LEARNING DOMAINS

COMMUNICATION

CLINICAL PRACTICE

PROFESSIONAL GROUPS

Dispensing opticians — CPD PROVIDER — General Optical Council

Optometrists — CPD PROVIDER — General Optical Council

CLOSING DATE: 8 July 2022

ANSWERS PUBLISHED: August 2022

CPD CODE: C-101394

MCQs AVAILABLE ONLINE: 1 April 2022

This CPD session is open to all FBDO members and associate member optometrists. Successful completion of this CPD session will provide you with a certificate of completion of one non-interactive CPD point. The multiple-choice questions (MCQs) are available online only from Friday 1 April 2022. Visit **www.abdo.org.uk.** After member login, scroll down and you will find CPD Online within your personalised dashboard. Six questions will be presented in a random order. Please ensure that your email address and GOC number are up-to-date. The pass mark is 60 per cent.

CPD CODE: C-101394

Exploring light perception

By Mark Hickton BSc (Hons) Cert Ed, FBDO, FHEA

As we move around our environment, our eyes take in light from the stimuli in our visual field. Primary sources of light, such as the sun or an electric lamp, illuminate objects, and those objects 'reflect' a proportion of light back to our eyes creating the experience of brightness and colour. Whilst this process seems relatively straightforward, what is not always apparent is the significant difference between the amount of light incident on the retina, and our *perception* of light levels.

This article will explore aspects of light and contrast perception, and how lighting considerations impact on low vision advice and support.

ILLUMINANCE AND LUMINANCE

Illuminance (measured in lux) refers to the amount of luminous flux falling onto a surface per unit area, or, more simply, how much incident light illuminates a surface. Illuminance is directly related to the luminous intensity (and photon output) of a light source.

Readers may remember their photometry theory at this point, and recall that the illuminance can be calculated by an inverse-square law:

$$E = \frac{I \times \cos\theta}{d^2}$$

Illuminance can vary by many degrees of magnitude; for example, bright sunlight can have an illuminance of over 100,000 lux, whereas moonlight from a full moon could have an illuminance of only 0.2 lux[1]. With the lowest threshold for illuminance in human vision in the order of 0.000001 lux, this means that environmental illuminance ranges over 10 log units of magnitude[2,3].

Luminance is the amount of light reflected by a given surface. Although we use the term 'reflected', this process is far more complicated, and involves absorption of light energy by atoms, followed almost immediately by emission of light energy. The light being re-emitted can be altered in intensity and

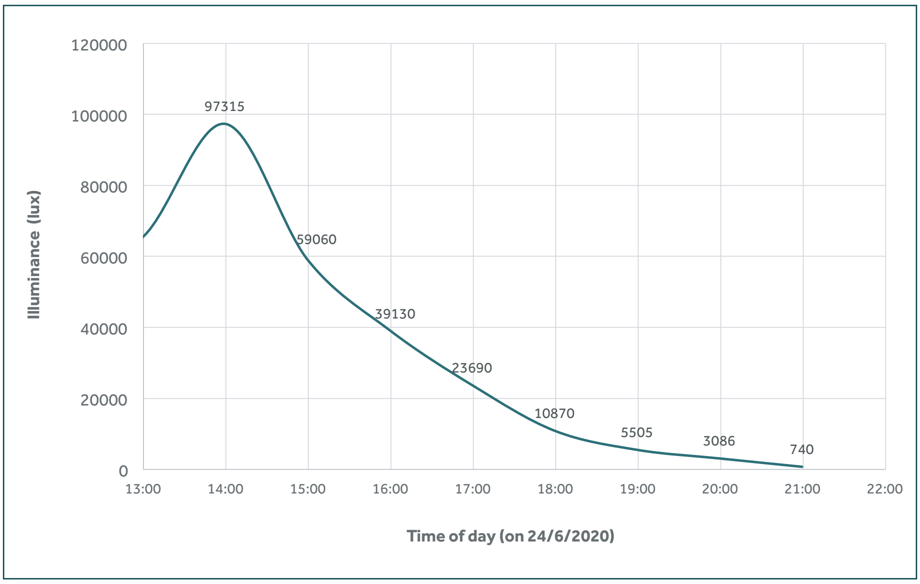

FIGURE 1: Variation of illuminance

wavelength depending on the atomic structure of the 'reflecting' material[4].

