C3.1 Integration of body systems

Interaction and interdependence—Organisms

Standard level and higher level: 5 hours

Additional higher level: 2 hours

Guiding questions

• What are the roles of nerves and hormones in integration of body systems?

• What are the roles of feedback mechanisms in regulation of body systems?

SL and HL

C3.1.1—System integration
This is a necessary process in living systems. Coordination is needed for component parts of a system to collectively perform an overall function.
Multiple organ systems function within each organism to sustain its life. **System integration** is the effective collaboration, coordination, and communication of different components of the organism, which depends on molecules, cells, tissues, organs, and the systems that arise from them.

C3.1.2—Cells, tissues, organs and body systems as a hierarchy of subsystems that are integrated in a multicellular living organism

Students should appreciate that this integration is responsible for emergent properties. For example, a cheetah becomes an effective predator by integration of its body systems.

Emergent properties are "properties that are not evident in the individual components of a system, but show up when combining those components". In other words, the whole is greater than the sum of its parts.

For example, one cardiomyocyte (heart cell) cannot pump blood to the body, and neither can just one chamber of the heart or the heart alone in its entirety, but combining the heart with the vascular system achieves the property of pumping and carrying blood to all the body. This property only emerges when different organs are *integrated*.

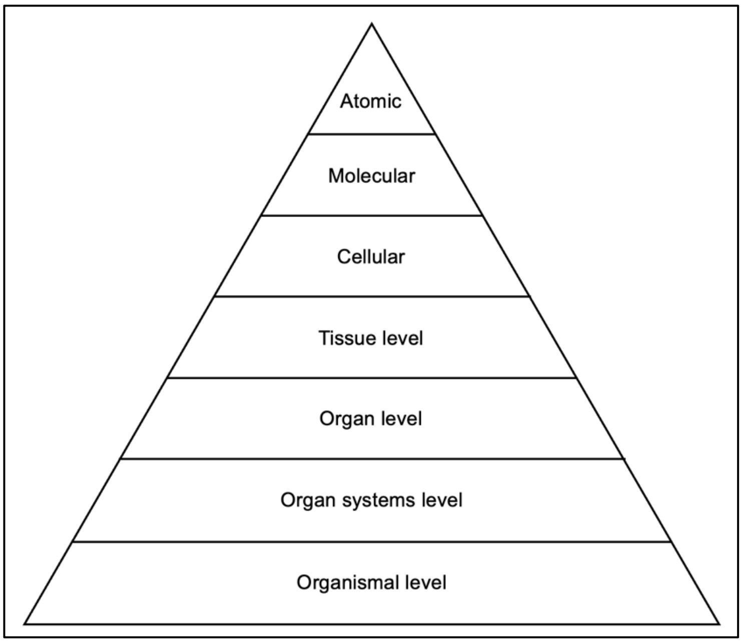

Figure 1: levels of organization within the human body *by size*.

C3.1.3—Integration of organs in animal bodies by hormonal and nervous signaling and by transport of materials and energy

Distinguish between the roles of the nervous system and endocrine system in sending messages. Using examples, emphasize the role of the blood system in transporting materials between organs.

There are two main methods of communication within the body – the **nervous** and **endocrine systems**. Each system achieves a certain type of communication, and when integrated together allow for effective internal communication.

The bloodstream (1) helps in the integration of organs in animal bodies (2) transports materials and energy to and from organs in order to facilitate functions other than homeostasis like nutrition and excretion.

Features	Nervous system	Endocrine system
Organs involved	Brain, spinal cord, nerves	Glands
Type of communication	Electrical (action potentials)	Chemical (hormones)
Transmission method	Neurons	Blood stream
Transmission speed	Very fast	Slower
Target (effector)	Glands or muscles	Target cells in certain tissue
Duration of effect	Short-lived (until electrical impulse stops)	Longer (until hormone is broken down)
Controls	Conscious and unconscious	Unconscious

C3.1.4—The brain as a central information integration organ

Limit to the role of the brain in processing information combined from several inputs and in learning and memory. Students are not required to know details such as the role of slow-acting neurotransmitters.

The brain is the central information integration organ, integrating both sensory inputs, contextual information, and past knowledge (memory) to generate responses and ultimately form perceptions.

Perception is the interpretation and organization of sensory stimuli by the brain, resulting in an *internal representation* of the stimuli and the *conscious* experience of it.

