

Chapter 1

INTRODUCTION TO NORMAL BINOCULAR VISION

1.1 The end product of binocular vision

Normal binocular vision is defined as the integration of monocular sensory and motor visual information into a combined percept of the surrounding physical space. This visual percept is heavily edited by the brain. It is affected by visual memory, and we sometimes react to visual stimuli before they pass into consciousness. This book sets out the processes and equipment involved in that editing.

Human binocular vision has several advantages over monocular vision. The obvious advantage is **single vision** rather than double vision, or vision alternating between each eye. Next, the subtle difference between the right and left viewpoints allows the most accurate form of depth perception, **stereopsis**. It is possible to see the effect of the different viewpoints in binocular vision by holding a hand edge in front of the eyes, and then closing each eye in turn. Stereopsis assists primates in hand–eye coordination and in precise interception of mobile food sources. Stereopsis helps to identify threats – adversaries may be spotted moving across the visual field with monocular vision, but when stationary, three-dimensional vision helps to identify a specific threat from background visual information. This is known as **figure–ground separation**, or breaking camouflage. With binocular vision, the amount of **binocular convergence** used to fixate a target with each eye allows an approximate assessment of the target distance by triangulation. Binocular vision also helps with **spatial localisation**: visual attention can be concentrated on objects situated in the plane of the binocular fixation point, allowing distracting stimuli nearer or farther away to be ignored. Binocular perception has advantages over monocular vision in assessing **surface curvature**. It also allows enhanced **surface material perception** using lustre perception.

At a higher level of visual performance, fine stereopsis allows very precise detailed tasks, e.g. using binocular operating microscopes, or mapping the apparent height of terrain using stereoscopic photographs. The brain also averages the visual input when combining right and left eye images, so that an individual with early cataract, who sees a letter ‘O’ as a ‘Q’ with one eye and as an inverted ‘Q’ with the other eye, correctly perceives ‘O’ in binocular vision. This process, binocular **visual summation**, improves binocular performance over monocular for:

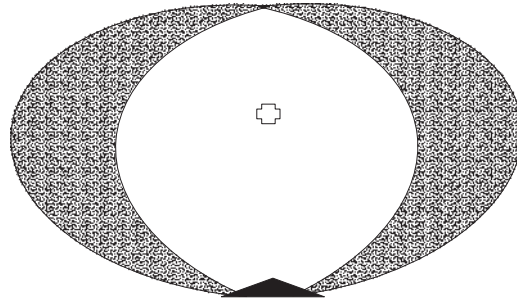


Figure 1.1 The human visual fields. With both eyes open and fixation on the central cross, binocular vision is possible where the right and left fields overlap. The lower triangle represents the highly variable influence of the nose. The grey areas show the monocular extensions of the binocular visual field on each side.

- high-contrast visual acuity, and the upper spatial frequencies of contrast sensitivity;
 - absolute light detection at threshold of perception;
 - threshold contrast sensitivity function;
 - reaction time to flashing visual stimuli, e.g. sine-wave bar gratings.
- This can be important in several occupational situations.

Two eyes and binocular vision supply a paired and therefore **spare organ**, true for many of the body's functions as insurance against injury and disease. Two eyes also give a **wider field of vision**. In animals that are subject to predators, the horizontal visual field may extend to 360 degrees, i.e. **panoramic vision**. In humans, the horizontal binocular visual field is 120 degrees, with a further monocular field of about 45 degrees (the temporal crescents) on each side of the binocular field, on the horizontal (medial-lateral) axis passing through the eyes, but reducing to zero superiorly and inferiorly (Fig. 1.1). The nose reduces binocular field inferiorly. In animals the monocular and binocular visual fields vary according to the species (Fig. 1.2).

1.2 The requirements for binocular vision

The requirements for binocular vision are as follows.

- **Two eyes**, and a separation between the eyes called the **interocular distance**, generally about 65 mm in adult humans.
- A **neural pathway** to transfer the two images to the brain (Fig. 1.3).
- **Neural processing systems** to integrate the different types of raw visual information, such as luminosity, size, movement relative to the eye, colour and contrast. These systems also analyse and produce further percepts, such as distance, shape, movement relative to the body and stereopsis.

