COMPETENCIES COVERED

DISPENSING OPTICIANS
Communication, Standards of Practice, Refractive Management, Paediatric Dispensing

OPTOMETRISTS
Communication, Standards of Practice, Binocular Vision

COMMUNICATION
PAEDIATRIC DISPENSING
BINOCULAR VISION
STANDARDS OF PRACTICE
COMMUNICATION
REFRACTIVE MANAGEMENT
STANDARDS OF PRACTICE

This CET has been approved for 1 point by the GOC. It is open to all FBDO members, and associate member optometrists. The multiple-choice questions (MCQs) for this month's CET are available **online only**, to comply with the GOC's Good Practice Guidance for this type of CET. Insert your answers to the six MCQs online at www.abdo.org.uk. After member login, go into the secure membership portal and CET Online will be found on the L menu. **Questions will be presented in random order**. Please ensure that your email address and GOC number are up-to-date. The pass mark is 60 per cent. The answers will appear in the November 2020 issue of *Dispensing Optics*. The closing date is 9 October 2020.

General Optical Council
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For Dispensing Opticians

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Exploring depth perception

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When we take photos of amazing landscapes or scenery and then review the images at a later date, it is often the case that the photos 'do not do the scene justice'; something seems to be missing. Of course, we are trying to compare a two-dimensional scene to a three-dimensional memory, and thus our perception of depth is not fully utilised and images can look flat.

Photographers and artists will often use techniques to help enhance the illusion of depth in an image, and this can help 'bring the image to life'. Some of these techniques are comparable to monocular depth cues exploited by our visual system to aid in our perception of depth. This article will explore not only the various visual cues that help form our rich three-dimensional experience of the world around us, but also pathologies that can impact on our perception of depth.

SEEING 'WITH YOUR BRAIN'

There are comparisons between the human eye and the camera; modern camera lens systems focus light onto a sensor, in a similar process to the biological lens system of the eye creating an image on the retina. From a light receptive point of view, the retina is a two-dimensional sensor, very much like the camera sensor. Unlike a camera, which produces two-dimensional images, we view the world as a three-dimensional perceptual model. How do we manage to achieve this from the two-dimensional sensor array?

Ophthalmic dispensing students are continuously advised by the author that 'you see with your brain'; the retina is a light-gathering structure that transmutes photon-induced chemical changes into electrical nerve impulses. These signals travel to various areas of the neural visual system and the brain 'interprets' the signal patterns to construct a probable three-dimensional perceptual model. It is within this neural processing that our perception of depth is formed[1].

STEREOPSIS

One of the most obvious mechanisms for depth perception is stereopsis. The majority of humans have good correctable vision from two eyes, with each eye

Figure 1: Stereoscopic images with disparity. To view this image in 3D, stare beyond these images to form a '3rd' image in the centre

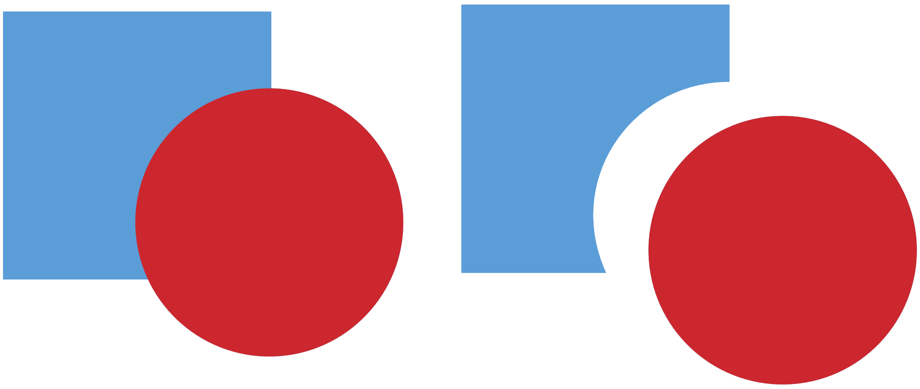

Figure 2: (a) possible occlusion; (b) mis-leading occlusion

receiving a slightly different image. The disparity between these two images is translated by the visual system to help form three-dimensional vision[2,3]. Stereoscopic photography simulates this mechanism by producing two slightly disparate photos that can be fused together by the viewer to create a three-dimensional experience (**Figure 1**). Whilst this stereoscopic mechanism works well for depth perception at close ranges, stereopsis becomes less informative when viewing more distant targets with very small disparities in the individual retinal images[4].