Memory is the mental system for receiving, encoding, and retrieving information within the brain. **Learning** is the process of acquiring new knowledge or behavior, which leads to the strengthening of connections between neural synapses.

Integrating sensory inputs to form perceptions enables us to create an understanding of the world around us, which forms the basis for learning.

C3.1.5—The spinal cord as an integrating centre for unconscious processes

Students should understand the difference between conscious and unconscious processes.

Conscious processes are voluntary, occur only when awake, and are carried out by the brain (specifically the cerebral hemisphere).

Unconscious processes are involuntary, occur both when awake and asleep, and are carried out by both the brain and the spinal cord.

The **Central Nervous System** (**CNS**) is composed of the brain and the spinal cord. The **Peripheral Nervous System** (**PNS**) is every other nervous tissue (i.e. nerves).

Neurons are the functional unit of the nervous system, and are divided into three classes:

- **Sensory neurons**: receive information about the internal and external environments, transmitting them to the CNS (via interneurons). *They **receive** signals.*
- **Interneurons**: are the most abundant class of neurons, and work to receive information from sensory neurons or other interneurons and transmit this information to either motor neurons or other interneurons. *They **integrate** incoming signals.*
- **Motor neurons**: receive signals from other neurons and convey commands to organs, glands, or muscles. *They **communicate** signals to target cells*.

The **spinal cord** is the extension of nervous tissue within the **vertebral column**. When observing the spinal cord and brain (in a dissection), two distinct regions appear: white and grey matter.

White matter is the region with many axons (it is called 'white' because axons are covered with lipid-rich **myelin**, which appears white). **Grey matter** is the region with many cell bodies and dendrites. Grey matter does not always appear 'grey,' it could be pink (due to blood) – it is just always a darker shade compared to white matter.

Distinguishing these two regions within the spinal cord enables us to explain how it functions – white matter mainly transmits information while grey matter receives and processes information. Thus, integrating their two functions within the spinal cord allows for effective response to stimuli.

C3.1.6—Input to the spinal cord and cerebral hemispheres through sensory neurons

Students should understand that sensory neurons convey messages from receptor cells to the central nervous system.

Sensory neurons 'sense' changes in the internal and external environments and transmit (input) them to the spinal cord and cerebral hemispheres within the brain (CNS). The structure of sensory neurons depends on the stimulus they are sensing.

C3.1.7—Output from the cerebral hemispheres to muscles through motor neurons

Students should understand that muscles are stimulated to contract.

The **cerebrum** is composed of the two **cerebral hemispheres**. The **primary motor cortex**, located in the **frontal lobes** of the cerebrum, exhibits the highest level of voluntary control over movement (and thus over muscles). It outputs a signal to motor neurons, which stimulates muscles to contract; the nervous and musculoskeletal systems are integrated such that the body is able to physically respond to stimuli.

C3.1.8—Nerves as bundles of nerve fibres of both sensory and motor neurons
Use a transverse section of a nerve to show the protective sheath, and myelinated and unmyelinated nerve fibres.

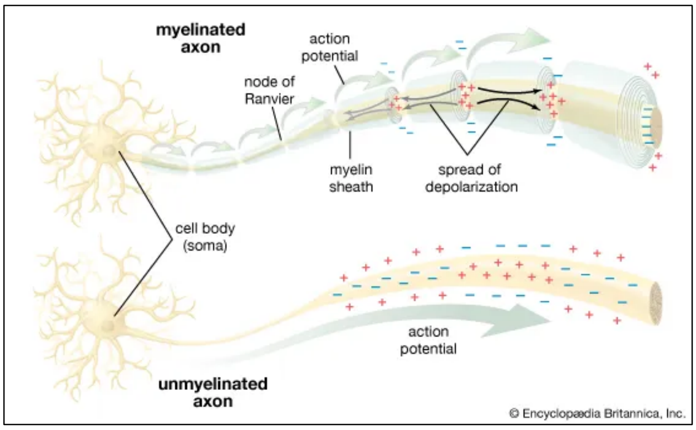

Figure 2: myelinated and unmyelinated nerve fiber (Britannica).

Nerves are bundles of nerve fibers (axons), containing both sensory and motor neurons (which can be myelinated or not). Nerves connect/integrate the nervous system to itself and to other organs.