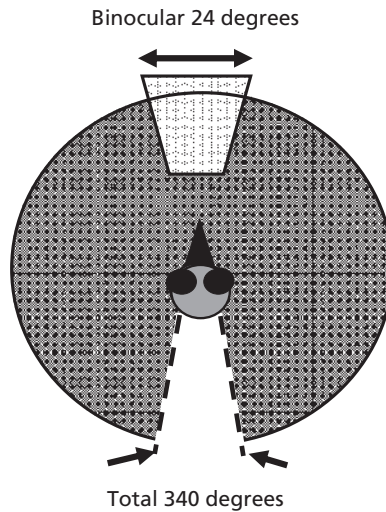


Figure 1.2 The visual fields of the pigeon, showing a 24-degree binocular field, and a total field of 340 degrees, mainly monocular (after Walls, 1942).

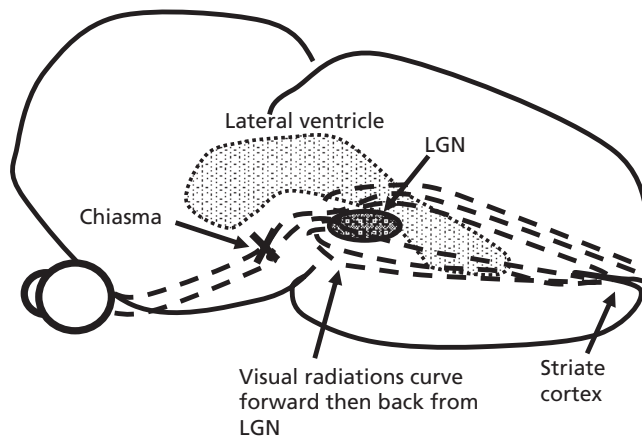


Figure 1.3 The human neural pathway for vision, from the retina to the visual cortex. LGN, lateral geniculate nucleus.

- **Extra-ocular muscles** to allow the object fixated to be imaged on appropriate retinal areas of each eye (Fig. 1.4).
- **Motor control systems** to govern voluntary and reflex eye movements – e.g. to maintain or vary fixation. Also there has to be a method of correlating binocular sensory input and binocular motor function: **motor correspondence**.
- Further enhancement of binocular perception is obtained by the **triangulation of objects** observed using head and body movements and the addition of other, monocular, clues to the total visual perception.

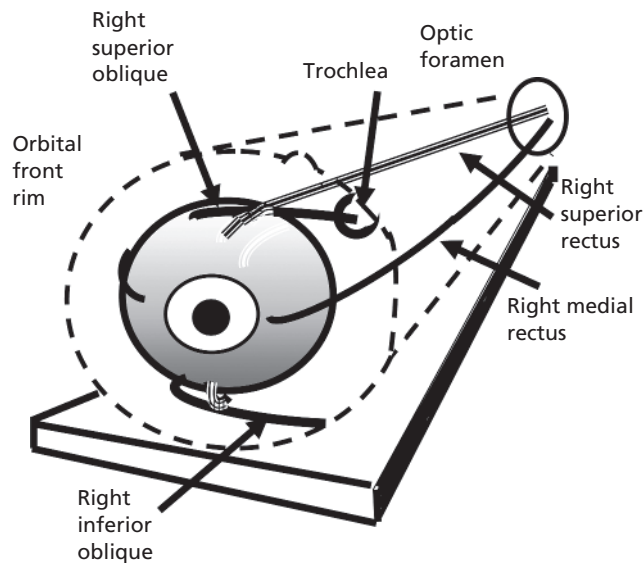


Figure 1.4 The extra-ocular muscles and the right orbit in outline. The orbit is represented as a cone extending backwards to the optic foramen. Only the superior rectus and the medial rectus are shown, with the two oblique muscles. While the recti pull backwards towards their origins at the rear of the orbit, the obliques pull towards the medial wall of the orbit. For clarity, the inferior and lateral rectus muscles are indicated but not labelled.

1.3 Monocular visual direction

Spatial sense is the body's recognition of the location of external objects, involving the tactile sense, hearing and vision. The determination of external locations by visual means involves the relationship between the external location, the eyes and the head position. **Visual direction** describes the visual position of an object in a two-dimensional plane, i.e. its vertical and horizontal location. To move from **physical space**, which exists without our presence, to **visual space** (the visual representation of physical space) involves initially the use of visual direction to build up the perceived picture. Complications in building up visual space may be illustrated by an experiment with inverted vision. It is possible to adapt to inverted vision (which can be produced by an optical system) so that after 2 weeks' wear, vision becomes upright. Upon removing the lenses it takes about 30 minutes of alternating upright and inverted vision before normal vision is stable.

