After working through this chapter, you should be able to:

- Discuss the importance of the special senses
- Name and identify the structures of the eye and ear
- Describe the physiological processes involved in vision and hearing
- Describe the physiological processes involved in the interpretation of taste and smell
- Provide an overview of the physiological response to noxious stimuli that results in the perception of pain

6.1 Introduction and clinical relevance

Each of the cases introduced in this chapter highlights how the integration of sensory information enables us to interpret our environment and its importance for health. These cases are presented to emphasize the knowledge about the sensory nervous system, perception and the impact of impairment of certain major senses on health and the ability to respond to risk and danger that is required for healthcare practice.

### Patient 6.1

Sally

Following a series of investigations, which included lumbar puncture, visual evoked potentials and magnetic resonance imaging (MRI), Sally was diagnosed with multiple sclerosis. Now at the age of 50 years, Sally’s mobility has become impaired and she is a wheelchair user. During the long course of her illness, Sally has experienced intense fatigue and various intermittent altered sensations in her body, including burning sensations in her hands and double vision.

### Patient 6.2

Sadia

Sadia is 82 years old and, although she has been fit and well for most of her life, she is currently mildly hypertensive, which is controlled by taking the diuretic bendroflumethiazide and the calcium channel blocker felodipine. Due to a family
In Chapters 4 and 5, the nervous and endocrine systems were discussed as the major systems for communication within the body. Making sense of the world in which we live and making appropriate responses to stimuli in our external environment is complemented by the homeodynamic response to stimuli in our internal environment, which together contribute to our protection and safety, for example maintaining our balance to prevent falls, avoiding touching hot materials that will damage the skin, and avoiding ingesting harmful or poisonous food. You may come across individuals with various types of neurological and sensory problems that may affect their ability, to varying degrees, to respond appropriately to changes in the external environment. Sally, Sadia and Denzel, due to sensory impairment, experience a variety of problems affecting their quality of life and maintenance of functional capacity. It is important for healthcare professionals to have appropriate background knowledge about the major senses to help inform the assessment, support, care and rehabilitation provided for individuals with neurological and sensory disorders.

6.2 What you need to know – essential anatomy and physiology

The role of special receptors monitoring the internal environment was discussed in Chapter 1. For health and wellbeing, there must be receptors integrated within systems to monitor the condition of the internal environment and to respond to changes. Sensory organs and systems are essential for monitoring and integrating environmental changes as part of homeodynamic adaptation and survival.
Changes in the internal and external environments (stimuli) are detected by sensory receptors, which take many forms. The term general senses describes sensitivity to stimuli such as temperature, touch and pressure. For example, thermoreceptors respond to temperature changes and baroreceptors detect changes in pressure and stretch. The term special senses refers to vision, hearing, taste and smell. In this chapter, each of the special senses will be discussed, as well as the general sense of touch.

### 6.2.1 Sensation and perception

Sensation requires transduction of the stimulus; for example, temperature, pressure or chemical stimuli are converted into another form (transduced), in this case a nerve impulse (action potential), by a sensory receptor. To hear sounds, fluctuations in air pressure are converted into waves in a fluid in the ear, which ultimately leads to alterations in specific receptors within the inner ear. Waves in the fluid stimulate the production of action potentials that are transmitted to the brain, where hearing is perceived. The sensations of smell and taste require the transduction of chemical stimuli into action potentials, which is achieved through the stimulation of taste and olfactory receptor cells. Similarly, for vision, packets of light energy (photons) stimulate photoreceptors that transduce photons into action potentials, which are transmitted via the optic nerve to the visual cortex of the occipital lobe of the brain where the action potentials are processed.

Sensory receptors may be discrete cells, such as those in the cochlea within the inner ear, or cells that form the retina of the eye. In addition, sensory receptors may be free nerve endings, such as those responsive to pressure or temperature. Free nerve endings may be abundant, as in the fingertips, or less densely packed, for example across the back.

Sensation refers to the immediate, unprocessed effect of stimulation of sensory receptors, while perception describes the interpretation of the world through the senses and involves the processing of action potentials from stimulated receptors. The interpretation of sensory impulses (perception) occurs in the cerebral cortex of the brain. Different regions of the cerebral cortex are concerned with specific senses; for example, the visual cortex is located in the occipital lobe. As described in Chapter 4, sensory (afferent) impulses, such as those arising from temperature changes, pressure or pain sensation (nociception), are conducted to the somatosensory area of the parietal lobe (somatic sensory cortex).

### 6.2.2 Vision and the eye

For vision, light energy (in the form of photons) from part of the electromagnetic spectrum called visible light, is focused onto specialized photoreceptors that lie within the retina of the eye. These receptors are activated according to the wavelength of the visible light. It is the spectrum of visible light (bands of colours) that we see when visible light is passed through a prism. When light stimulates the photoreceptors, chemical changes occur to create action potentials, which are conducted along sensory pathways to the primary visual cortex in the occipital lobe of each cerebral hemisphere.
The eye is a slightly irregular spherical object divided into two transparent fluid compartments. These are known as the anterior and posterior cavities and are separated by the lens and associated structures, including the ciliary body and iris (see Figure 6.1). The anterior cavity, which has an anterior and posterior chamber, contains a thin watery fluid called aqueous humour, which is continuously formed by the ciliary body. The formation and circulation of aqueous humour is important as it supplies oxygen and nutrients to the lens and cornea, which both lack blood vessels; if blood vessels were present, the passage of light would be obstructed. The constant production, circulation and drainage of aqueous humour maintain a constant intraocular pressure to help support the eye internally. The posterior cavity, which lies behind the lens, is filled with vitreous humour, a colourless, transparent, jelly-like fluid. Vitreous humour contributes to the intraocular pressure, transmits light and ensures that the two layers of the retina remain attached.