Transverse section feature	Myelinated	Unmyelinated
Axon diameter	Large (2-20 μm)	Small (0.1-2 μm)
Myelin	Present, forming ~200-300 turns of myelin	Absent
Axon diameter to nerve fiber (axon + myelin) ratio	Fixed (~0.6-0.7)	–

C3.1.9—Pain reflex arcs as an example of involuntary responses with skeletal muscle as the effector
Use the example of a reflex arc with a single interneuron in the grey matter of the spinal cord and a free sensory nerve ending in a sensory neuron as a pain receptor in the hand.

Pain is both a sensation and a perception. **Pain receptors** (**nociceptors**) are free nerve endings that specifically respond to damaging or potentially damaging stimuli. The signal initiated by nociceptors are always transmitted through specific nerve fibers to the spinal cord, and then to the brain (not always).

A **reflex** is an involuntary and instantaneous movement in response to a noxious stimulus. The **pain reflex arc**, also known as the **withdrawal response** or **nociceptive flexion reflex**, is the neural pathway that acts on the impulse before it has reached the brain. Instead of directly travelling to the brain, the action potential travels to the spinal cord and then to effector cells (muscle) through the following pathway:

1. **Sensation**: nociceptors in upper/lower limbs sense a noxious stimulus and generate an action potential that travels through 1 afferent sensory neuron to the spinal cord.
2. **Relay**: the sensory neuron transmits the action potential to a relay neuron (interneuron) in the spinal cord by means of a synapse. The interneuron then transmits the signal to an efferent motor neuron through a synapse in the spinal cord.
3. **Contraction**: the motor neuron completes the reflex arc by exiting the spinal cord and entering the PNS to depolarize and cause the contraction of target muscles at the neuromuscular junction through releasing acetylcholine.

The reflex arc is an important evolutionary adaptation that enhances survival by quickly reacting to stimulus that damages or could damage the body.

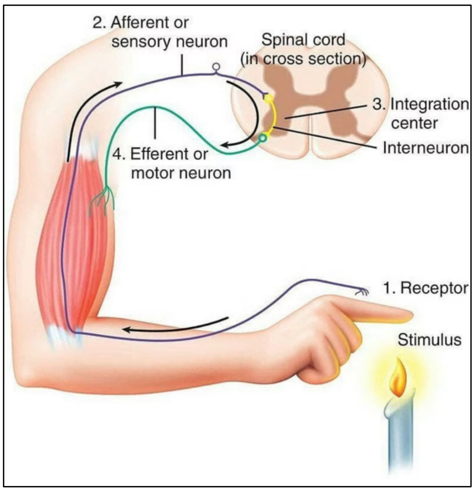

Figure 3: pain reflex arc (Louise).

C3.1.10—Role of the cerebellum in coordinating skeletal muscle contraction and balance
Limit to a general understanding of the role of the cerebellum in the overall control of movements of the body.

The **cerebellum** is responsible for **muscle coordination** and **balance** but is unable *to initiate muscle contraction*.

C3.1.11—Modulation of sleep patterns by melatonin secretion as a part of circadian rhythms

Students should understand the diurnal pattern of melatonin secretion by the pineal gland and how it helps to establish a cycle of sleeping and waking.

Melatonin is the only hormone produced by the pineal gland. The pineal gland is located outside the blood brain barrier, losing its connection to the CNS. This allows for:

- Large intake of tryptophan, the chemical the pineal gland uses to synthesize melatonin, thus allowing for **high melatonin production**
- **Relative protection from premature degradation** by enzymes (which would otherwise lead to a 10-20-fold decrease in melatonin levels)

"The rate of melatonin production is affected by the photoperiod (length of time during which a person is exposed to light). During the day photoperiod, little melatonin is produced; however, melatonin production increases during the dark photoperiod (night)"; its production is stimulated by *darkness* (Masters).

"In some mammals, melatonin has an inhibitory effect on reproductive functions by decreasing production and maturation of sperm, oocytes, and reproductive organs" (Masters).

"Although melatonin has effects on various cells in the human body, its sleep-promoting actions are mostly caused by its feedback to the **suprachiasmatic nucleus (SCN)**, located in the anterior part of the hypothalamus. By working on the SCN, melatonin helps to synchronize the circadian rhythm by affecting both the **phase** (the timing of the rhythm's trough and peak within 24 hours) and **amplitude** (the difference between the trough and peak) of the rhythm" (Masters).