The recognition of monocular visual direction is attained by the association of a visual receptor in the retina with the external position of an object imaged on that visual receptor. The line passing through the centre of the entrance pupil, to any object of regard is called a **line of sight** (Alpern, 1969). For an object fixated by the fovea, this line is known as the **primary line of sight** or, in clinical practice, the **visual axis** (Ogle, 1950). The entrance pupil is the image of the actual pupil formed by the cornea, as seen by an observer.

The visual axis is more strictly defined as the external light ray that, after refraction by the optical system of the eye, will fall on the fovea (Freedman and Brown, 2008). The fovea is the retinal area that receives images from objects observed straight ahead. Visual acuity and colour perception are normally best at the fovea. When the object of regard is imaged on the fovea, the oculomotor system ceases to initiate any eye movement. The fovea is thus the retino-motor zero point, or retino-motor centre.

Disambiguation note: the term ‘zero point’ is also used in relation to retinal correspondence (see section 4.5 in Chapter 4).

Note:

- In 1907 Maddox used the terms ‘visual line’ and ‘fixation line’ (Maddox, 1907).
- The visual axis must pass through the nodal point(s), and as there are two nodal points in the eye situated 7.13 and 7.41 mm behind the corneal vertex, a single visual axis cannot strictly connect the fovea with the object of regard (Rabbetts, 2007; Harris, 2010). For simplicity hereafter the terms ‘visual axis’ and ‘primary line of sight’ are used synonymously, and this is indicated in the text.
- The visual axis is not (usually) the same as the **optic axis** of the eye, which is why the anterior corneal reflection is not usually in the centre of the pupil (Fig. 1.5). The measurement of these axes is discussed by Dunne *et al.*, (2005).

The **primary line of sight** (the visual axis) is said to have the **principal visual direction**, i.e. from the fovea to the object imaged on the fovea. All non-foveal retinal receptors have **secondary visual directions**. The angular value of a secondary visual direction is calibrated by reference to the primary visual direction. The general term ‘line of sight’ includes both primary and secondary visual directions. Non-foveal lines of sight are referred to as ‘secondary’ lines of sight, or ‘lines of direction’ (Cline *et al.*, 1980). Hereafter,

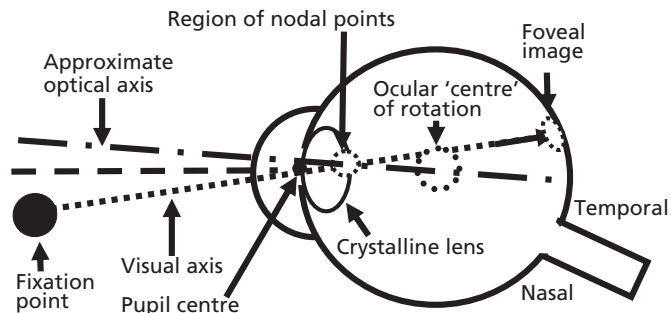


Figure 1.5 The visual, pupillary and optic axes. View of the human right eye from above, indicating the conventional directions of various axes relative to the route from the fixation point to its retinal image, via the pupil, and the assumed nodal points. The pupillary axis lies between the other two axes.

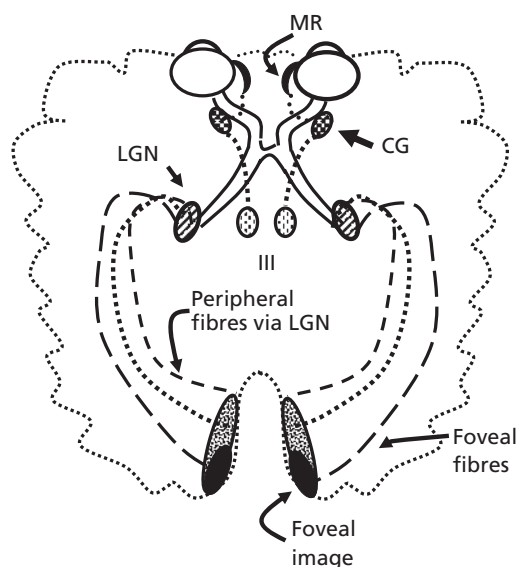


Figure 1.6 The visual system sensory and third nerve motor pathways. A schematic plan view of the visuuum showing the location in the striate cortex of sensory input from the central and peripheral retina. The motor route from the third cranial nerve nuclei to the medial rectus muscles is also shown. CG, ciliary ganglion; LGN, lateral geniculate nucleus; MR, medial rectus.

