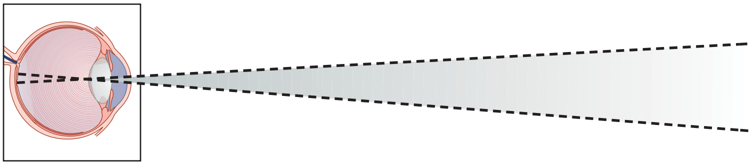

10

Depth Perception

It is sometimes assumed that depth perception is predicated on binocular vision. If one eye is covered, however, a strong sense of depth persists, pointing to the importance of monocular depth cues. Although depth is noted monocularly, it is generally enhanced when viewing binocularly, especially at near distances.

In this chapter, we introduce both monocular and binocular cues to depth. Although we touch some of the processes involved in binocular vision, this discussion is limited to background material sufficient to gain a basic understanding of stereopsis. More detailed information on binocular vision can be found in texts dealing exclusively with this broad topic. Steinman et al. (2000) is recommended.

MONOCULAR DEPTH CUES

Monocular depth cues are perceived just as strongly when viewed with one eye as when viewed with both eyes. The major classes of monocular depth cues are pictorial, angular declination below the horizon, motion parallax, and accommodation (Fig. 10–1).

Pictorial Depth Cues

Pictorial depth cues (relative size, familiar size, linear perspective, texture, interposition, clarity, and lighting and shadow) can be presented in a two-dimensional representation, such as a photograph or painting.[1] Monocular individuals manifest surprisingly robust depth perception due largely to these cues.

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[1] The sense of depth created by pictorial cues can be substantial. Artists are masterful at manipulating them to create a strong sense of depth in a two-dimensional painting.

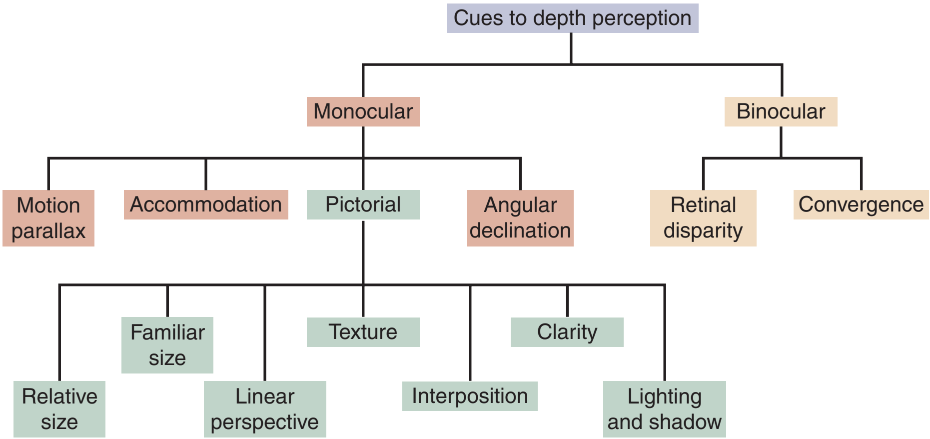

Figure 10–1. Classification of depth cues.

Relative Size. Figure 10–2 depicts two illuminated balloons in an otherwise dark room. Which appears closest to you? Like most observers, you probably perceive the larger balloon as closest. This perception of depth is rather compelling even though you know that the two images are actually the same distance from your eyes (Ittleson and Kilpatrick, 1951).

How can we explain this? Because we have no reference, we assume that the two balloons are of the same size. The object that produces the smaller retinal image size is perceived as farther away. Relative size is an important depth cue when viewing a scene that includes objects whose sizes can be compared to each other.

Familiar Size. This cue is used when viewing objects of known size. Imagine a barn surrounded by nothing but snow. *Relative* size is not useful for determining the

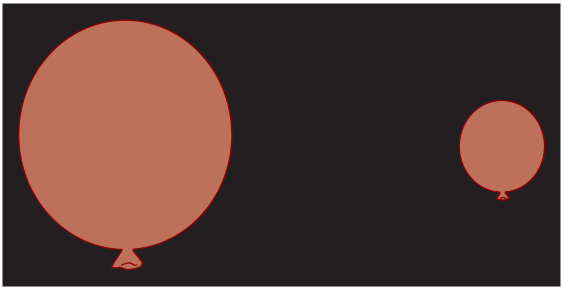

Figure 10–2. Two illuminated balloons in an otherwise dark room. Although both balloons are the same distance from your eyes, you probably perceive the larger one to be closer than the smaller one, demonstrating that relative size is a strong monocular depth cue.