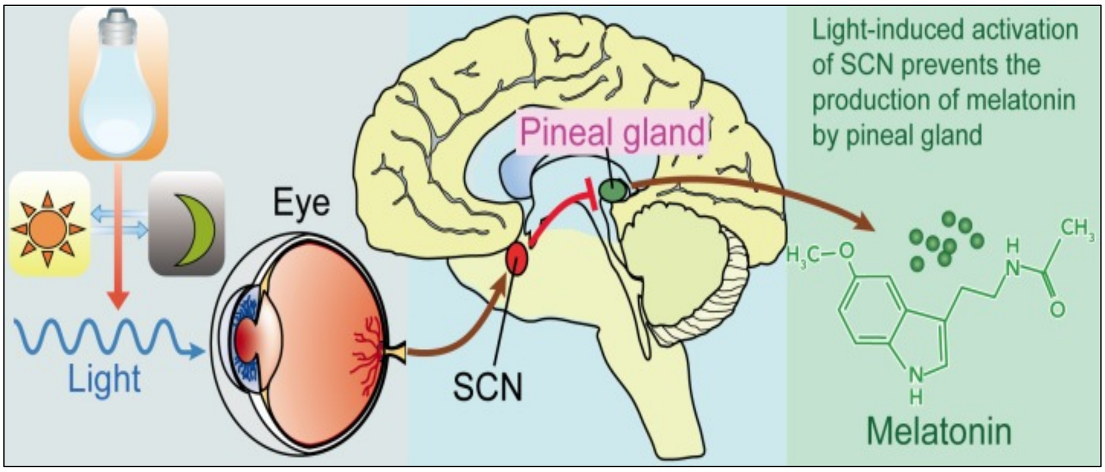

Figure 4: mechanism of regulating melatonin production ("Melatonin").

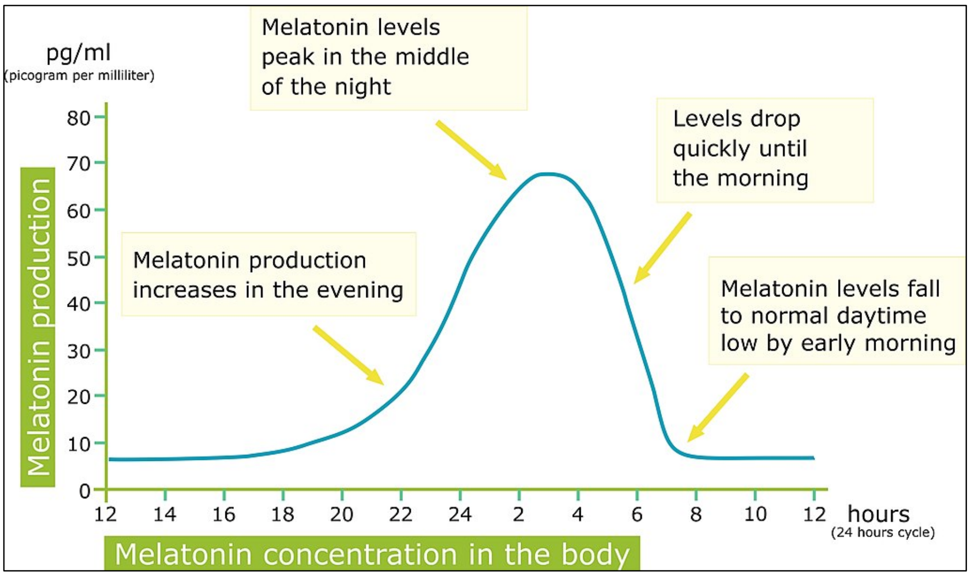

Figure 5: melatonin production and concentration in the body throughout 24 hours ("Melatonin").

C3.1.12—Epinephrine (adrenaline) secretion by the adrenal glands to prepare the body for vigorous activity

Consider the widespread effects of epinephrine in the body and how these effects facilitate intense muscle contraction.

Epinephrine, also known as **adrenaline** or the 'fight or flight hormone/neurotransmitter' is produced by the adrenal glands and has several functions:

- Increasing contraction of vascular smooth muscle, pupillary dilator muscle (in the iris), and intestinal sphincter muscle
- Increasing rate of glycogen breakdown in liver (thus increases blood sugar levels)
- Increasing heart rate (it overrides normal homeostatic mechanisms)
- Relaxation of bronchial smooth muscle

Exercise is a physiological stimulus to epinephrine secretion.