‘the line of sight’ will refer to the primary line of sight, unless otherwise stated. **Any number of objects situated on the same (primary or secondary) line of sight will stimulate the same receptor.** This is the **law of oculocentric direction**: the direction of all these objects is the same and given by reference to the single eye involved. The law relates to the use of one eye only. So when the fovea of that eye re-fixates on an object in a different direction, the **oculocentric visual direction** moves with it.

The recognition of visual direction by retinal receptors is called **local sign**: each retinal receptor sends a neuro-visual signal and encodes the direction in vertical and horizontal coordinates, but not the distance. Each retinal receptor–cerebral sensory unit has a unique ability to detect a particular direction. These signals are conveyed through the lateral geniculate nucleus to the visual cortex (Fig. 1.6). In other words, each retinal receptor is associated with the particular direction from which it receives a stimulus. This association extends as far as the visual cortex: there is said to be **retinotopic mapping** of neurones in the visual system (Zeki and Shipp, 1988). This has been demonstrated in reverse by stimulating cortical neurones electrically. The subject sees a flash of light in the direction associated with the stimulated cortical neurone.

The local sign is the angular subtense between a retinal receptor’s secondary visual direction and the primary visual direction of the fovea (Lotze, 1852). The high precision of local sign is a result of a cortical averaging process, which takes the mean of both spatial and temporal fluctuations in

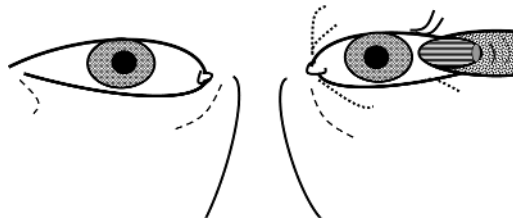


Figure 1.7 Visual local sign may be demonstrated by gently pressing on the temporal sclera. A phosphene (apparent light) is seen in the nasal visual field. The direction of the phosphene is linked with the eccentricity of the stimulated retinal area.

a stimulus (Reading, 1983). Local sign is a general attribute of sensory perception: the sensation of touch on any part of the human body surface is linked to related cortical sensory neurones. The operation of visual local sign can be demonstrated by gently (and briefly) pressing one finger on the eyelids at the outer canthus (Fig. 1.7). This is best done in a dim room. A small bright disc of light will be seen on the nasal side of the visual field. Similar mechanical stimulation of the retina occurs in retinal detachment and posterior vitreous detachment. Also by directing a small light beam onto the retina using an ophthalmoscope the impression is obtained of a small light seen in physical space. In clinical practice this subjective impression may be described as ‘**projection**’, demonstrating the inherent association of retinal points with specific visual directions. However, ‘projection’ is not strictly appropriate, and a term such as ‘external reference’, or ‘apparent spatial location’, may be more suitable. The ancient Greeks actually hypothesized that the eyes projected light onto the object of regard!

1.4 Binocular visual direction and retinal correspondence

The recognition of binocular visual direction is attained by averaging the simultaneous input from both eyes from the external position of an object. When objects are located by reference to the simultaneous input from both eyes, the reference position, the egocentre, is an imaginary point halfway between the two eyes. This form of localisation is **egocentric localisation**. An object fixated will be imaged on each fovea and will have an oculocentric impression of being ‘straight ahead’, relative to each eye. But the combined binocular percept will be as if the images were both located on the retina of a virtual shared eye in the middle of the forehead (Sheedy and Fry, 1997). A practical experiment to illustrate the difference between oculocentric and egocentric localisation consists of holding a cardboard tube between the thumb and fingers of the left hand, looking through the tube with the left eye across the room. The right hand, held before the right eye, provides the visual effect of a hole in the hand, being a stimulus upon which the left eye’s restricted field is superimposed, suggested in Fig. 1.8. The egocentre is