The eye has an outer protective fibrous covering called the sclera, and this can be seen as the white part of the eye. The sclera is attached to the orbital bone of the skull by extrinsic muscles, which enable the eye to move and focus on objects. The sclera becomes much thinner and clearer towards the front of the eye, forming the cornea (see Figure 6.1). When exposed to air, the sclera and cornea dehydrate quickly and therefore need to be kept constantly moist, and this is achieved by the formation of tears from the lachrymal glands, which are located underneath the top of the eyelid. Keeping the cornea and sclera moist is important to prevent eye infections and damage to the cornea. The importance of the mucus membrane of the eye (the conjunctiva), blinking and the production of tears as protective mechanisms to prevent infection is discussed in Chapter 11. Some people who suffer from dry eyes can benefit from the use of artificial tears, applied by eye drops, to keep the cornea moist.

![Figure 6.1 – A cross-section of the eye.](image-url)
The layer of tissue beneath the sclera is a highly vascular tissue with three regions: the choroid, the ciliary body and the iris. The choroid forms the posterior part of the vascular tissue, providing nourishment for the retina. The brown pigment of the choroid helps to absorb light, thus preventing light scatter within the eye. Towards the front of the eye, the choroid becomes the ciliary body, which encircles and supports the lens (see Figure 6.2). The ciliary body comprises interlacing smooth muscle cells called the ciliary muscle that controls the shape of the lens. Towards the back of the lens, the ciliary body has folds called ciliary processes (ciliary trabeculae), which produce the aqueous humour. Aqueous humour flows and drains away continuously (see Figure 6.3); it flows from the ciliary processes, filling the posterior chamber, through the pupil into the anterior chamber in front of the iris. From the anterior chamber, the aqueous humour drains into the venous system through the canal of Schlemm (scleral venous sinus). Obstruction to the flow and drainage of aqueous humour can result in an increase in the fluid pressure within the eye, which can be so severe as to compress the retina and optic nerve, resulting in an opthalmic condition known as glaucoma (see Sadia, Patient 6.2).

The lens is situated behind the iris and is held in place by the suspensory ligaments (see Figure 6.2) which help to support the lens and change the shape of the lens to focus light onto the retina (discussed later in the chapter). The suspensory ligaments are attached to the ciliary processes. The iris of the eye, with its opening, called the pupil, lies between the cornea and the lens. Formed by circular and radial smooth muscle cells and elastic fibres, the iris, under the influence of the autonomic nervous system, can contract or relax, causing constriction or dilation.
of the pupil and thus regulating accommodation (discussed later). Activation of the sympathetic nervous system causes contraction of radial muscle fibres, resulting in the pupil dilating, whereas constriction of the pupil occurs due to contraction of the circular muscles following stimulation by the parasympathetic nervous system (see Chapter 4). Assessing the responsiveness of the eye to light using a pen torch and observing constriction or dilation of the pupil is an important part of a neurological assessment. The normal pupillary reflex is where bright light causes constriction of the pupil. An abnormal pupillary light reflex, where one or both pupils remain dilated and unresponsive to the light, is an important diagnostic indicator of brainstem damage or damage to the optic nerve.

The retina (see Figure 6.1) is the innermost tissue of the eye, containing light receptor cells called rods and cones whose response to light will be discussed later in this chapter. The inner surface of the retina contains a network of blood vessels that nourish it. Fibres of the optic nerve exit the eye at a feature of the retina called the optic disc, which is slightly off centre to the incident plane of light that travels through the eye onto the retina. The positioning of the optic disc ensures that the plane of light stimulates light receptors, as the retinal tissue at the optic disc does not contain light receptors; hence, the alternative name for the optic disc is the blind spot. The retina, optic disc and network of blood vessels can be visualized with an ophthalmoscope (see Figure 6.4). Retinal vessels are readily visible using an ophthalmoscope, and changes to the appearance of these vessels can be an early indicator of chronic disease such as diabetes mellitus and hypertension.

The lens is a biconvex, transparent, flexible disc made up of concentric layers of highly organized cells. The crystalline lens comprises an outer lens capsule, the lens epithelium and lens fibres. A dense fibrous capsule surrounds the lens. The capsule is highly elastic, contributing to the change in the shape of the lens for focusing. The lens epithelium comprises cuboidal-shaped cells found on the anterior side of the lens. These cells are progenitor cells for lens fibre cells, which are elongated, transparent, tightly packed and found deep in the lens. Mature lens fibre cells are transparent, as they do not contain nuclei or organelles, but they do contain water-soluble proteins called crystallins, which make up the bulk of the lens. Crystallins contribute to the transparency and refractive properties of the lens and have a protective function against the development of age-induced deterioration of the lens, delaying the development of cataracts until older age (see Box 6.1). Lens fibres are added to the lens as ageing occurs, causing the lens to enlarge and become more convex and less flexible. Thus, the ability to focus also becomes impaired with age.

**Physiology of vision**

Eyes respond to visible light, which is the part of the electromagnetic spectrum that covers wavelengths from 400 to 700 nanometres (see Figure 6.6a). When light in the visible range of wavelengths travels through a prism, the light is dispersed to form a visible band of colours (spectrum). Objects have colour because they absorb light rays of certain wavelengths while reflecting other wavelengths. Objects that look white reflect all wavelengths. Colour vision occurs because the cones in the retina respond to different wavelengths of light (see Figure 6.6b).
Cataracts

A cataract is an opacity (cloudy area) in the lens (see Figure 6.5). According to the World Health Organization, cataracts are the most common cause of blindness worldwide. They can affect one or both eyes and, while more commonly associated with age, can result from other factors such as trauma, reaction to certain drugs and prolonged exposure to ultraviolet light (see the SunSmart guidelines in Chapter 12). Cataracts can be classified according to the part of the lens that is affected and whether or not they are congenital (occurring in children from birth), juvenile (occurring in young children) or adult. The presence of the cataract in the lens changes its transparency so an individual with a cataract will experience blurred and cloudy vision, and may find the glare from bright lights and the sun particularly problematic.

The lens is a transparent avascular structure with a high refractory index, which is a measure of the extent to which light bends when passing from air into another medium; in this case, it is the extent to which light is refracted when it meets the lens. These properties are achieved by the presence of structural proteins called crystallins within lens fibres. With age, long exposure to bright sunlight and oxidative stress, defective crystallins can accumulate, causing opacity in the lens (cataracts). The development of cataracts is also associated with several other factors including diabetes mellitus and a family history. Mutations in specific genes that encode specific crystallins also make crystallins more sensitive to damage by thermal and chemical stress, leading to the development of cataracts.