C3.1.13—Control of the endocrine system by the hypothalamus and pituitary gland

Students should have a general understanding, but are not required to know differences between mechanisms used in the anterior and posterior pituitary.

The **endocrine system** is responsible for internal chemical signaling within the body through the bloodstream (not to be confused with the exocrine system, which secretes into *ducts*). It is controlled by the **hypothalamus** (which links the nervous and endocrine systems together) and **pituitary gland**.

The pituitary gland has an **anterior lobe**, which secretes Growth Hormone (GH), Prolactin, FSH, and LH (among others), and a **posterior lobe**, which secretes ADH and Oxytocin.

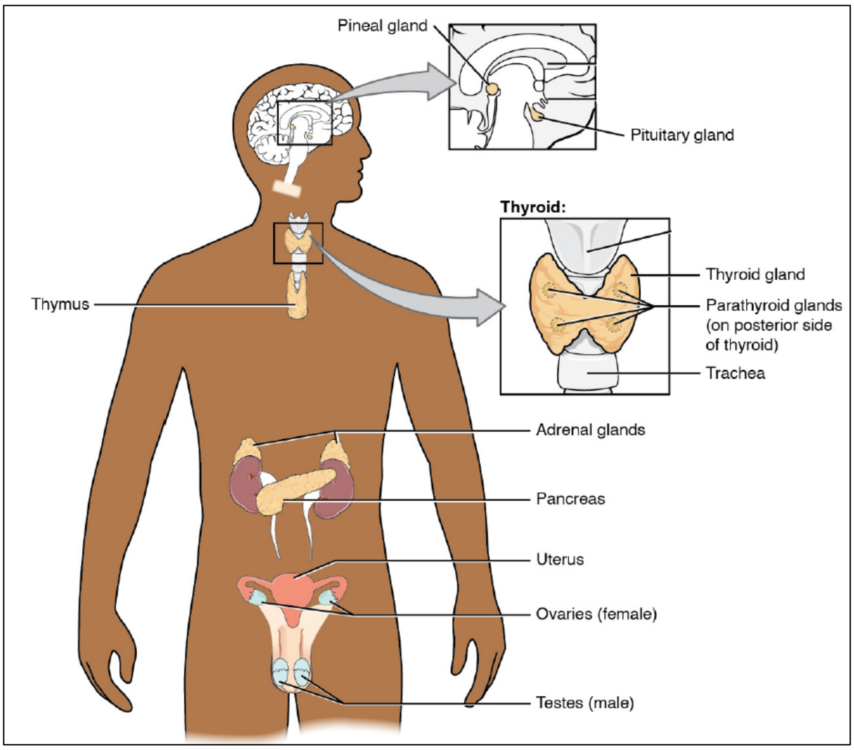

Figure 6: basic anatomy of the endocrine system (Gordon Betts).

C3.1.14—Feedback control of heart rate following sensory input from baroreceptors and chemoreceptors

Include the location of baroreceptors and chemoreceptors.
Baroreceptors monitor blood pressure. Chemoreceptors monitor blood pH and concentrations of oxygen and carbon dioxide. Students should understand the role of the medulla in coordinating responses and sending nerve impulses to the heart to change the heart's stroke volume and heart rate.

The **Medulla Oblongata** is a region within the human brain that contains a **cardiovascular center** which regulates cardiac output and activity. It is an element of the **autonomic nervous system** (part of the PNS). The ANS is divided into the **sympathetic**, **parasympathetic**, and **enteric nervous systems**.

Sympathetic stimulation increases **heart rate** and **stroke volume** (volume of blood ejected from ventricles per one cardiac cycle), whilst parasympathetic stimulation (via the **Vagus nerve**) decreases them.

Baroreceptors are a type of mechanoreceptors (sensory neurons that sense mechanical changes in the environment) that aid in regulating blood pressure.

"The cardiovascular center monitors baroreceptor firing to maintain cardiac homeostasis, a mechanism called the **baroreceptor reflex**. With increased pressure and stretch, the rate of baroreceptor firing increases, and the cardiac center decreases sympathetic stimulation and increases parasympathetic stimulation. As pressure and stretch decrease, the rate of baroreceptor firing decreases, and the cardiac center increases sympathetic stimulation and decreases parasympathetic stimulation" (Gordon Betts).

Chemoreceptors are sensory neurons that sense changes in metabolic byproducts such as carbon dioxide, pH, lactic acid, and oxygen levels. "These chemoreceptors provide feedback to the cardiovascular centers about the need for increased or decreased blood flow, based on the relative levels of these substances."

