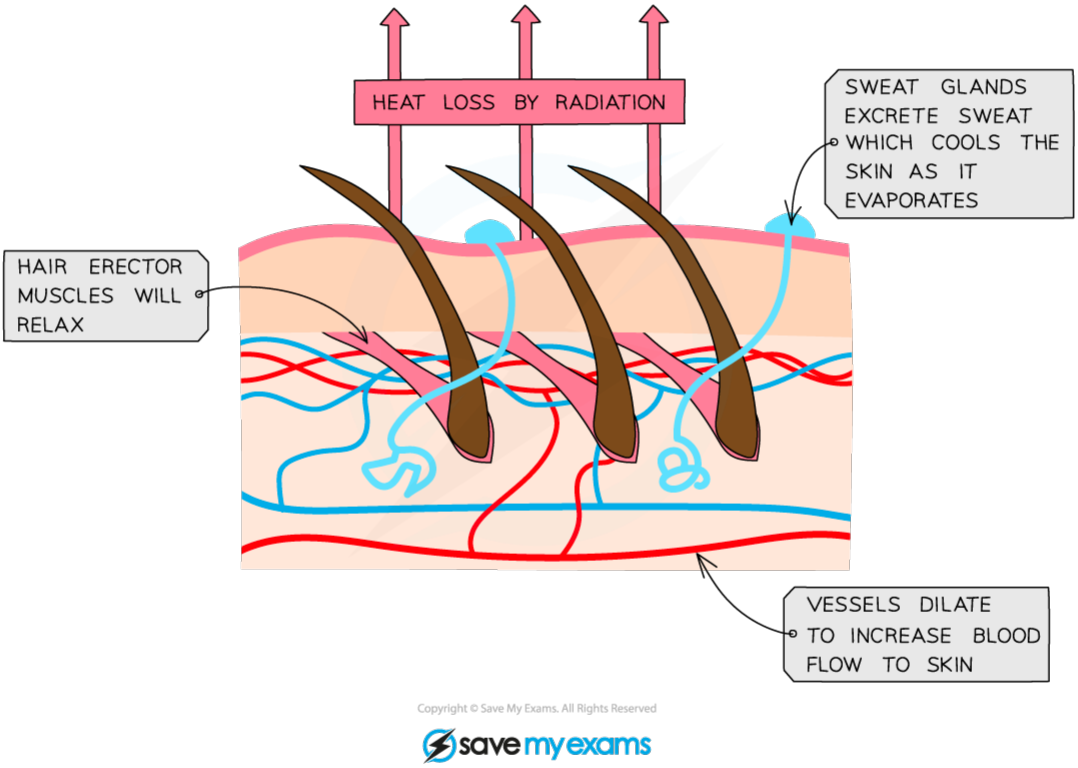

Responses in the skin when the body temperature is too high and needs to decrease

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Warming mechanisms in endotherms

- **Vasoconstriction of skin capillaries**
  - One way to decrease heat loss is to supply the capillaries in the skin with a smaller volume of blood, minimising the loss of heat to the environment via radiation
  - During vasoconstriction, the muscles in the arteriole walls contract, causing the arterioles near the skin to constrict and allowing less blood to flow through capillaries
  - Instead, the blood is diverted through shunt vessels, which are further down in the skin and therefore do not lose heat to the environment
  - Vasoconstriction is not, strictly speaking, a 'warming' mechanisms as it does not raise the temperature of the blood but instead reduces heat loss from the blood as it flows through the skin
- **Boosting metabolic rate**
  - Most of the metabolic reactions in the body are exothermic (heat-producing) and this provides warmth to the body
  - In cold environments, the hormone thyroxine (released from the thyroid gland) increases the basal metabolic rate (BMR), increasing heat production in the body
- **Shivering**
  - This is a reflex action in response to a decrease in core body temperature (this means it is a nervous mechanism, not a hormonal one)
  - In this case, muscles are the effectors and they contract in a rapid and regular manner
  - The metabolic reactions required to power this shivering generate sufficient heat to warm the blood and raise the core body temperature
- **Erection of hairs**
  - The hair erector muscles in the skin contract, causing hairs to stand on end
  - This forms an insulating layer over the skin's surface by trapping air between the hairs and stops heat from being lost by radiation