Figure 10–3. We assume the railroad track has the same width throughout the scene. Since track that is higher in the photograph produces a smaller retinal image than that lower in the photograph, it is perceived as more distant. The rocks appear less densely packed in the foreground than the background, contributing to the sense of depth. (*Photograph courtesy of Lenge Hong.*)

barn's distance; there are no other objects to which it can be compared. In judging its distance, we would probably assume it is the size of a typical barn. If it produces a small retinal image, the barn would be seen as far away.

Linear Perspective. Related to relative size, this cue can be experienced by looking down a railroad track or long corridor. When viewing Fig. 10–3, we experience a strong sense of depth because we assume that the width of the railroad track is the same throughout the scene. The retinal image size of the rail separation in the background, however, is smaller than for the foreground, creating an illusion of depth. It is an illusion because all aspects of the photograph are physically the same distance from your eyes.

Texture. The rocks in the foreground of Fig. 10–3 appear larger and less densely packed together than those in the background, contributing to the sense of depth created in this photograph. This effect can also be seen in Fig. 10–4 where the bricks in the background appear more densely packed together than

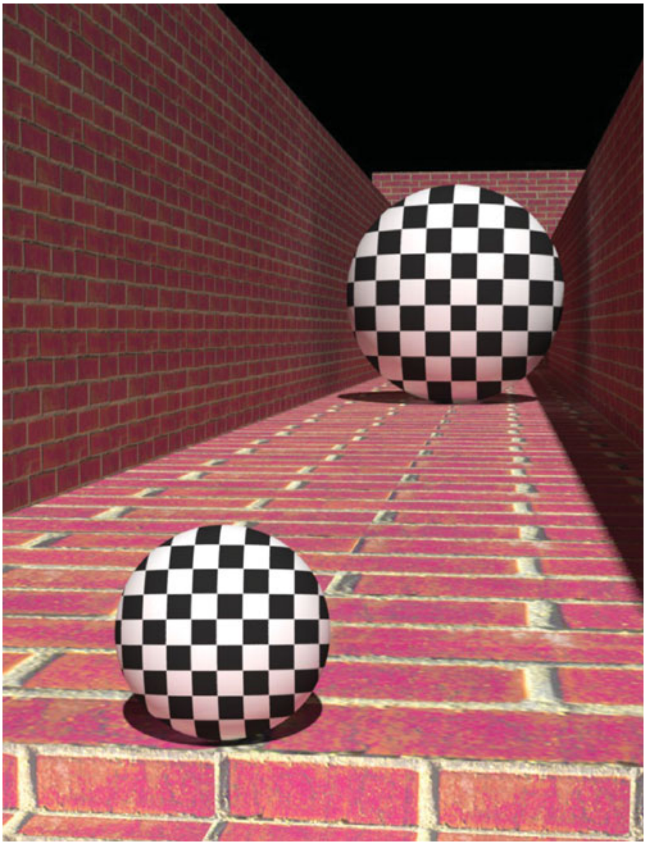

Figure 10–4. Corridor illusion. Although the two plaid balls produce equally sized retinal images, the ball in the background, which is perceived as larger, activates a larger area of primary visual cortex. This finding suggests that perceived size is encoded early in cortical processing. (*Image courtesy of Dr. Scott Murray.*)

those in the foreground. Predictable from considerations of relative size, densely packed objects that produce smaller retinal image sizes are perceived as more distant.

Interposition. Interposition can occur when the view of a scene is partially obstructed. In Fig. 10–5, the church is interposed between the observer and the mountains that are perceived as lying distant to it.