C3.1.15—Feedback control of ventilation rate following sensory input from chemoreceptors

Students should understand the causes of pH changes in the blood. These changes are monitored by chemoreceptors in the brainstem and lead to the control of ventilation rate using signals to the diaphragm and intercostal muscles.

Ventilation rate is the number of breaths per unit time.

Chemoreceptors in the brainstem detect pH and oxygen levels, and regulate ventilation rate accordingly.

Since carbon dioxide dissociates into acid in blood,

High CO_2 = low pH = higher ventilation rate to excrete more CO_2 and lower acidity.
Low CO_2 = high pH = slower ventilation rate to increase blood acidity.

C3.1.16—Control of peristalsis in the digestive system by the central nervous system and enteric nervous system
Limit to initiation of swallowing of food and egestion of faeces being under voluntary control by the central nervous system (CNS) but peristalsis between these points in the digestive system being under involuntary control by the enteric nervous system (ENS). The action of the ENS ensures passage of material through the gut is coordinated.
Peristalsis is the antagonistic contraction of longitudinal and circular smooth muscles to push food in a unidirectional manner throughout the alimentary canal. *Initiation* of swallowing food and egestion of faeces is under the control of the (CNS); it is a voluntary and conscious process. Peristalsis between these points (through the esophagus, stomach, and intestines) is under the control of the enteric nervous system (ENS); an involuntary and unconscious process.

Additional higher level

C3.1.19—Phytohormones as signaling chemicals controlling growth, development and response to stimuli in plants
Students should appreciate that a variety of chemicals are used as phytohormones in plants.
Phytohormones are a large variety of signaling chemicals that control the growth, development, and stimulus response in plants. Examples include **indole-3-acetic acid (IAA)** – the major type of **auxin** in plants, **cytokinin**, and **ethene**.

C3.1.20—Auxin efflux carriers as an example of maintaining concentration gradients of phytohormones
Auxin can diffuse freely into plant cells but not out of them. Auxin efflux carriers can be positioned in a cell membrane on one side of the cell. If all cells coordinate to concentrate these carriers on the same side, auxin is actively transported from cell to cell through the plant tissue and becomes concentrated in part of the plant.

Auxin transport helps us understand *how* this hormone integrates different parts of the plant and allows it to react to external stimuli. It occurs through two mechanisms:

- **Mechanism 1: (directional) polar transport**

"In contrast to the other major plant hormones, auxins can be transported in a specific direction (polar transport) through **parenchyma** (plant tissue) cells.

The cytoplasm of parenchyma cells are neutral (pH = 7), but the region outside the plasma membranes of adjacent cells (the apoplast) is acidic (pH = 5). When auxin is in the cytoplasm, it releases a proton and becomes an anion (IAA-). It cannot pass through hydrophobic portion of the plasma membrane as an anion, but it does pass through special auxin efflux transporters called **PIN proteins**.

When IAA- enters the acidic environment of the apoplast, it is protonated, becoming IAAH. This uncharged molecule can then pass through the plasma membrane of adjacent cells through diffusion or via influx transporters, but not out of the cells. PIN proteins can be unevenly distributed around the cell (for example, only occurring on the bottom of the cell), which directs the flow of auxin" (Melissa Ha).

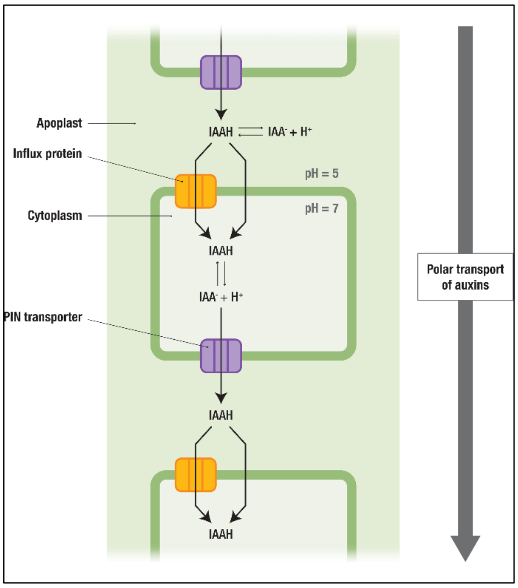

Figure 7: **Polar transport of auxin (Ha, Melissa).**

- **Mechanism 2: (non-directional) non-polar transport**

Auxin can also pass through the sap, or phloem, of the plant as nutrients are translocated.