Figure 6.5 – Image of a cataract in the lens.

Figure 6.6 – (a) The electromagnetic spectrum and (b) photoreceptor (cone) sensitivities.
Focusing of light onto the retina

When light meets a transparent medium with a different density, its speed changes, and if the light rays meet the surface of the new transparent medium at an angle, the light rays bend. This is called refraction and occurs when light rays in air meet the lens of the eye. When light passes through the eye, it travels through the cornea, the aqueous humour of the anterior segment, the lens, the vitreous humour of the posterior segment and the entire thickness of the retina to stimulate the photoreceptors in the retina. Light is refracted as it passes through the cornea and on entering and leaving the lens. Changing the shape of the lens bends the rays of light so they converge onto the retina. Thus, light from objects at various distances can be focused onto the retina – a process called accommodation. If light passing through the cornea and lens is not refracted correctly, the image will appear distorted.

In normal vision, the farthest point of vision beyond which no further change in lens shape is required for focusing is 6 metres (20 feet). This distance is used as a normal standard for visual acuity. The term 20/20 vision is used to express the clarity or sharpness of vision measured at a distance of 20 feet. 20/20 vision means you can see clearly at 20 feet what should normally be seen at that distance. If a person can only see at 20 feet what someone with ‘normal vision’ could see at 40 feet, then that individual is described as having 20/40 vision. The term 20/20 vision does not mean perfect vision; it only describes the level of clarity or sharpness of vision at a particular distance. During distant vision, the lens is flattened as the ciliary muscle relaxes, producing tension in the suspensory ligaments, which pull the lens, making it stretch and flatten (see Figure 6.7a).

When focusing on a close object, light rays are divergent and therefore the lens shape needs to be adjusted to increase refraction (see Figure 6.7b). To restore focus, three actions occur: accommodation of the lens, constriction of the pupil and convergence of the eyes (the eyes turn inward). Accommodation of the lens involves contraction of the ciliary muscle, enabling it to move forwards towards the pupil. Tension is then released in the suspensory ligaments so that the elastic fibres of the lens recoil, causing the lens to bulge. Accommodation is gradually lost with age as the lens becomes less elastic, causing presbyopia, a condition where there is difficulty focusing on close images.

![Figure 6.7 – Accommodation: focusing for (a) distant vision and (b) close objects.](image-url)
The retina and photoreceptors

The retina comprises two layers – an outer pigmented layer that is in contact with the choroid, and a transparent inner layer called the neural layer (see Figure 6.8). The pigmented layer absorbs light and prevents light scatter. The neural layer contains the photoreceptors, called rods and cones. The junction between the pigmented layer and the neural layer is structurally weak and can separate, resulting in a condition called a detached retina, which is a cause of altered vision.

Photoreceptors (rods and cones) are modified neurones, with an inner segment and an outer segment. The outer segment of photoreceptor is embedded in the pigmented layer of the retina, whereas the inner segment connects to the cell body of the neurone in the neural layer (see Figure 6.8). The outer segment is the receptive zone and contains a mass of visual pigments that alter shape as they absorb light. Rods are more numerous, amounting to approximately 110–130 million, and are spread throughout the retina, including the peripheral region. There are fewer cones (approximately 5–7 million), and these are concentrated in an area called the fovea centralis of the retina.

Rods and cones contain proteins called opsins, which are bound to retinal, a light-absorbing molecule derived from vitamin A, to form specific visual photopigments that absorb different wavelengths of light. Rods contain the photopigment rhodopsin (a combination of a specific opsin and retinal). Rods contain much more photopigment than cones, and this explains in part their greater sensitivity to light. Cones contain different forms of opsin combined with retinal to form photopsins. There are three distinct types of cone, defined by the photopsins present within them, each responsive to a particular wavelength within the visible spectrum. One type of cone is more sensitive to short wavelengths (S cones), one to medium wavelengths (M cones) and the third to medium to long wavelengths (L cones) (see Figure 6.6b). They are often called blue cones, green cones and red cones, respectively. The variation in signals from each cone type enables the brain to perceive colour. Cones that are stimulated by wavelengths

![Figure 6.8 - A simplified diagram of the retina.](AAPH_0608.eps)
reflecting green and red are particularly located in the fovea centralis onto which light is focused, ensuring greatest visual clarity. Cones that are responsive to light in the blue wavelength, which account for approximately 2% of all of the cones, are more sensitive to light compared with the other cones and therefore they lie outside the fovea centralis. Rods and cones, via intermediary neurones, connect to retinal ganglion cells in the neural layer of the retina (see Figure 6.8). Retinal ganglion cells transmit action potentials from the rods and cones to the brain via the optic nerve.

Rods are very sensitive to dim light and hence ideal for night vision. As they are predominantly located in the peripheral retina, they have an important role in peripheral vision. Rods only contain rhodopsin, and therefore vision is perceived only in grey tones, and because many rods connect with a few retinal ganglion cells, visual acuity is reduced and vision less clearly defined. Cones are activated by bright light and, due to the three different classes of photopsins, vision is perceived in colour. Colour vision depends on the overlap in sensitivity to a range of wavelengths of light across all three receptor types. The activity of one or more types of cone may be impaired, which can lead to colour blindness; this is described in Box 6.2. Stimulation of cones produces vision that is sharp and distinct because individual cones connect to individual retinal ganglion cells and therefore perception in the visual cortex is of a higher resolution.

In bright light, rods are inactivated as rhodopsin is bleached by the intensity of the light. Initially, both rods and cones are stimulated, providing a brief glaring effect. As the cones recover following the initial intense stimulation and the rods become deactivated, colour vision and visual acuity improve. This occurs over 5–10 minutes. Moving from areas of light to darkness results in deactivation of cones and the gradual reactivation of rods, as rhodopsin is formed and accumulates slowly. Adaptation from bright sunlight to complete darkness takes approximately 20–30 minutes.