Clarity. A form of interposition, clarity acts as a depth cue when unobscured objects in a photograph, picture, or actual scene are perceived as closer than those

Figure 10–5. By partially blocking the view of the mountains, the interposing church contributes to the sense of depth. Also note the texture cue present in the sidewalk.

that are obscured by haze. Fog, smoke, rain, and smog may act as interposing elements that obscure the view of objects, causing them to appear more distant. In Fig. 10–6, the coastal fog contributes to the sense of depth.

Lighting and Shadow. When light falls on an object, the object casts a shadow. The shadow is interpreted as falling behind the object; consequently, a sense of depth is created (Fig. 10–7).

Angular Declination Below the Horizon

Consider a monocular observer, standing upright and still in an otherwise empty room, who views an object located on the floor at a distance of, say, 10 ft. Despite

Figure 10–6. The coastal fog contributes to the sense of depth by reducing the clarity of the lighthouse. Also note the texture cue presented by the rocks. (*Photograph courtesy of Sherrie Grunfeld.*)

Figure 10–7. The shadows cast upon the mountains and trees contribute to the sense of depth.

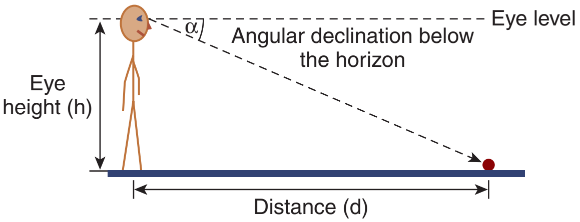

Figure 10–8. Angular declination below the horizon is a monocular cue used to determine distance. (*Diagram courtesy of Dr. Teng-Leng Ooi.*)

the absence of pictorial depth cues, the observer is able to judge correctly the object's distance. How is this done? As indicated in Fig. 10–8, the object makes an angle with the horizon referred to as **angular declination below the horizon.** The visual system apparently uses this angle to determine object distance (Ooi et al., 2001).

Motion Parallax

Motion parallax is a **kinetic monocular depth** cue that results when a moving observer fixates an object while noticing the relative motion of surrounding objects. It can be demonstrated by placing your two index fingers directly in line with each other, with one located 15 cm, and the other 30 cm, in front of your right eye. Close your left eye. Fixate on the distant finger while moving your head sideways. Without changing your fixation, notice that the near finger appears to move in the opposite direction of your head (against-motion). Now fixate the near finger and again move your head sideways. This time, notice that the far finger appears to move in the same direction as your head (with-motion). In both cases, relative motion provides information regarding relative distance.

Recordings from neurons in the middle temporal area (area MT/V5) of monkey cortex reveals cells that encode motion parallax information (Nadler et al., 2008). Area MT/V5 is also thought to play a role in processing binocular disparity (defined later in this chapter) and motion (Movshon et al., 1985; Uka and DeAngelis, 2006).

Clinical Highlight

Motion parallax has useful clinical applications when viewing ocular structures with a monocular instrument. Consider a small, dot-like opacity that is observed during monocular ophthalmoscopy. If the clinician fixates on the iris and moves her head sideways, the opacity will show against-motion when located anterior to the iris; with-motion will be noted when the opacity is located posterior to the iris.

Accommodation

During accommodation, the dioptric power of the crystalline lens increases, allowing near objects to be focused clearly on the retina. Although the signal to accommodation contains information that could be used to determine the distance of viewed objects, the extent to which this information is utilized is not known.

BINOCULAR DEPTH CUES

Stereopsis

Figure 10–9 depicts an observer viewing a ball centered between two other balls. While fixating the central ball, the observer is able to judge the relative distances of the three balls even if all monocular depth cues (e.g., relative size, interposition) are eliminated. How is this accomplished?