The neural pathways relating to depth perception, as with the majority of visual processes, develop as we grow. The processing of stereopsis begins in the primary visual cortex (sometimes referred to as the striate cortex, V1), but many extrastriate neural areas are also involved in the processing of disparity to create our perception of depth[5,6]. If these areas of the neural visual system are not adequately stimulated in our early years, problems with stereopsis will arise.

If strabismus is present (i.e. a squint in which the eyes are misaligned during fixation), or if there is a significant level of anisometropia, the visual system will struggle to combine the visual outputs from the eyes into a single percept; if left untreated within the critical period, patients will develop amblyopia. Studies suggest that between two to three per cent of the population are amblyopic[1,7], showing a significant reduction in visual acuity and contrast sensitivity in one eye.

As a result, amblyopia is one of the major inhibitors of stereopsis; this pathology can cause a significant reduction in depth perception[6-8], especially in relation to strabismic amblyopia[9]. Though stereoscopic vision is permanently disadvantaged if amblyopia is present after the critical period, there are some studies which suggest that a level of stereopsis, mostly in relation to anisometropic amblyopia, can be regained through perceptual training[9].

As well as stereopsis, physiological oculomotor cues, such as convergence and accommodation, reinforce our perception of depth[8,10]. The action of these mechanisms generate muscular responses that allow us to decide whether we are viewing an object close up or at distance[2]. Accommodation also alters our plane of focus; when viewing close objects, distant objects will go out of focus. This effect can be duplicated in photography (and by artists and computer imagery) by the use of the *bokeh* effect; the taking of an image with a narrow focal plane.

Although stereoscopic vision and convergence cues significantly aid with depth perception, it does not mean to say that patients restricted to monocular vision (due to amblyopia or enucleation, for example) have no depth perception at all. If you possess good binocular vision and cover one eye, the world around you does not reduce to a two-dimensional photograph; this is due to monocular depth cues that the visual system uses to help augment the perceptual internal model[11].

OCCLUSION

Occlusion is perhaps one of the most apparent monocular depth cues (**Figure 2a**). Here we can see that the red circle is occluding some of the blue square and thus it is logical to assume that the circle is in front of the square. This assumption, however, is based on the guess that the blue object is a square, and not shaped, as in **Figure 2b**.

In this example, the visual system is using 'best guesses', or heuristics, when deciphering the image, and many of these *heuristics* are formed from visual experience.

Another experiential depth cue is the relative size of objects. **Figure 3** shows two 'objects'; if the objects were quite abstract in nature, then it would be difficult to discern the relative depth of the objects. However, we know by experience that children are bigger than footballs and therefore deduce that the football is closer.

Figure 3: Relative size tells us that the ball must be closer to us than the child

Figure 4: Converging lines reinforcing depth perception

PERSPECTIVE CONVERGENCE

One of the most effective means of establishing depth in art and photography is by the use of converging lines that converge to a point in the distance[3]. This perspective convergence is also used as a depth cue in monocular vision[2,12] (**Figure 4**).

Whilst this depth cue is reliable for the majority of the time, misinterpretation of perspective convergence by the visual system can sometimes confuse the visual system and lead to illusionary perceptions. The Ponzo illusion is a strong example of this[2], and is demonstrated in Figure 9 (*we will discuss the suggested cause of this illusion later*).

Perceptual analysis of landscape scenes can utilise perspective convergence in relation to determining probable object depths; as the stimuli appear further above or further below the horizon line, the more likely they are to be closer. Consider observing clouds in the sky when looking into the horizon; nearby clouds appear higher in the visual scene (and have a larger visual angle from the primary gaze position), whereas more distant clouds appear closer to the horizon (with a smaller visual angle from the horizon).

MONOCULAR DEPTH INDICATIONS

The visual quality of the perceived environment can also offer monocular depth indications to the visual system, and involve cues such as atmospheric perspective and texture gradient[2]. Light from very distant objects will need to pass through more airborne particles; due to atmospheric conditions causing light to scatter, distant objects will tend to present poorer visual contrast to the observer and to appear more hazy than closer objects[13].