C3.1.18—Positive phototropism as a directional growth response to lateral light in plant shoots
Students are not required to know specific examples of other tropisms.

Positive phototropism is the directional movement/growth of plant towards light (**negative phototropism** is movement *away* from light, i.e. in roots).

C3.1.21—Promotion of cell growth by auxin

Include auxin's promotion of hydrogen ion secretion into the apoplast, acidifying the cell wall and thus loosening cross links between cellulose molecules and facilitating cell elongation. Concentration gradients of auxin cause the differences in growth rate needed for phototropism.

Mechanism of positive phototropism:

- Phototropins in one side of the plant sense more light than the other side
- This promotes the efflux of auxin from the lighter side to the darker, shaded side
- A high concentration of auxin causes the release of H+ ions in the cell walls of shaded cells
- Lower pH disrupts bonding of cellulose molecules in cell walls, causing a loss of rigidity and elasticity
- Auxin also upregulates the production of expansins (proteins), which further disrupt the cell wall
- Auxin also increases *elongation rate* of darker side compared to brighter side
- This results in the swelling of the cell and increases the weight of the shaded side
- As a result, the stem begins bending towards the side exposed to more light

C3.1.22—Interactions between auxin and cytokinin as a means of regulating root and shoot growth

Students should understand that root tips produce cytokinin, which is transported to shoots, and shoot tips produce auxin, which is transported to roots. Interactions between these phytohormones help to ensure that root and shoot growth are integrated.

Auxin is produced in **shoot tips** and transported to roots, promoting **meristematic differentiation**, cell elongation, leaf development, apical dominance, and tropisms whilst inhibiting *lateral (horizontal) growth*.

Cytokinin is produced in **root tips** and transported to shoots, promoting **growth/cell division** (cytokinesis) whilst inhibiting *leaf and root development*.

The concentrations of both phytohormones regulate shoot and root growth, as seen below. High levels of auxin and low levels of cytokinin induce shoot formation, whereas low levels of auxin and high levels of cytokinin induce root formation. Relatively equal amounts result in **callus formation**, which is just filler plant tissue. Thus, **antagonistic** and **cooperative** interactions can occur between the two hormones.

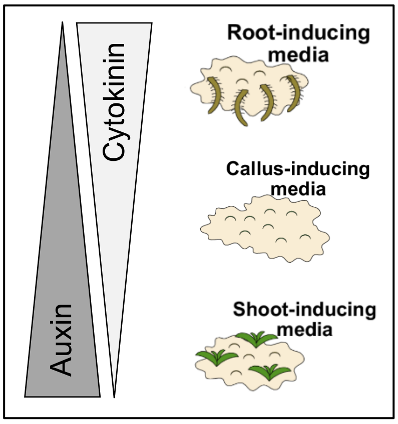

Figure 8: diagrammatic visualization of interactions between auxin and cytokinin (Melnyk).

C3.1.23—Positive feedback in fruit ripening and ethylene production

Ethylene (IUPAC name: ethene) stimulates the changes in fruits that occur during ripening, and ripening also stimulates increased production of ethylene. Students should understand the benefit of this positive feedback mechanism in ensuring that fruit ripening is rapid and synchronized.

Once a plant reaches the **seed dispersal stage** during reproduction, a positive feedback mechanism is initiated between **ethene** and the ripening fruits. The more ripening occurs, the more ethene produced, and vice versa.

C3.1.17—Observations of tropic responses in seedlings

Application of skills: Students should gather qualitative data, using diagrams to record their observations of seedlings illustrating tropic responses. They could also collect quantitative data by measuring the angle of curvature of seedlings.