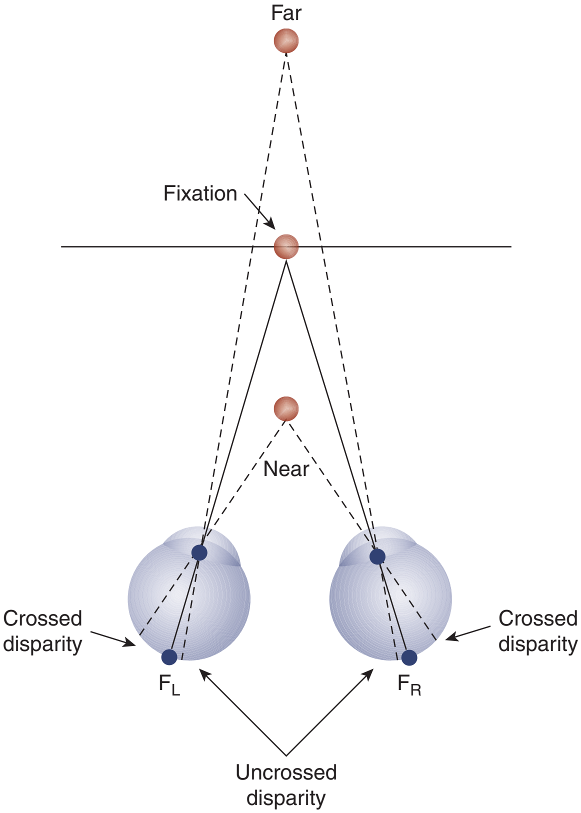

Figure 10–9. Uncrossed disparity results in an object being perceived as farther away than the fixation point, whereas crossed disparity results in an object being perceived as closer than the fixation point. (*Reprinted with permission from Steinman SB, Steinman BA, Garzia RP*. Foundations of Binocular Vision: A Clinical Perspective. *McGraw-Hill; 2000.*)

Consider the retinal images produced by the most distant ball. Light rays emanating from it strike the retinas nasal to the foveas, giving rise to **retinal disparity,** a binocular depth cue that allows the visual system to determine that the ball is distant to the fixated object. When the images fall nasal to the fovea, as in this example, the retinal disparity is said to be **uncrossed.**

Now take the case of the nearest ball, which is imaged temporal to the foveas. Here, the disparity is **crossed,** signaling that the ball is located closer than the fixated object.

The perception of depth that is produced by retinal disparity is referred to as **stereopsis**, an important contributor to finely tuned depth perception at near distances (particularly within arm's length when other depth cues are absent). Stereopsis is less important when viewing objects at far distances because the threshold for retinal disparity, which is specified as an angle at the eye, requires such objects to be separated by great distances.

Retinal disparity produces stereopsis only if it is sufficiently small to allow fusion. If the disparity is too large, the images fall on retinal positions that signal grossly different directions, resulting in **physiological diplopia** (double vision).

You can experience physiological diplopia by holding one index finger about 15 cm from your nose and your other index finger directly behind it at arm's length. Fixate on the near finger. Notice that the distant finger is doubled. Now slowly move the distant finger toward your nose while maintaining fixation on the near finger. Note that before you reach the near finger, the physiological diplopia disappears and only the sense of depth is noted. At this point, the retinal disparity is sufficiently small to allow fusion and stereopsis.

As discussed in Chapter 14, certain binocular cortical neurons are maximally responsive when a stimulus is located at a specific distance from the eyes (see Fig. 14–9). The same stimulus, when positioned at other distances, elicits a less vigorous neural response. By encoding disparity, these neurons may contribute to the physiological basis for stereopsis.

Convergence

The eyes converge when we view near objects and diverge when we view distant objects. Although the degree of convergence can potentially provide information regarding distance, the manner in which this information is incorporated into the conscious perception of depth, if at all, is unresolved (Brenner and Van Damme, 1998).

SIZE ILLUSIONS

Visual illusions are erroneous perceptions. We limit our discussion to certain illusions that can result when pictorial depth cues are used to determine object size.