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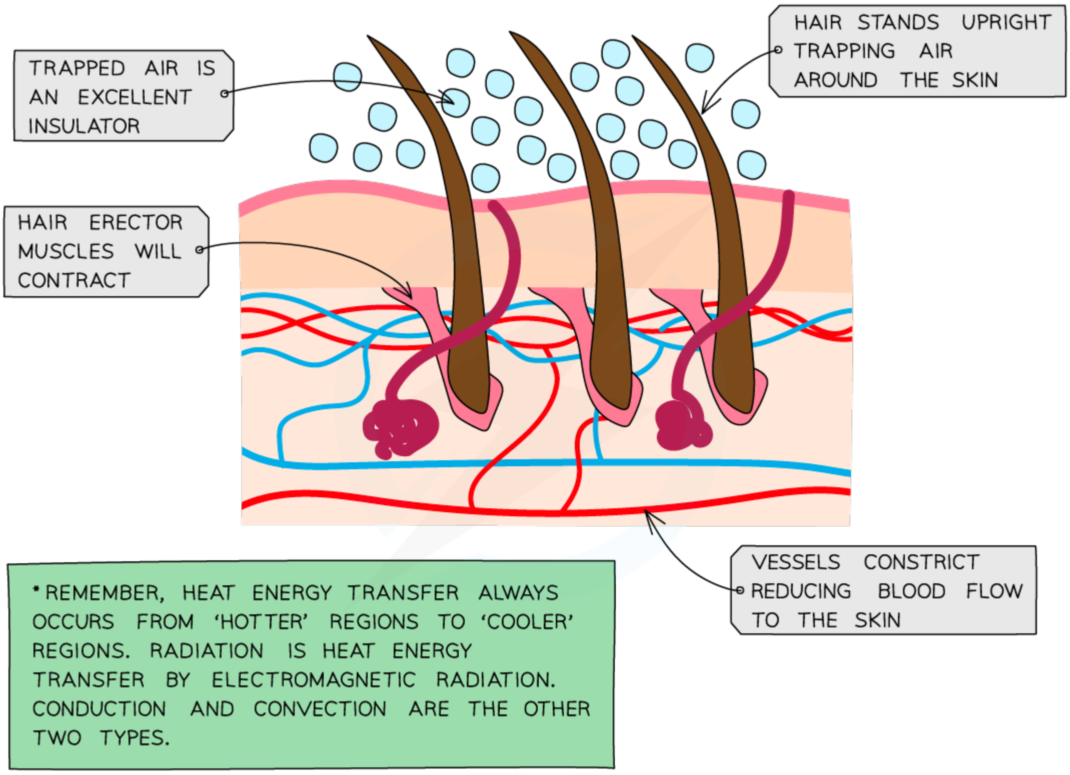

Responses in the skin when body temperature is too low and needs to increase

Body temperature control table

Body temperature too high	Body temperature too low
• Sweat is secreted by sweat glands in the skin • Sweat evaporates, cooling the skin • Heat energy from the body is lost as liquid water in sweat becomes water vapour (a state change)	• Skeletal muscles contract rapidly and shivering occurs • Skeletal muscle contraction is involuntary and requires energy from respiration (which releases heat energy)
• Hairs lie flat against the skin, allowing air to freely circulate • This reduces the insulating effect of air against the skin, increasing heat loss	• Erect hairs allow an insulating layer of air to be trapped against the skin • This reduces heat loss to the surroundings