Also, as short wavelength light is scattered more than long wavelength light, the colour of more distant objects may shift towards the blue end of the spectrum[12] (**Figure 5**). Distant objects also subtend smaller visual angles, so our ability to resolve fine detail, such as the texture and detail of an object, is diminished as an object gets further away.

Lighting and shadows also give clues to depth within our visual field. Photographers often discuss the 'golden hour' after sunrise and before sunset as an ideal time to undertake landscape photography. With the sun low on the horizon, shadows become more prominent and longer in length. The enhancement of shadows in this way can augment the perception of texture and features, and aid our perceptual systems with the assessment of depth and shape of objects[2,4].

Two-dimensional images can be given the illusion of depth by taking advantage of lighting heuristics adopted in visual processing; the brain assumes light generally comes from above[3,14], and this can give rise to the false perception of depth, as shown in **Figure 6**.

When viewing Figure 6 upright, the majority of viewers will perceive the

Figure 5: Atmospheric perspective

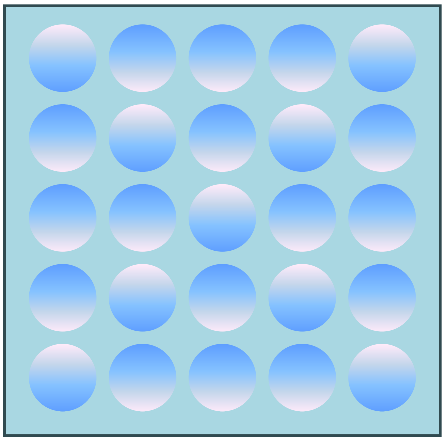

Figure 6: Illusionary depth due to lighting interpretation[15]

diagonal 'spheres' tend to stand out the page, following the 'light-from-above' heuristic, with the other features looking like depressions[14,15]. When the figure is turned upside down, we generally perceive a reversal of depth, with the diagonal features turning into depressions in the image. Interestingly, this illusionary depth is more difficult to perceive when viewing the figure from the side, as the light-from-above rule has less relevance.

MOTION PARALLAX

Motion can also contribute significantly to our perception of depth. Motion parallax is a monocular depth cue in which closer objects move more quickly in the field of view compared to more distant objects as the observer moves through the environment[4,11,16]. This effect can easily be observed when travelling in a car or train; closer objects in the foreground will pass by more rapidly, whereas features in the far distance barely seem to move (**Figure 7**).

As well as augmenting the perception of depth with humans, parallax is thought to be essential for depth perception in many prey animals, such as pigeons, in which the eyes are laterally positioned with little overlap (and thus little stereopsis)[17].

In a similar way to static occlusion, objects can pass in and out of view as the observer moves through their environment. When more distant objects move out-of-view behind another object (deletion), or when further objects are revealed behind closer objects (accretion), these act as further relative depth cues to help augment our depth perception of the observed environment (see **Tables 1a and 1b**).

APPARENT DEPTH PERCEPTION

As discussed earlier, we can deduce the depth of an object in space relative to other familiar objects of the same size, with further objects appearing smaller. Our perception of size, however, is also influenced and altered by the apparent depth of an object.

Consider this (and try at home): if you hold a playing card at 60cm, and then move it to 30cm, by simple geometry and similar triangles, the retinal image will now be twice the size. From this, we would expect our perception of the size of the card to double if its distance is halved, but this is not what is experienced. Instead our brain alters the perception of size so that we approximately perceive the 'natural' size of the object, regardless of distance; this is known as **size constancy**[2,3,18].

To see through this neural illusion, hold two playing cards at the above different distances and look at them both