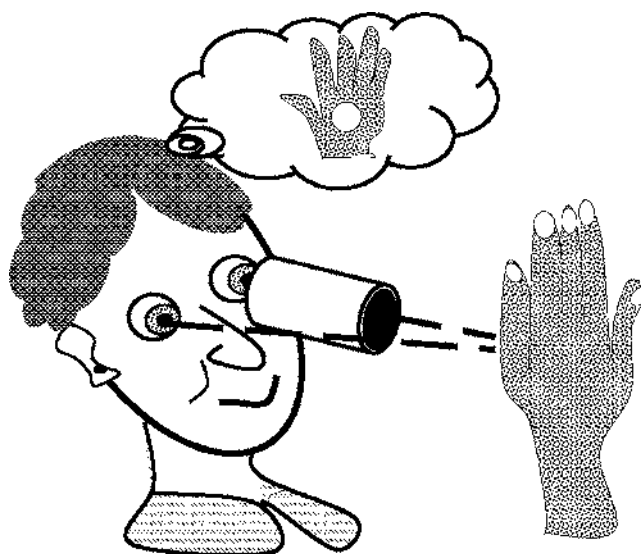


Figure 1.8 The hole in the hand. This is simultaneous perception of different images from each eye: the right and left oculocentric views are combined into a single egocentric view.

in the region of the bisector of the line connecting the two (right and left eye) entrance pupils, which are situated 3 to 4 mm anterior to the nodal points (Rabbetts, 2009). The advantage of egocentric localisation is the three-dimensional percept of the object being seen. It adds **distance** to the two-dimensional perceptions of direction produced by oculocentric localisation. Later it will be seen that even egocentric localisation can be subject to modification. For example, a dominant eye may shift the egocentre towards that eye (Ono and Barbeito, 1982). Visual illusions, lens and prism alterations may also alter the perceived localisation of an object, as will oculomotor paresis (see section 12.3 in Chapter 12). Egocentric localisation allows perception of the position of objects as seen from our egocentre. We can also localise objects in relation to each other: this is called **relative localisation** (see section 8.2 in Chapter 8).

Binocular vision needs a combination of the visual fields of the right and left eyes: the binocular visual field. The monocular visual directions have to be transformed into a binocular visual direction. This is achieved by **retinal correspondence**. The output of the fovea of one eye is linked with that of the other fovea in the visual cortex. The foveas are said to be **corresponding retinal points**. There are also non-foveal corresponding retinal points of each eye that are similarly linked to allow a binocular percept across the entire binocular visual field. So corresponding retinal points consist of a pair of retinal receptors, one in each eye, which receive stimulation from an object that is perceived to appear in the same visual direction for each eye: the law of identical visual directions. This is explained in more detail in section 4.4, Chapter 4.

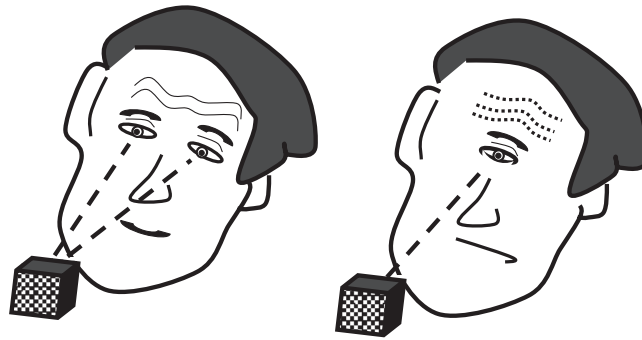


Figure 1.9 The effective human cyclopean view. The direction of the fixated object seen with both eyes open is linked with a virtual eye position midway between the right and left eyes.

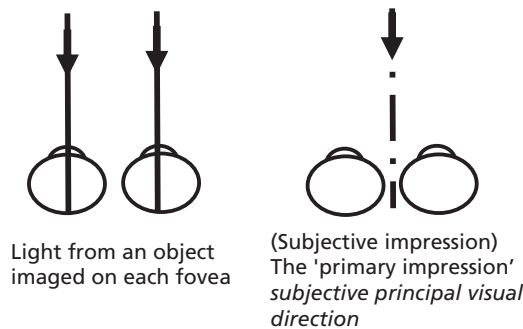


Figure 1.10 Primary common subjective principal visual direction. Light from an object stimulating both foveas produces a common visual direction.