The visual pathway
This involves the conduction of sensory nerve impulses from activated photoreceptors to the brain, where signals are processed in the visual cortex of the occipital lobe. The sensory nerve axons from the retinal ganglion cells are organized into the optic nerve (cranial nerve II) (see Figure 6.9a). The arrangement of the axons within the optic nerve means that the activity of the photoreceptor

**Box 6.2**

**Colour blindness**
In order to see the full array of colour, the correct proportions of the three types of cone (blue, green and red) are required to be present. Colour blindness is due to mutation of the genes that code for the specific opsins associated with one or more cones. Colour blindness is usually classified as an autosomal recessive X-linked condition (see Chapter 3), although mapping of the human genome has identified causative mutations on at least 19 other chromosomes. As the mutations are more commonly linked to the X chromosome, colour blindness is more common in males. The most common form of colour blindness involves the absence of or a reduced number of cones that respond to red or green wavelengths of light.
cells of the left side of the retina of each eye is conducted to the left occipital lobe and the activity from the right side of the retina of each eye to the right occipital lobe. In other words, each occipital lobe processes information from the same visual field (see Figure 6.9a). Fibres from the medial (nasal) aspect of each eye cross over. The crossing over of the fibres occurs at the optic chiasma. Crossing over of the fibres is useful as it helps visual processing by the brain, enabling the perception of depth and three-dimensional images. The relay of sensory impulses to the occipital lobe of the brain and the processing of visual information is complex, involving different parts of the cerebral cortex and areas of the brain including the thalamus. Some people who experience a stroke may have damage to the neural pathways altering vision, such as a homonymous hemianopia where there is a loss of vision in either the left or right half of the visual field (see Figure 6.9b).

Control of eye movement
Six extrinsic (extraocular) eye muscles control the movement of each eyeball. The eye muscles are attached to the bones that form the eye socket (bony orbit) and to the sclera. The muscles effectively support the eye in the orbit and allow the eye to follow objects. The term strabismus (also called a squint) refers to a condition where the eyes deviate (eye turning) when looking at a specific object. This is usually due to a lack of coordination between the extrinsic muscles of the
eyes and can be evident in babies and children. Strabismus can cause amblyopia, a condition commonly known as ‘lazy eye’, where there is reduced vision in one eye and the brain favours signals from the eye with clearer vision. Treatment for strabismus and amblyopia commonly involves glasses with prescriptive lenses, eye exercises and vision therapy, botulinum toxin injections and corrective eye surgery.

6.2.3 Taste and smell

The sensations of taste and smell are not mutually exclusive. Taste and smell arise from stimulation of chemoreceptors. In the case of smell, chemicals stimulate chemoreceptors in the nasopharynx and oropharynx, whereas with taste, chemicals within food dissolve in the saliva and activate taste receptors, which are found mainly on the tongue. Activation of receptors involved in the sensation of smell is an important part of our perception of taste. Taste and smell can result in pleasurable sensations, but chemoreceptors involved with taste and smell also have important protective functions; for example, we are less likely to eat harmful food that smells or tastes disgusting.

The sense of taste

Taste sensation usually involves a combination of qualities. Taste receptors are located in taste buds, the majority of which are located on the tongue. There are five main groups of taste receptors (taste buds) currently recognized. These are sweet, sour, salty, bitter and umami (savoury). Taste is an important aspect governing appetite and nutritional intake, as well as the avoidance of harmful chemicals. Activation of specific taste buds has traditionally been mapped to various parts of the tongue (see Figure 6.10a); however, new scientific techniques indicate that different taste qualities can be elicited from all areas of the tongue where there are taste buds. Nevertheless, it is clear that a single taste bud can only respond to a single and specific chemical combination (taste quality).

Most taste buds are located in the papillae of the tongue. Papillae give the tongue a rough appearance and feel. Each taste bud contains numerous taste cells (gustatory cells), with each cell having hair-like projections on the upper surface that project through a taste pore onto the epithelial surface of the tongue (see Figure 6.10b). The hairs are the sensitive part of the gustatory cells. Coiled tightly round the gustatory cells are the dendrites of sensory nerves that form the initial part of the taste (gustatory) sensory pathway. When stimulated, taste cells release neurotransmitters that activate sensory neurones. Sensory stimulation of the posterior third of the tongue is conducted to the brainstem along the glossopharyngeal nerve (cranial nerve IX) and that of the remaining two-thirds of the tongue via the facial nerve (cranial nerve VII). Sensory impulses from taste receptors located in the soft palate, pharynx and epiglottis are conducted by the vagus nerve (cranial nerve X). Sensory impulses are conducted through the medulla of the brainstem to a relay station in the thalamus of the brain and then on to the sensory cortex in the insula lobe of the brain (see Figure 6.11 and Chapter 4), producing the conscious perception of taste.
Alterations in taste, for example the development of a metallic taste, can occur for a variety of reasons, including teeth and gum disease, acid reflux and some drugs.

The sense of smell: olfactory epithelium and neural pathways

The sense of smell depends on activation of olfactory receptors (a type of chemoreceptor) present in a region of epithelial tissue (olfactory epithelium) in the roof of the nasal cavity (see Figure 6.12). The nasal epithelium contains millions of ciliated olfactory receptor cells coated with a thin mucus produced by olfactory glands. Inhaled chemicals dissolve in the mucus and activate specific receptors located within the membrane of the olfactory receptor cell cilia. When olfactory receptors become saturated, the sense of smell becomes blunted.

Stimulation of olfactory receptors leads to the formation of sensory nerve impulses conducted via axons that collect together to form the filaments of the olfactory nerve (cranial nerve I). These filaments pass through gaps in a section of the ethmoid bone in the roof of the nose called the cribriform plate (see Figure 6.12). Filaments of the olfactory nerve then synapse with olfactory bulbs overlying the cribriform plate. From the olfactory bulbs, which form the ends of the olfactory tract, sensory nerve impulses are conducted to the olfactory cortex in the frontal lobe of the cerebrum. In addition, sensory impulses are also relayed to other parts of the brain such as the hypothalamus and limbic system (see Chapter 4), triggering an emotional response, such as pleasure or a sense of danger, or a protective reflex response such as sneezing.