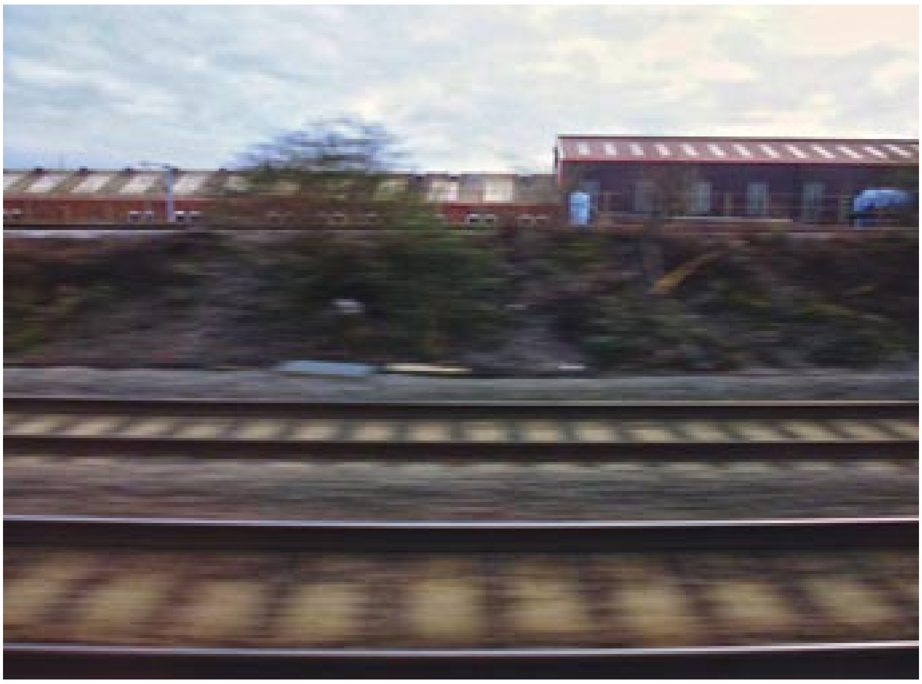

Figure 7: Motion parallax observed on a train

DEPTH CUE	0-2 METRES	2-20 METRES	ABOVE 20 METRES
Occlusion	✓	✓	✓
Deletion and accretion		✓	✓
Relative height		✓	✓
Atmospheric perspective			✓

Table 1a: Cues that indicate relative depth

DEPTH CUE	0-2 METRES	2-20 METRES	ABOVE 20 METRES
Relative size	✓	✓	✓
Texture gradients		✓	✓
Motion parallax	✓	✓	
Accommodation	✓		
Convergence	✓		

Table 1b: Cues that contribute to determination of actual depth

Figure 8: Overcoming size constancy and perceiving the size of identical objects based on their retinal image size

with one eye (**Figure 8**); you will see that the furthest playing card will be half the size in relation to the closest.

Size-distance scaling relates the perceived size of an object (S) with the perceived depth (D), and the retinal image size (R) by the formula[2]:

$S=K(R\times D)$ *(where K is a scaling constant)*

Since K is a constant, we can see as that as D increases and R decreases, the perceived size (S) stays the same.

Whilst this neural modification allows us to perceive objects in the world with a relatively constant size regardless of their distance, our visual system can be deceived when the *illusion* of depth is present; this brings us back to the Ponzo illusion (**Figure 9**).

Both spheres in the image are the same size, however, the majority will perceive the top sphere being larger than the bottom. Although the figure is a flat two-dimensional image, the converging lines fool the brain into thinking that the higher sphere is further away than the lower sphere[2,18]. The retinal image size is the same; however, the perceived distance of the higher sphere is judged to be further away due to perspective convergence.

Thus, from size-distance scaling, R would remain the same but the value for D will increase; this will increase the perceived size of the image, S, exactly what we experience when viewing this illusion.

PATHOLOGIES AFFECTING DEPTH PERCEPTION

We have seen from these discussions that refractive and strabismic amblyopia has a detrimental effect on stereoscopic depth perception, although any pathology that affects binocular fixation of the eyes, including disease and trauma[19], can lead to a breakdown of binocular vision and impact on depth perception. Whilst such conditions affect the eye or oculomotor muscles controlling fixation, there are other pathologies that can affect the visual processing of depth in the visual cortex or extrastriate areas of the visual system.

As significant disparity comparison begins in the primary visual cortex (V1), any lesions or pathology in this area is likely to impact on depth perception; impact on depth perception from damage to this area is difficult to assess, however, as lesions in V1 generally tend to lead to cortical blindness due to the primary processing of most visual functions[6].

As sensory information is processed beyond V1, monocular depth cues are combined with disparity information to build up our overall perception of depth[8,14,16]. Extrastriate areas of the brain, forming the dorsal and ventral visual processing pathways, also have roles in processing visual depth perception[4,5,11], and therefore any acute lesions or trauma of these areas can impact on the perception of depth[6,19].