The effect of egocentric localisation is to produce a **common subjective principal visual direction**. This is sometimes referred to as the **cyclopean eye effect**. Cyclops was the giant in Greek mythology with a single eye in the middle of his forehead (Fig. 1.9). Binocular visual localisation is centred on the cyclopean eye. An object imaged on each fovea is seen binocularly in the **primary** common subjective visual direction (Fig. 1.10).

Similarly, for every non-foveal point in one eye there is a related point in the other eye, which shares the same visual direction, these two non-foveal points being corresponding retinal points. The object seen by the two corresponding non-foveal points lies in a **secondary** common subjective visual direction, which is located by reference to the primary common subjective principal visual direction associated with the two foveas (Fig. 1.11). The existence of the common subjective principal visual direction can be demonstrated by masking a photographic flashlight to produce a vertical slit. One eye is covered, the centre of the vertical slit is fixated and the flash is generated. Repeat with the other eye with the slit held horizontally and the first eye occluded. The binocular after-image seen is a cross, demonstrating the common visual direction. This will work both for the foveas and the non-foveal corresponding points. In the latter case, the subject fixates a

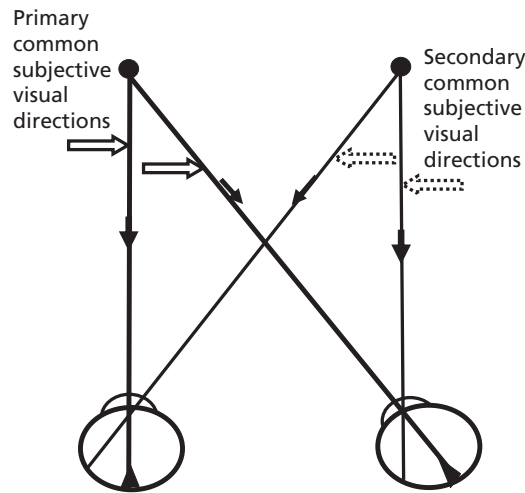


Figure 1.11 Secondary common subjective principal visual direction. Light from a non-fixated object produces a secondary common visual direction.

central target, and the flashlight is held in a fixed position away from the central area.

There are two further complications of visual localisation perception. Oculocentric visual direction gives information in two dimensions, and egocentric visual direction extends this to three dimensions. That information would only be useful if the eyes did not move relative to the head. To measure the localisation of a new object of regard in a different binocular gaze position, or to assess the location of a moving object being followed by the eyes, information about eye movement from the extra-ocular muscle control centres is needed. This permits **headcentric localisation**: an object located on the line of sight will be seen in the same headcentric direction for any given gaze direction. The reference system is centred on the head of the subject. This facility will also allow the assessment of the relative localisation in visual space of two or more separate objects. Finally, **visuo-motor memory** will allow us into the fourth dimension, by calculating the localisation of objects in time, e.g. when and where an object rotating around us will be likely to re-appear in vision. These binocular vision faculties may appear obscure, but they are the basis for the spatial awareness skills that allow a 3-year-old child to carry a broomstick around the corners of a corridor without much difficulty, for example, and actually help the development of spatial localisation, visual prediction and – it is said – mathematics (e.g. topology).

1.5 The Vieth–Müller circle

A circle can be drawn that intersects the nodal points of each eye with the object fixated by both foveas (Fig. 1.12). Vieth and Müller predicted that any object point on the Vieth–Müller circle (VMC) would stimulate a retinal

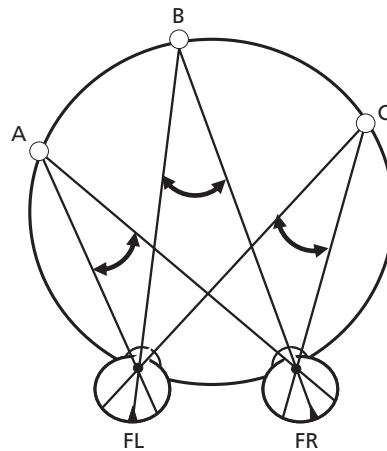


Figure 1.12 The Vieth-Müller circle (VMC; the basic form of the horopter). Three objects in space are imaged on the two retinas, each object forming images on corresponding 'points' (or areas). The geometry of the figure dictates that the angles shown are all equal to each other. The points through which the three lines pass in each eye are usually considered to represent the nodal points of the eyes, and fall on the VMC. However, opinions differ, some writers using the entrance pupils or even the assumed centres of rotation of the eyes. FL, left fovea; FR, right fovea.

point on each eye, which would have the same angular subtense relative to each fovea. Thus the VMC is a **theoretical model** of the positions of objects in space, which are imaged on corresponding retinal points. Any point on this circle would be seen binocularly as a single object.