6.2.4 Hearing

Hearing is the perception of sound, which can be described subjectively in terms of loudness and pitch (high or low). Sound consists of fluctuations of pressure, taking the form of waves with alternating high pressure (compression of molecules) and decompressions (rarefactions) that are transmitted in air and, as explained later, also in fluid. In air, a pressure wave produced by a single tone (pure tone) can be illustrated using a sine wave, where positive peaks represent high pressure and negative peaks (troughs) represent decompression (see Figure 6.13a). Sound can be regarded as a mixture of pure tones.

The amplitude of the sine wave (see Figure 6.13b) is associated with the loudness of the tone. The number of cycles of the wave determines the frequency and is associated with the perception of the pitch of the sound (see Figure 6.13a). Frequency is measured in terms of cycles per second or hertz (Hz), and one cycle per second is equal to 1 Hz. Typically, young adults can detect sound over a range between 20 and 20 000 Hz where 20 Hz is low frequency and 20 000 Hz is high frequency. With age, the ability to detect higher frequencies deteriorates and the maximum frequency detected by middle-aged adults can fall to 14 000–16 000 Hz.

The magnitude of the pressure wave is referred to as the amplitude. The greater the amplitude, the louder the sound will be perceived. Sound intensity is measured in decibels (dB) based on a logarithmic scale from 1 to 140 dB. A decibel is a relative and not an absolute measurement as it expresses how many units one
A normal conversation may register as 45–60 dB, while maximum sound through an MP3 player may reach 115 dB. Sustained sound intensity above 85 dB can cause permanent hearing loss. Sudden sounds of 115–120 dB can cause ear pain and disturbance of balance.

Structure of the ear

The ear is divided into three parts (see Figure 6.14): the outer (external), middle and inner ear. The outer and middle ear are involved with hearing, whereas the inner ear is concerned with both hearing and balance. The outer and middle ear are referred to as the conductive system, as they conduct sound waves from the environment to the inner ear.

The external ear comprises the pinna, which is also called the auricle, and the external auditory meatus (external auditory canal). The pinna is composed of cartilage covered in skin and is organized into folds, which funnel sound waves into the external auditory meatus. The surface of the auditory meatus comprises skin with hairs and ceruminous glands, which secrete cerumen (ear wax). Cerumen and hairs provide additional protection, preventing infection. Excessive accumulation and impaction of cerumen in the meatus can impede the conduction of sound waves, resulting in deafness. The external auditory meatus meets the tympanic membrane (ear drum), which divides the external and middle ear. The tympanic membrane is a thin, transparent and flexible membrane covered with skin on the external side of the ear, and is able to vibrate. It is shaped like a flattened cone with the apex of the cone pointing into the middle ear. Thinness of the tympanic membrane provides flexibility, allowing the membrane to vibrate when hit by sound waves.

The middle ear is an air-filled cavity, lined by mucosa (mucus-producing epithelial cells), situated within a bony cavity within the temporal bone of the skull. There

Figure 6.12 – The olfactory epithelium and olfactory tract.

Figure 6.13 – The sine wave: a pure tone sound.
are openings in the bony cavity – the oval window, the round window and the Eustachian tube (pharyngotympanic tube) (see Figure 6.14). This tube runs down to the nasopharynx, linking it with the middle ear, and is responsible for draining mucus produced by cells in the middle ear and for equalizing air pressure in the middle ear, particularly during times of sudden changes in air pressure. For example, when descending in an aeroplane, swallowing and chewing help to keep the tube open. It is not uncommon to have some slight hearing loss when suffering from a cold (an upper respiratory tract infection). This is often because the Eustachian tube becomes blocked due to swelling of the mucosa, leading to a build-up of fluid and air pressure, which impedes vibration of the tympanic membrane. In children, the tube is shorter, narrower and less vertical, increasing the risk of frequent middle ear infections (otitis media).

The middle ear is spanned by the smallest bones in the body (see Chapter 13) – the ossicles: the malleus (hammer), the incus (anvil) and the stapes (stirrup). The handle of the malleus is attached to the tympanic membrane and the stapes abuts the oval window. Via small synovial joints, the malleus articulates with the incus, which articulates with the stapes, collectively transferring the vibration of the tympanic membrane into vibration of the oval window. A way to remember the order of the ossicles is to think ‘the hammer hits the anvil to make the stirrup’. Two
very small skeletal muscles are associated with the ossicles and these help to protect the hearing receptor cells from damage during loud noises by tensing the tympanic membrane and restricting the movement of the stapes against the oval window.

The inner ear comprises the vestibular apparatus, concerned with balance, and the cochlea, which houses the hearing receptors, in a structure called the organ of Corti. As illustrated in Figures 6.15a and b, the cochlea is a spiral, bony chamber shaped like a snail shell, composed of three chambers that spiral around a bony pillar called the modiolus. The chambers are the scala vestibule, which abuts the oval window, the scala tympani, which ends at the round window, and a middle chamber called the scala media (also known as the cochlear duct), which houses the organ of Corti. The scala vestibuli and the scala tympani merge at the apex where they connect at a region called the helicotrema.

Each of the spiralling chambers is fluid filled. The scala media has a membranous lining filled with a fluid known as endolymph, produced by cells in the membrane. The scala vestibuli and scala tympani contain perilymph, which has a similar composition to cerebrospinal fluid. The floor of the cochlear duct is a flexible structure called the basilar membrane, which supports the organ of Corti.

**Physiology of hearing**

Hearing occurs when the primary auditory cortex in the temporal lobe is stimulated. In the initial stage of hearing, sound waves are conducted down the external auditory meatus, causing the tympanic membrane to vibrate at the same frequency as the sound waves. The greater the amplitude of the sound waves, the greater the displacement of the tympanic membrane. The pressure change against the tympanic membrane is transmitted through the middle ear by articulation of the ossicles, leading to movement of the oval window by the stapes. The action of the ossicles amplifies the motion of the tympanic membrane because the tympanic membrane is much bigger than the oval window and so the pressure exerted on the oval window is about 20 times greater than that exerted on the tympanic membrane. This greater pressure overcomes the resistance in the fluid (perilymph) in the scala vestibuli of the cochlea to the transmission of the pressure wave.