In spite of changes in retinal image size, the apparent size of an object does not normally change with viewing distance. Although an automobile that is nearby produces

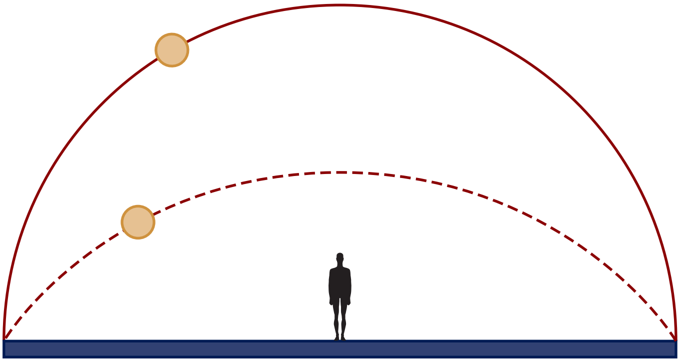

Figure 10–10. The actual trajectory of the moon is given by the solid line and the perceived trajectory by the dashed line. When viewed on the horizon, the moon is judged as farther away than when viewed overhead. Because the angular subtense of the moon is the same under both conditions, the moon looks larger on the horizon.

a larger retinal image than when it is farther away, it is not perceived as larger. Our visual system compensates for differences in retinal image size by taking into account the relative distance of an object, a phenomenon referred to as **size constancy.** When judgments of distance are erroneous, such as when viewing a flat picture, size constancy may fail, resulting in a **size illusion.**

In the **corridor illusion,** size constancy fails because monocular depth cues provide incorrect information regarding the relative distance (Fig. 10–4). Although the two plaid balls are the same distance from your eyes, the top one is perceived as farther away. This leads to the illusion that the top ball is larger. In fact, the two balls have the same dimensions.

When viewed on the horizon, the moon appears larger than when viewed at its zenith, even though its angular subtense is the same under both conditions. This well-known **moon illusion** is considered by some to be a size illusion (Kaufman and Rock, 1962). Because trees, houses, fields, and other interposing objects cause the moon to be seen as farther away when viewed on the horizon, it appears larger (Fig. 10–10).

The famous **Müller–Lyer illusion** (Fig. 10–11) can be understood by considering the vertical lines to be corners of a room (Gregory, 1978). The line that appears to form an outgoing corner is judged as farther away than the line that appears to form an ingoing corner. Because the lines are equal in length (producing equally sized retinal images), the line that is judged to be farther away is perceived as longer.

At what level in the visual system is perceived size encoded? This question can be answered by using functional magnetic imaging (fMRI) to examine the primary visual cortex while a human subject views a scene such as in Fig. 10–4. Although the two plaid balls are physically the same size (producing equally sized retinal images) the ball in the background appears considerably larger, resulting in a size illusion. Interestingly, the area of cortical activation reflects the perceived size of the ball, not its physical size, suggesting that perceived size is encoded early at the earliest stages of cortical processing (Murray et al., 2006).