Note: some versions of the **Vieth-Müller circle** diagram use the eyes' entrance pupils or even the centres of rotation instead of the nodal points.

The VMC is used to describe the optical **formation of images** on the retina of each eye. The VMC concept **assumes** that corresponding retinal points are placed at regular and equal horizontal distances from the fovea of each eye. However, the **measured locus** of every point in space that actually stimulates corresponding retinal points for a particular binocular fixation is called **the horopter**, and this will not be the same as the VMC (see Chapter 6).

1.6 Horizontal retinal binocular disparity

An object – let us call it object 'A' – whose image falls on corresponding retinal points of each eye will be seen as a single object. Where a second object 'B' situated on the same horizontal meridian as object 'A', is imaged on non-corresponding retinal points in each eye, the percept will be that object 'B' is seen as nearer or further from object 'A' (Fig. 1.13 and Fig. 1.14). Where the second object is situated slightly closer than the VMC, its secondary lines of sight would intersect nearer than the fixation point and

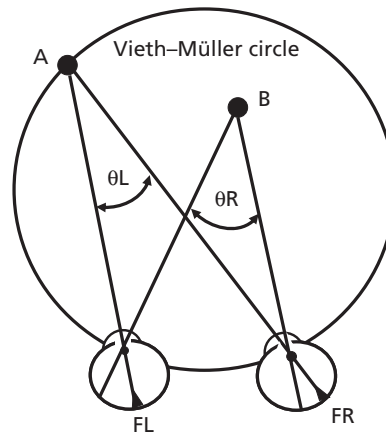


Figure 1.13 Crossed disparity. The fixated target A is situated on the Vieth–Müller circle, and the non-fixated target B is placed nearer. The right and left images of B do not fall on corresponding retinal points, but on retinal points, which are near enough for Panum’s fusional area to operate. The non-fixated target B will be seen in depth, nearer than the fixation point, A. FL, left fovea; FR, right fovea.

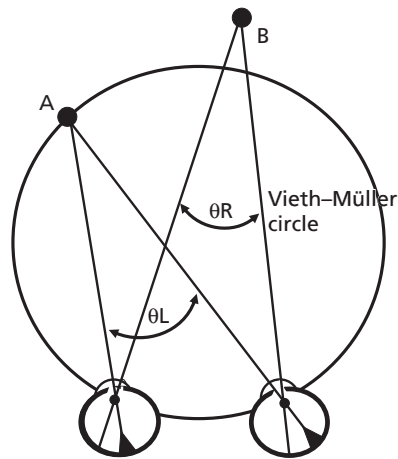


Figure 1.14 Uncrossed disparity. The fixated target A is on the Vieth–Müller circle and the non-fixated target B is placed further away. The right and left images of B do not fall on corresponding retinal points, but on retinal points, which are near enough for Panum’s fusional area to operate. The non-fixated target B will be seen in depth, further away than the fixation point, A.

produce crossed disparity. Objects situated slightly beyond the VMC have secondary lines of sight intersecting beyond the fixation point and produce uncrossed disparity. A small amount of disparity is the physiological requirement for the perception of stereopsis. However, if an object is even further from the VMC, and stimulates non-corresponding retinal points sufficiently far apart, then the object will be seen in diplopia, i.e. double vision. All images of a single object falling on non-corresponding retinal points are described as **disparate**. For a particular object, the angle between the

principal visual direction and the secondary visual direction in which the object is seen is called the **subtense angle**. The angular difference between the subtense angles of the right and left eyes is called the **(horizontal) retinal binocular disparity** (usually abbreviated to **disparity**). Although the example given above was of objects on the same horizontal meridian, the actual orientation of the retinal binocular disparity may be **horizontal**, **vertical** or **oblique**. The value, i.e. the quantification of the retinal binocular disparity, may be positive, negative or, for corresponding retinal points only, zero.