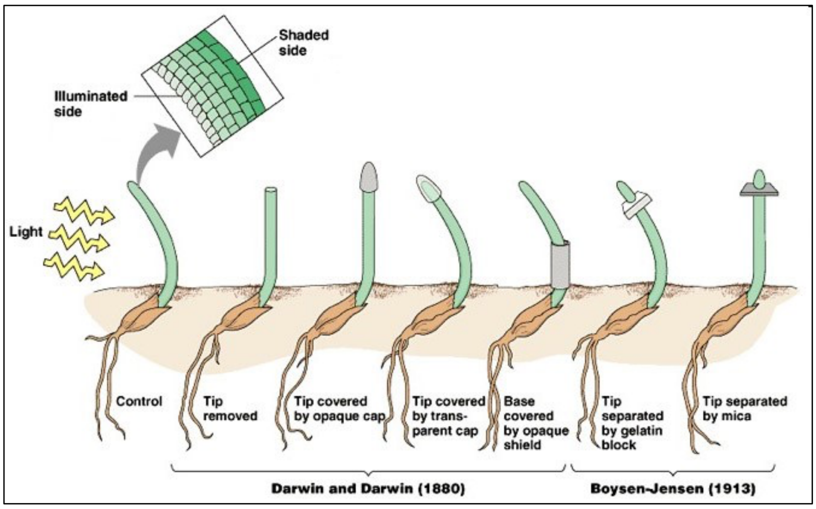

Figure 9: early phototropism experiments by Darwin and Boysen-Jensen (Science Buddies Staff).

The diagram above shows how scientists investigated the effects of auxin on phototropism; since auxin is produced in the shoot, separating the shoot from the rest of the stem by a **physical barrier** prevents its efflux to the shaded/darker regions, thus inhibiting phototropism.

You can investigate the effect of light intensity on the degree of phototropism exhibited by seedlings by measuring the **angle of curvature** (using a protractor), among others.

NOS: Students should be able to distinguish between qualitative and quantitative observations and understand factors that limit the precision of measurements and their accuracy. Strategies for increasing the precision, accuracy and reliability of measurements in tropism experiments could be considered.

Qualitative	Quantitative
Non-numerical data (words)	Numerical data
Subjective	Objective
Used to *support* quantitative evidence	*Main* evidence in hypothesis testing

Accuracy is how close an experimental result is to the true (literature) value.

Precision is the degree of certainty in measured data ***or*** how close trial values are to each other.

Reliable data = accuracy + precision

For example, when measuring the angle of curvature of seedlings when investigating phototropism, one can use a protractor with at least 2 decimal places for precision, and conduct at least 3-5 trials for reliability.

Linking questions

- What are examples of branching (dendritic) and net-like (reticulate) patterns of organization?
- What are the consequences of positive feedback in biological systems?

Review questions

SL and HL

- Define emergent property. [1]
- State the significance of systems integration within the human body. [1]
- Suggest why smelling smoke when sitting at a campfire does not make you alarmed, but the smell of smoke in your bedroom does. [1]
- Outline the divisions of the nervous system. [2]
- Distinguish between the roles of the cerebellum and cerebrum. [2]
- Outline the role of the blood stream in the human body. [2]
- Describe the structure of the endocrine system. [3]
- Describe the baroreceptor reflex. [3]
- Explain the functions of epinephrine. [3]
- Outline how muscle contraction is initiated and controlled. [3]
- Describe, using an example, the levels of organization within the human body. [3]
- Explain how nerves are adapted to their function. [3]
- Outline the divisions of the nervous system. [3]
- Outline the role of the brain in integration of body systems. [3]
- Compare and contrast baroreceptors and chemoreceptors. [4]
- Explain how melatonin regulates circadian rhythm in the human body. [4]
- Explain how, using an example, one organ can be a member of more than one organ system. [4]
- Explain how the spinal cord functions as an integrating centre for unconscious processes. [4]
- Describe, using an example, how different structures in the human body work together to carry out a pain reflex arc in the hand. [6]
- Describe the roles of nerves and hormones in integration of body systems. [6]
- Compare and contrast the nervous and endocrine systems. [7]
- Explain how heart rate is regulated in the human body. [7]
- Discuss, using examples, the significance of having more than one method of communication within the human body. [7]
- Describe using **two** examples the role of feedback mechanisms in regulation of body systems. [7]

Additional higher level

- List three named phytohormones. [1]
- Define positive phototropism. [1]
- Outline the action of ethene (ethylene). [2]
- Distinguish between quantitative and qualitative data. [2]
- Explain how the structure of cellulose is affected by acidification, and the role this plays in guiding plant growth. [3]
- Describe the interactions between auxin and cytokinin in regulating plant growth. [4]
- Explain how accuracy and precision can be achieved while collecting quantitative and qualitative data to observe tropic responses in plants. [4]
- Compare and contrast communication within the human body and plants. [6]
- Describe how auxin is transported in plants. [7]
- Explain positive phototropism. [7]

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