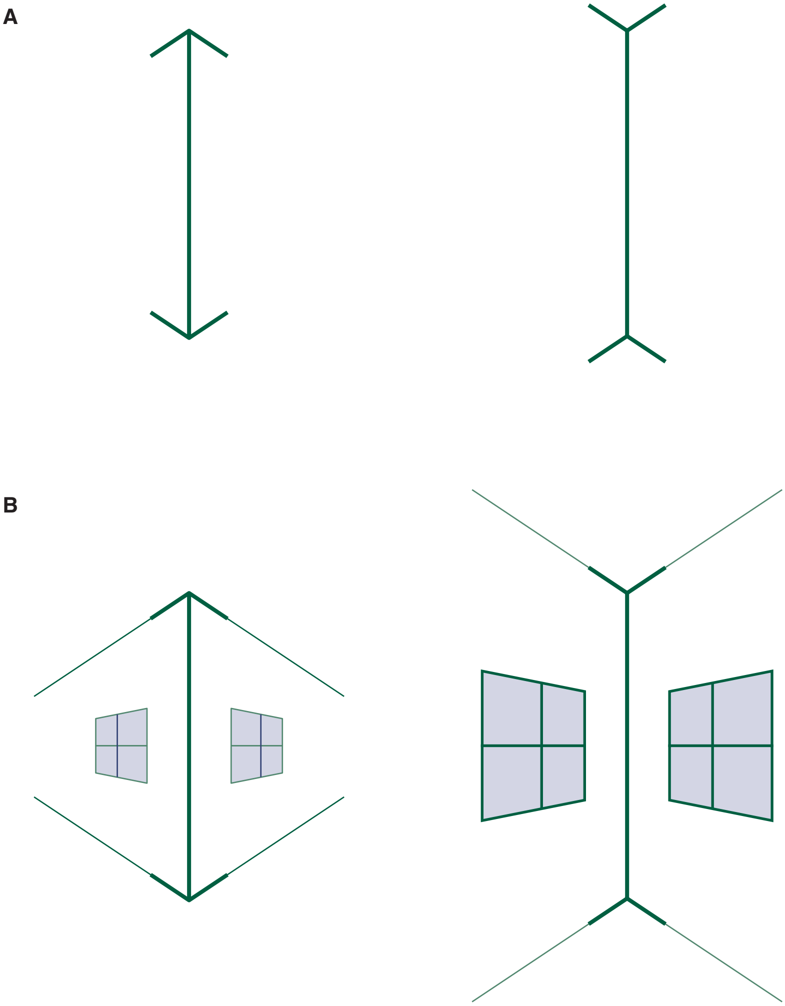

Figure 10–11. **A.** The Müller–Lyer illusion. The two lines are the same length. **B.** One explanation for the illusion is that the arrows may be likened to outgoing and ingoing corners of a room.

ADDITIONAL CLINICAL CONSIDERATIONS

Stereopsis and Visual Development

The measurement of a patient's degree of stereopsis provides important information regarding the status of his or her visual system. Stereopsis is measured clinically by asking a patient to view a flat surface that has two identical figures separated by a very small distance. Using Polaroid or red and green glasses, only one object is presented to each eye. The separation of the images is designed to produce retinal disparity, and this disparity results in stereopsis. In a typical stereopsis test, the minimum amount of disparity required for the patient to perceive depth is determined. This threshold disparity is referred to as the patient's **stereoacuity** (a form of hyperacuity), and it can be as small as 3 seconds of arc.[2]

Clinical Highlight

For there to be highly developed stereoacuity, the visual cortex must contain a normal complement of binocular neurons. This can only occur if the visual system is exposed to a normal visual environment during its development. Disorders of binocular vision, such as anisometropia and strabismus, may alter an infant's visual experience and retard the development of binocular cortical neurons, resulting in a reduction in stereoacuity (Birch and Stager, 1985). Consequently, the clinical measurement of stereoacuity provides important information regarding a patient's visual development.[3]

Monovision

Monovision is the common clinical practice of correcting one eye of a presbyope for distance and the other eye for near, thereby enabling the patient to alternate between the two eyes to see both distant and near objects clearly.[4] Because the unused eye is largely suppressed, diplopia does not typically occur. Monovision may, however, interfere with stereopsis because the patient's binocularity is reduced at all distances. Nonetheless, these patients may retain a substantial amount of depth perception because many important cues to depth are monocular. In fact, a patient with only one eye manifests excellent depth perception. Although stereopsis is an important depth cue for near distances, especially within arm's length, it is less important at greater distances.

Will monovision correction cause a reduction in stereopsis that interferes with driving safety? This is not an easy question to answer because each individual adapts to monovision at a different rate and to a different extent. Some patients perform well with monovision, while others do not. Although many of the judgments required in driving are for far distances, where stereopsis is less important, other judgments are for relatively near distances.

Clinical Highlight

At a minimum, monovision patients should be advised of a reduction in depth perception that could potentially interfere with driving. Distance correction of the eye normally used for near vision should be considered.

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[2] Monocularly visible contours are not required for the perception of stereopsis. In random-dot stereograms, neither eye sees a contour, but one emerges after fusion (Julesz, 1960).

[3] See Chapter 17 for a more detailed discussion of visual development.

[4] Monovision is most often used in conjunction with contact lenses or refractive laser procedures. Whenever a monovision laser procedure is contemplated, it is advisable for the patient to first undergo a monovision contact lens trial to see if he or she can successfully adapt.

SUMMARY

The cues for depth perception are both monocular and binocular in nature. Stereopsis, a form of binocular depth perception, is dependent on normal visual development. Important information regarding a patient's visual status and development is obtained by clinical measurement of stereoacuity, making it a common and highly useful screening test.

Self-Assessment Question

1. Could monovision contact lenses interfere with a pilot's ability to safely fly an airplane? Explain.