Horizontal retinal binocular disparity is the trigger for the perceptive faculty known as **stereopsis**, disparity sensitivity or binocular depth perception (see True binocular depth perception in Chapter 11). The disparity must be enough to produce stereopsis, but not so large as to cause diplopia. For a three-dimensional object there are different amounts of horizontal retinal binocular disparity relating to different elements of the object, some being seen nearer and some further away than the part of the object fixated by the foveas. So looking at the windscreen of an approaching car, the headlamps will be seen closer and the rear door further away. The windscreen would fall on the VMC; the headlamps would be within the VMC and the rear door beyond the VMC. The lines of sight for the headlamps would have **crossed disparity**, and those of the rear door would have **uncrossed disparity**.

Disambiguation note: all images of objects seen binocularly on the same meridian, which are situated closer or further than the VMC, will be disparate. The term ‘disparity’ implies stereoscopic fusion, but the term ‘disparate’ includes objects seen in diplopia, as well as those capable of stereoscopic fusion.

1.7 Vertical retinal binocular disparity and cyclofusion

If a vertical line in physical space is imaged on the vertical meridians of each retina of a subject, the retinal meridians are corresponding meridians, and the line will be seen without any stereoscopic effect. This is because all the horizontal elements that make up the vertical images will have zero horizontal disparity. If the line in physical space is now tilted with the top towards (or away from) the subject, the image of the line will fall on non-vertical retinal meridians. Each eye will have a different side view of the physical line. It is possible to work out the angle (D degrees) between the ocular non-vertical meridians, if the interpupillary distance ($2a$ in mm), and the distance from the eyes to the vertical line (b) are known, using the formula:

$$\tan D = 2a/b \times \tan i$$

where i is the inclination in degrees of the physical line towards the subject. The line in physical space will now be seen stereoscopically, as leaning towards (or away from) the subject. A discussion of the effect in this situation on cyclovergence and cyclofusion will be found in section 12.10, Chapter 12.

Vertical retinal disparities, together with horizontal disparities, allow cortical assessment of eye position (from the retinal data alone). However, the size of vertical disparities can be deduced from purely horizontal retinal disparity, because a vertical disparity adjusts the cortical receptive field position of corresponding points to the next higher or lower row of horizontal cortical sensors. Directions of gaze and of vergence thus can be recovered from horizontal disparity information (Read and Cumming, 2006). Where a vertical disparity occurs in near vision, any vertical diplopia is normally controlled by vertical vergence, and perceptual ambiguities because of asymmetrical convergence are resolved by the vertical disparity analysis capacity of the visual system (Brautaset and Jennings, 2005).

1.8 Cortical binocular disparity

To complicate things a little, the actual arrangement of **neural pathways** from the retina to the visual cortex determines **cortical (receptive field) binocular disparity**, with zero disparity for single, non-stereoscopic, vision. It is possible for the visual cortex to adapt, producing single vision even where zero retinal binocular disparity is not present, as where a subject has an anisometropic spectacle correction producing unequal retinal images but has adapted to see an undistorted visual percept. Here there would be zero cortical binocular disparity despite non-zero retinal binocular disparity.

Chapter 1: Revision quiz

Complete the missing words, perhaps in pencil. Only look at the answer when you have really tried. It would be useful to look back at the text and then try all these questions again.

Binocular vision has the advantage of s_____ (1) over double vision. The subtle difference between right and left viewpoints allows d_____ (2) perception, also called stereopsis. In addition, binocular vision allows visual summation, which imp_____ (3) binocular over monocular performance in a variety of ways.

Monocular visual direction allows the location of an object in t_____ (4) dimensions. Local sign is the angle between the direction of the fovea and the direction of a n_____ (5) -foveal receptor. Binocular visual direction is achieved by ret_____ (6) correspondence, the presence of which can be demonstrated by using af_____ (7) -images.

The theoretical model of the surface in physical space that locates objects that stimulate corresponding retinal points is called the V_____–M_____ c_____ (8).

Objects that are almost but not quite stimulating corresponding retinal points produce horizontal retinal binocular dis_____ (9), which is the basis for stereopsis.

Answers

(1) single; (2) depth; (3) improves; (4) two; (5) non; (6) retinal; (7) after; (8) Vieth–Müller circle; (9) disparity.