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**Figure 6.15** – (a) The cochlea, (b) a cross-section of the cochlea and (c) the organ of Corti.
The vibration of the oval window, induced by the motion of the stapes, creates pressure waves through the perilymph from the basal end of the scala vestibuli towards the helicotrema, distorting the basilar membrane at different locations depending on the frequency of the pressure wave. Close to the beginning of the cochlear duct, the basilar membrane is narrow and under tension at its base, and responds best to high-frequency sounds. Towards the helicotrema, at the apex, the basilar membrane becomes wider and under less tension and is therefore adapted to respond to lower-frequency sounds.

The movement of the basilar membrane excites the receptor cells of the organ of Corti. The organ of Corti is located on top of the basilar membrane and comprises supporting cells and cochlear hair cells (receptor cells) (see Figure 6.15c). The hair cells typically are arranged as a single row of inner cells and three rows of outer hair cells. Each hair cell has numerous hair-like structures called stereocilia that protrude into the endolymph, with the longest stereocilia embedded in an overlying gel-like membrane called the tectorial membrane. Sensory fibres from the cochlear nerve (a division of the vestibulocochlear nerve – cranial nerve VIII) are coiled around the base of the hair cells. Localized movement of the basilar membrane, due to the pressure wave in the endolymph, bends the stereocilia (see Figure 6.16). Displacement of the stereocilia causes the neurone at the base of the hair cells to generate an action potential that is conducted along the afferent cochlear nerve, which forms part of the vestibulocochlear nerve, to the auditory cortex located in the temporal lobe of the cerebrum for interpretation of the sound. In this way, the hair cells in connection with the basilar membrane transduce mechanical events into neural information. Many factors can influence the transmission of sound waves from the external environment to their eventual transduction and perception as hearing (summarized in Box 6.3).

**Mechanisms of hearing loss and tinnitus**

The mechanisms associated with hearing loss are complex, but essentially hearing loss can arise from a problem with how sound is conducted to the inner ear via the outer and middle ear (conductive hearing loss) and, more commonly, from problems located within the structures of the cochlea (sensorineural hearing loss). There are a number of causes of sensorineural hearing loss, including age-related changes to sensory cells (presbycusis), certain types of drugs (e.g. some types of chemotherapy used to treat cancer, or specific antibiotics) and exposure to loud noises.

Persistent exposure to loud noises causes metabolic fatigue and death of cochlear hair cells. Mutations in genes required for the development of hair cells are associated with childhood congenital deafness and age-related hearing loss.

**Tinnitus** is the perception of noise in the ears without any external auditory stimulus and is often a subjective phenomenon, making it difficult to measure using objective audiological tests. It is often described as a ringing noise, buzzing or high-pitched whining. Tinnitus is caused by a number of factors, the most common of which is noise-induced hearing loss. Various theories have been proposed to explain the cause of tinnitus and most converge on alterations in the processing of neural stimuli in the ear and central nervous system.
The vestibular system and the physiology of balance

The vestibular system in the inner ear responds to changes in movement of the head, sending motor signals that stimulate head and eye movements to provide the retina with a stable visual image and to cause adjustments in muscle tone for the maintenance of posture and balance. Maintaining balance involves not only information from the vestibular system but also sensory information from the eyes and proprioceptive receptors in joints and muscles. We will focus briefly on the vestibular system in the inner ear.

The vestibular apparatus

Sensory receptors, located in the semicircular canals and vestibule, respond to changes in head position and are collectively called the vestibular apparatus. The semicircular canals and the vestibule, composed of the utricle and saccule, are illustrated in Figure 6.17. Semicircular canals are rigid, bony structures lined with a membranous labyrinth and contain endolymph.

Sensory receptors called maculae detect linear acceleration (changes in movement of the head in a straight line). Each macula, one located in the wall of each utricle and saccule, contains hair cells that project into the otolith membrane, a gel-like mass (see Figure 6.18a and b). The otolith membrane is studded with calcium carbonate crystals called otoliths. When the head starts or stops moving, the otolith membrane slides forwards or backwards, bending the hair cells, producing sensory nerve impulses that are conducted to the brain via the vestibular nerve (a branch of the vestibulocochlear nerve – cranial nerve VIII).

Rotational movement of the head is detected by a specialized sensory receptor called the crista ampullaris located in the ampulla of each semicircular canal. Each crista is composed of individual hair cells (similar to the hair cells in the

Figure 6.17 – The vestibular apparatus.
organ of Corti and the maculae), each with stereocilia and a single kinocilium (a special type of cilium) embedded in a gelled mass called the cupula (see Figure 6.18c). When the head rotates in the plane of the semicircular duct, the movement of the endolymph along the length of the duct pushes the crista to one side. Movement of the crista bends the stereocilia. Bending of the stereocilia towards the kinocilium produces an action potential in the hair cell. Movement of the endolymph in the opposite direction, so that the stereocilia bend away from the kinocilium, inhibits the production of an action potential. The cristae in each semicircular duct operate in a complementary way. Depending on the rotational movement of the head and the sudden movement of the endolymph, hair cells in the crista of one semicircular duct will be stimulated, while in another crista the hair cells will not be activated. The positioning of the semicircular canals and ducts is therefore important for determining the position and movement of the head and in achieving equilibrium. Even complex movement can be reduced to three rotational planes. For example, a horizontal motion, as in shaking the head to say no, stimulates the hair cells in the lateral semicircular ducts. Nodding the head stimulates hair cells in the anterior semicircular duct, while tilting the head from side to side excites receptors in the posterior semicircular duct. Sensory impulses from the sensory receptors in the semicircular ducts and vestibule are conducted via the vestibular branch of the vestibulocochlear nerve to the brainstem and cerebellum for processing.

Balance problems and dizziness can be caused by a number of factors, including age, a sudden fall in blood pressure (e.g. postural hypotension) and heart rhythm disturbances, as well as vestibular problems (see Box 6.4); falls due to balance problems present a significant health burden.

6.2.6 Touch

Touch receptors are classified as mechanoreceptors. The sensory endings of touch receptors may be free or encapsulated. Touch receptors include the following:
• **Merkel's discs** – these are free nerve endings in contact with cells in the epidermis of the skin.