Chronic degenerative conditions, such as posterior cortical atrophy (PCA, sometimes referred to as visual Alzheimer's), can affect the posterior lobes of the brain, and therefore the processing of depth information. PCA can be difficult to diagnose as, although it is considered an atypical variant of Alzheimer's, patients tend to initially have relatively intact memories and cognitive processes; instead, this condition initially affects the occipital cortex and the dorsal and ventral processing streams. Symptoms tend to manifest with visual problems, including the loss of depth perception and the ability to cognitively identify objects[6,20,21].

Stereoscopic impact should also be considered with refractive correction. Monovision correction is used within various spheres of ophthalmic practice, including contact lenses, intraocular lens (IOL) implants, and refractive surgery. Whilst this method of visual correction allows presbyopic patients to experience distance and near vision regardless of the viewing angle, there is potential for disruption of stereoscopic vision which may impact on the processing of depth in the visual field[22,23].

Patients should be informed of potential binocular vision issues relating to monovision correction; whilst contact lens patients could be prescribed a monovision correction on a trial basis, monovision IOL surgical treatments may be more difficult to amend.

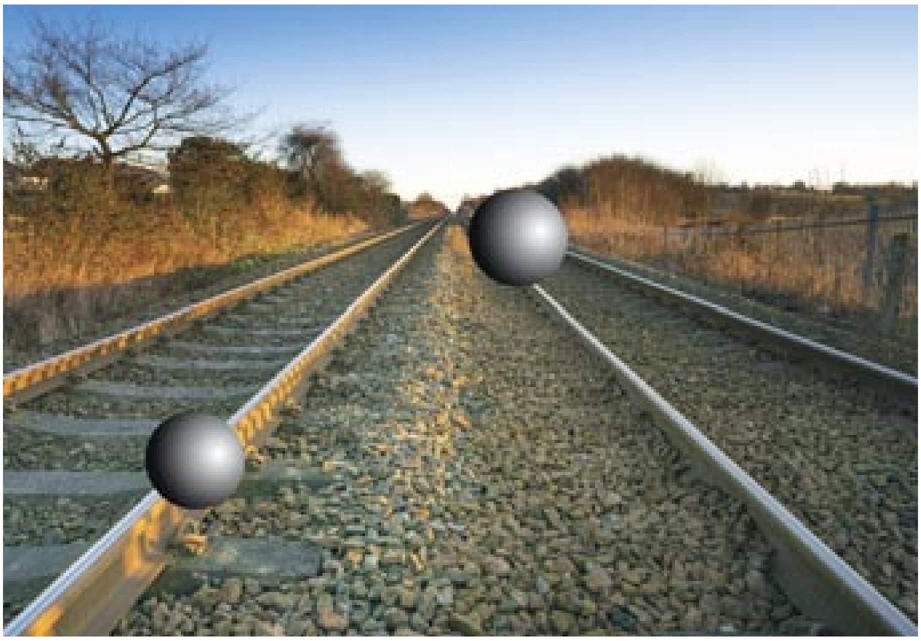

Figure 9: The Ponzo illusion: which sphere is bigger?

Despite the possible stereoscopic impact from monovision, the vast majority of patients tend not to experience any depth perception deficit[24]; however, such issues may need to be factored in when considering certain occupations that demand a high level of stereoacuity[22].

As well as contact lens and IOL refractive corrections, it is also suggested that aniseikonia, as a result of anisometropic spectacle prescriptions, can also contribute to a loss in stereopsis[12,25] with unequal retinal image sizes affecting normal disparity processing.

SUMMARY

Over the years, stereoscopic technological advances, such as 3D spectacles and virtual reality headsets, have provided us with the means to view images and film in three dimensions with a more realistic experience of depth. However, such technology is still crude compared to the neural processing power of human perception.

This article highlights the importance of stereoscopic vision in the development of depth perception processes, and rationalises the importance of prompt optometric and orthoptic treatments of amblyopia. With a significant proportion of the brain involved in the processing of vision[4,5,26], we are constantly rewarded with the rich visual experience that our perceptual system creates to interact with the world around us, a system which is taken for granted every day.

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