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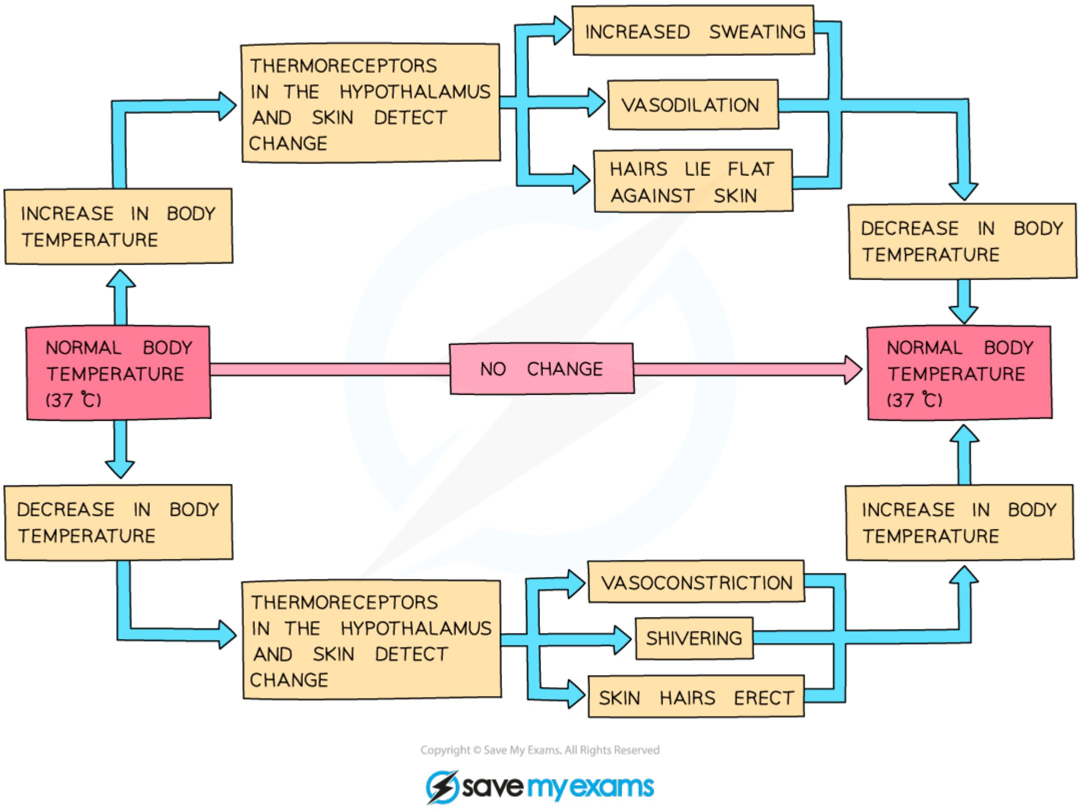

Remember homeostasis involves the maintenance of a constant internal environment; temperature control is an example of negative feedback

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Thermoregulation in ectotherms

- On land, environmental temperatures can **vary greatly** between seasons or even over the course of a single day
- Ectothermic animals need to **avoid extremes of temperature**
    - For example, if they get too cold their low body temperatures decreases the speed they are able to move at, which decreases their ability to catch prey or escape predators
- To heat up, ectotherms seek out the sun or warmer surfaces and rest or 'bask' in these locations as they warm, until their body temperature has been increased sufficiently
- To cool down, ectotherms seek shade or water
- This means the behaviour of ectotherms is more **restricted** by environmental temperatures compared to endotherms, meaning that they **cannot easily colonise habitats that are very hot or cold**
- In contrast, endotherms require **much more energy** to maintain their body temperature, meaning their **metabolic rate** (and therefore their **food requirement**) is **much greater**
- This, in turn, can restrict the behaviour of endotherms and means that ectotherms can actually survive better in environments where **food is limited** (they need less and can last longer without food)
- Lastly, aquatic ectotherms actually have relatively minor difficulty maintaining a stable internal body temperature as water temperatures are **significantly less variable** than those on land (this is due to the high **specific heat capacity** of water)

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Exam Tip

Remember, vasodilation and vasoconstriction are caused by the relaxing and contracting of muscles in the arterioles, **not** the capillaries. Capillaries do not have muscles in their walls. Make sure you study the two images below carefully to ensure you understand the changes that occur during vasodilation and vasoconstriction.