• **Meissner's corpuscles** – these are located deep within the dermis of the skin and are egg-shaped structures in which nerve endings are encapsulated.

• **Pacinian (lamellar) corpuscles** – these encapsulated receptors are oval structures in the dermis that are sensitive to on and off pressure stimuli. Pacinian corpuscles are also located in the deep subcutaneous tissue, in submucosal tissue, in tissue around joints and in mammary glands.

The sensation of an itch (pruritis) arises from stimulation of itch receptors, located superficially within the basal layer of the epidermis of the skin. They respond to the same range of chemicals (histamine and non-histamine) that are also involved in the perception of pain when noxious chemicals stimulate nociceptors.

**Nociceptors and the perception of pain**

The International Association for the Study of Pain describes pain as 'an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage'. The perception of pain is complex and subjective, and is influenced by social and cultural factors, mood and belief systems, as well as neurophysiology. Pain is an unpleasant sensory and emotional phenomenon that can have a significant impact on a person’s quality of life, psychological wellbeing, social interactions and economic status.

The perception of pain offers protective functions and, in part, limits ongoing damage that may be associated with the sensation of pain. The experience of pain can be categorized as acute or chronic (when the sensation of pain lasts more than 6 months). Acute pain evoked by brief noxious stimuli and the associated sensory transmission is generally well understood, but this is not the case with chronic pain syndromes, which remain to some extent a mystery. This section is not aimed at discussing the perception and management of pain but simply highlights nociception as a major part of sensory function.
The perception of pain starts with the stimulation of nociceptors, which are relatively unspecialized nerve endings that respond to various stimuli (chemical, thermal and mechanical). Some nociceptors respond to only one type of noxious stimuli, such as chemical (e.g. histamine, bradykinin and prostaglandins released by damaged cells), while others are polymodal, responding to more than one stimulus. Nociceptors are nerve endings of particular afferent fibres. Nociceptors associated with the perception of sharp pain are connected to small-diameter myelinated A-delta (\(\delta\)) sensory fibres, which conduct sensory impulses rapidly (5–25 m/second). The perception of an ache, and with that the feeling of nausea, is associated with nociceptors located at the distal end of smaller, unmyelinated C fibres that conduct sensory impulses relatively more slowly at 0.5–2.0 m/second. Nociceptors attached to the fast A\(\delta\) fibres are located in the skin and mucous membranes, whereas the C fibre nociceptors are found throughout the skin and body tissues, excluding brain tissue.

Afferent impulses from stimulated nociceptors are conducted to the spinal cord and then travel up the spinal cord to the brain, for example via the major ascending pathway called the spinothalamic tract (see Chapter 4). The relay of sensory information and interpretation of the sensory impulses involves various regions in the central nervous system including the brainstem, thalamus and higher centres of the primary sensory cortex of the parietal lobe of the brain.

The transmission of sensory impulses from nociceptors and the perception of pain can be modulated in a number of ways, such as the secretion of naturally occurring opioids (endorphins), and through the release of inhibitory neurotransmitters at synapses within the spinal cord as a result of descending influences from the brain. Pain is a subjective experience and therefore difficult to define simply in objective terms. This has given rise to a number of theories of pain perception, the most accepted being the neuromatrix theory of pain, which proposes that pain is a multidimensional experience produced by characteristic patterns of nerve impulses generated by a widely distributed neural network and that transmission of sensory impulses via ascending pathways in the spinal cord is modulated by a gating mechanism in the dorsal horn. Synapses that occur between neurones function as gates. Sensory impulses are transmitted to the brain when the gate is open and are inhibited when the gate is closed. Excitatory neurotransmitters are released at the synapse to ‘open the gate’ and inhibitory neurotransmitters ‘close the gate’, preventing the transmission of sensory impulses to the brain and thus the perception of pain. A\(\beta\) afferent fibres, when stimulated, release inhibitory neurotransmitters in the spinal cord and can be activated by massage, acupuncture and the use of transcutaneous electrical nerve stimulation (TENS). These techniques are utilized in healthcare to help alleviate pain.

6.3 Clinical application

The special senses and the ability for us to perceive the world are important for responding to others and our environment. Impairment of our senses can leave us exposed to risk, which may result in significant health problems. The cases in
this chapter highlight some of the challenges that can occur when one or more of the special senses are impaired.

- **Sally (Patient 6.1)** suffers with multiple sclerosis, a progressive neurological condition affecting sensory and motor function. As a consequence, Sally experienced a number of altered sensations around her body and developed problems with her vision.
- **Sadia (Patient 6.2)** demonstrates how a relatively simple surgical procedure such as cataract removal can make a remarkable improvement to her quality of life, enabling Sadia to retain her independence.
- **Denzel (Patient 6.3)** illustrates some of the problems individuals can experience following exposure to loud noise over time, inducing hearing loss and tinnitus, which can affect the quality of life and awareness of hazards.

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**Patient 6.1**

Sally presented to her family doctor with a series of non-specific neurological symptoms that collectively suggested a diagnosis of multiple sclerosis (MS). Sally experienced a burning feeling in her hands, double vision and an inability to focus. Double vision (diplopia) is a common symptom associated with MS due to poor coordination between the eye muscles as a result of impaired nerve conduction to one or more of the eye muscles. Patients sometimes report abnormal sensations including 'pins and needles', stabbing pains, pruritis, burning and numbness (paraesthesia), all of which suggest disordered sensory function. The signs and symptoms are often intermittent and non-specific, making MS difficult to diagnose, especially in the earliest stages of the disease. Sally underwent magnetic resonance imaging (MRI) of the brain, and this demonstrated the presence of lesions called plaques in the white matter of her central nervous system (see **Chapters 4 and 13**), consistent with MS.

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**Patient 6.2**

Over a period of one year, Sadia had successful cataract operations on each eye. On both occasions, the operation and Sadia's recovery were uneventful. Removal of the cataracts and insertion of new intraocular lenses, with appropriate changes in her prescription for her reading glasses, have dramatically improved Sadia's quality of life. With the restoration of her vision, Sadia has a new confidence when walking, shopping and undertaking daily activities. She is more positive in her mood and is once more enjoying reading and knitting, activities that enhance the quality of her life. Importantly, her improved vision also enhances her safety, as she is able to detect and avoid hazards and is less likely to stumble and fracture her hip.
Following band gigs over a number of years, Denzel experienced ringing in his ears and some hearing loss. Denzel is able to identify key moments when he felt the damaging effects of loud noise while playing in the band. Denzel wore ear plugs for monitoring purposes and not as ear protection. At points when the music was very loud, he experienced sudden discomfort in his ears and felt the room spin. Unfortunately, over the years Denzel did not wear ear defenders developed for musicians when playing in the band and has consequently developed symptoms associated with acoustic trauma – tinnitus (persistent ringing and hissing in the ears) and hearing loss. Fortunately, Denzel is able to cope with the tinnitus and has not needed specific therapy such as counselling and sound therapy. Denzel underwent an audiogram, and a similar audiogram to Denzel's, associated with acoustic trauma, is illustrated in Figure 6.19. The circles and crosses on the audiogram indicate the intensity level at which the person just starts to hear a sound at different frequencies (Hz), represented as the hearing level in decibels (dB HL). If a person can only just hear the sound at 20 dB HL or higher, he or she is judged to have a hearing impairment. The audiogram illustrates that hearing loss increases progressively as the higher frequencies are tested. For example, at 3000 Hz the hearing level for the right ear is 40 dB HL, which is at a level regarded as abnormal. In Denzel's case, his hearing loss was most noticeable at 3000 Hz and above. With a hearing loss at high frequencies, a hearing aid is not always required. Denzel is able to hear others talk in most conversations, he can engage fully in work and social interactions, and he is not at risk, for example by not hearing traffic approach, so he does not require a hearing aid.

**Figure 6.19** – Audiogram demonstrating the effects of noise exposure, showing the results of a normal hearing test and an impaired-hearing test.
6.4 Summary

- Sensation refers to the immediate, unprocessed stimulation of sensory receptors, and perception describes the interpretation of the world through the processing of sensory information. Both are essential for responding to the environment to ensure survival.
- Vision involves the processing of stimuli from light-sensitive receptors (rods and cones) contained in the retina of the eye (see Figure 6.8).
- Taste and smell result from stimulation of chemoreceptors primarily on the tongue (taste) and nasal cavities (smell) (see Figures 6.10, 6.11 and 6.12).
- Hearing involves the conduction of pressure waves through the external, middle and inner ear, resulting in the displacement of the hair cells of the organ of Corti (see Figure 6.16) and the production of action potentials, which are conducted via the acoustic nerve to the temporal lobe of the brain.
- Balance is maintained through the integration within the central nervous system of complex sensory information involving stimulation of sensory receptors located in the vestibular apparatus of the inner ear caused by changes in the position of the head, initiating motor responses to maintain balance (see Figure 6.17).
- Touch involves the activation of specialized mechanoreceptors located throughout the body such as in the skin, subcutaneous tissue and joints.
- The perception of pain commences with the stimulation of nociceptors, which respond to various noxious stimuli. Nociceptors may either be specific for one chemical or polymodal, whereby they respond to a variety of stimuli (chemical, thermal and mechanical).

6.5 Further reading

Blindness and impaired vision present a huge global burden with approximately 39 million blind people and 246 million people with low vision. The World Health Organization (WHO) provides a useful resource highlighting the burden of blindness together with strategies to prevent blindness: www.who.int/blindness/en/

Understanding the cause, assessment and management of pain is an important aspect of healthcare but pain can be difficult to describe and sometimes difficult to manage. The web pages for the International Association for the Study of Pain (IASP) contain a wealth of valuable resources to guide health professionals: www.iasp-pain.org/

The following textbook is an excellent reference source, covering a comprehensive range of topics, including basic aspects, clinical states, therapeutic aspects, neurophysiology, psychology and the measurement of a variety of pain syndromes: McMahon, S.B., Koltzenburg, M., Tracey, I. and Turk, D. (2013) Wall and Melzack’s Textbook of Pain. 6th edn. Elsevier Churchill Livingstone, Philadelphia, USA.
6.6 Self-assessment questions

Answers can be found at www.scionpublishing.com/AandP

(6.1) Select the one correct response. Conduction of sound from the middle ear to the inner ear involves the movement of:
(a) the malleus against the oval window
(b) the incus against the tympanic membrane
(c) hair cells in the organ of Corti
(d) air along the external auditory canal
(e) the stapes against the oval window

(6.2) Select the one correct answer. The impairment of drainage of aqueous humour can result in which of the following conditions?
(a) Conduction deafness
(b) Glaucoma
(c) Colour blindness
(d) Cataracts
(e) Compaction of wax in the external auditory canal

(6.3) Select the one correct response. The perception of smell occurs in the olfactory cortex in the:
(a) occipital lobe
(b) frontal lobe
(c) insula
(d) parietal lobe
(e) brainstem

(6.4) Select the one correct response. Polymodal nociceptors are stimulated by:
(a) light rays
(b) only chemical stimuli
(c) fluid waves
(d) only thermal changes
(e) noxious chemical, thermal and mechanical stimuli

(6.5) Identify the type of receptor involved in each sensory activity by indicating the appropriate letter from the key (each receptor type may be used once, more than once, or not at all).

<table>
<thead>
<tr>
<th>Sensory activity</th>
<th>Receptor type key</th>
</tr>
</thead>
<tbody>
<tr>
<td>You have just scalded yourself with hot water</td>
<td>A. Chemoreceptor</td>
</tr>
<tr>
<td>You feel uncomfortable after a very large meal</td>
<td>B. Photoreceptor</td>
</tr>
<tr>
<td>You have bumped your arm and it is sore</td>
<td>C. Nociceptor</td>
</tr>
<tr>
<td>You enjoy the smell of newly cut grass</td>
<td>D. Thermoreceptor</td>
</tr>
<tr>
<td>You react quickly to the glare of bright sun</td>
<td>E. Mechanoreceptor</td>
</tr>
</tbody>
</table>

(6.6) Outline how rods are involved in the adjustment from light to dark environments.

(6.7) Outline why it is good to check for compacted ear wax if a person starts to complain of hearing loss.