The emitted light will, therefore, determine how bright the object is perceived to be, and the colour of that object. Objects that emit no light in the visible spectrum will appear black (though black is not really a colour, but an *absence* of light); thus, when reading a book with black ink on a white background, it is the light from the white background that is primarily stimulating the photoreceptors, not the printed words.

Luminance can be calculated by the formula:

$$L = E \times \rho$$

where E is the illuminance, and ρ is the reflectance of the surface.

Most 'black' surfaces we encounter will still reflect some light; Gilchrist[5] states that 'black' surfaces reflect around three per cent of light, whereas 'white' surfaces reflect around 90 per cent.

LIGHT LEVELS AND PERCEPTION

Although light meters and other gauges can objectively quantify illuminance and luminance, the measured values do not correspond directly with our subjective perception of brightness. Take, for example, the outdoor illuminance throughout the day; the author conducted an experiment with a light meter on a cloudless day in Northern England, just after the summer solstice, measuring illuminance. At its peak, the illuminance reached over 97,000 lux, but at sunset the illuminance dropped to less than 1000 lux; the illuminance at sunset was approximately one per cent of the peak illuminance for that day **(Figure 1)**.

If our perception was purely based on the absolute light levels, then we would experience very large differences in the perceived lighting of our environment, with everything looking one per cent as bright near dusk compared to the brightest time of day, and indoor living room lighting being 0.05 per cent as bright as the peak outdoor illuminance (based on the floor illumination of the author's living-room, under artificial illumination at night, of approximately 50 lux).

Of course, we do not actually experience these radical changes in light levels within our visual environment due to our ability to light and dark adapt. This disparity between objective light levels and perceived light levels can also be observed with sunglasses. If the perceived light was proportional to the objective transmitted light through a sunglasses tint, then we would notice a very dramatic drop in light levels **(Figure 2)**; instead, we perceive a relatively modest reduction in light levels.

FIGURE 2: An objective comparison of light level reduction with an approximately 18 per cent LTF grey tint; this differs to our perceptual experience with sunglasses

LIGHT PERCEPTION AND THE VISUAL SYSTEM

In relation to light perception, our visual system is dynamic; the maximum and minimum illuminance that we can perceive at any one time can be thought of as a sliding scale that covers a dynamic range of around 3-4 log units[3,6]. Even though we cannot perceive the entire illuminance range of the physical environment *at the same time*, our perception utilises light and dark adaption mechanisms to perceive the full range of illuminances in the environment. This 'sliding-scale' effect on our perception of brightness can be observed in everyday life: imagine viewing a mobile phone device indoors.

Assuming the brightness of the device is fixed, moving from an indoor environment to a sunny outdoor environment will make the screen appear a lot darker (even though the luminous intensity is the same). The brighter environment forces the upper limit of our dynamic range to adapt to higher luminance, but at the cost of bringing our lower light perception limit higher **(Figure 3 - page 22)**. Indeed, many mobile devices now use adaptive brightness technology to change the intensity of the screens in-line with the environment and our changing light perception.

Visual input involves both rod and cone cells and, depending on the lighting levels, one system or both may be involved; the study of this rod/cone interaction in governing our day and night vision is known as the *duplicity theory of vision*[8,9].

Each of these photoreceptor cell types respond to light, but with marked differences in sensitivity and wavelengths. Cone cells generally govern our vision in **photopic** conditions (daylight conditions), whereas rod cells primarily function in **scotopic** conditions (dark conditions). Although our cone cells allow our visual system to discriminate colour and contribute to a high level of spatial sensitivity, their performance in low level illumination is limited[3,7] as they cease responding to light levels below 0.01 cd.m^{-2}.

In contrast, our peripheral rod receptor cells are very sensitive to light[2], responding to light illumination levels as low as 0.000001 cd.m^{-2}. Under photopic conditions, the photopigments in these cells become overloaded and 'bleached', providing no useful visual information (though they still influence non-visual functions, such as the circadian system and pupil control pathway[10]).

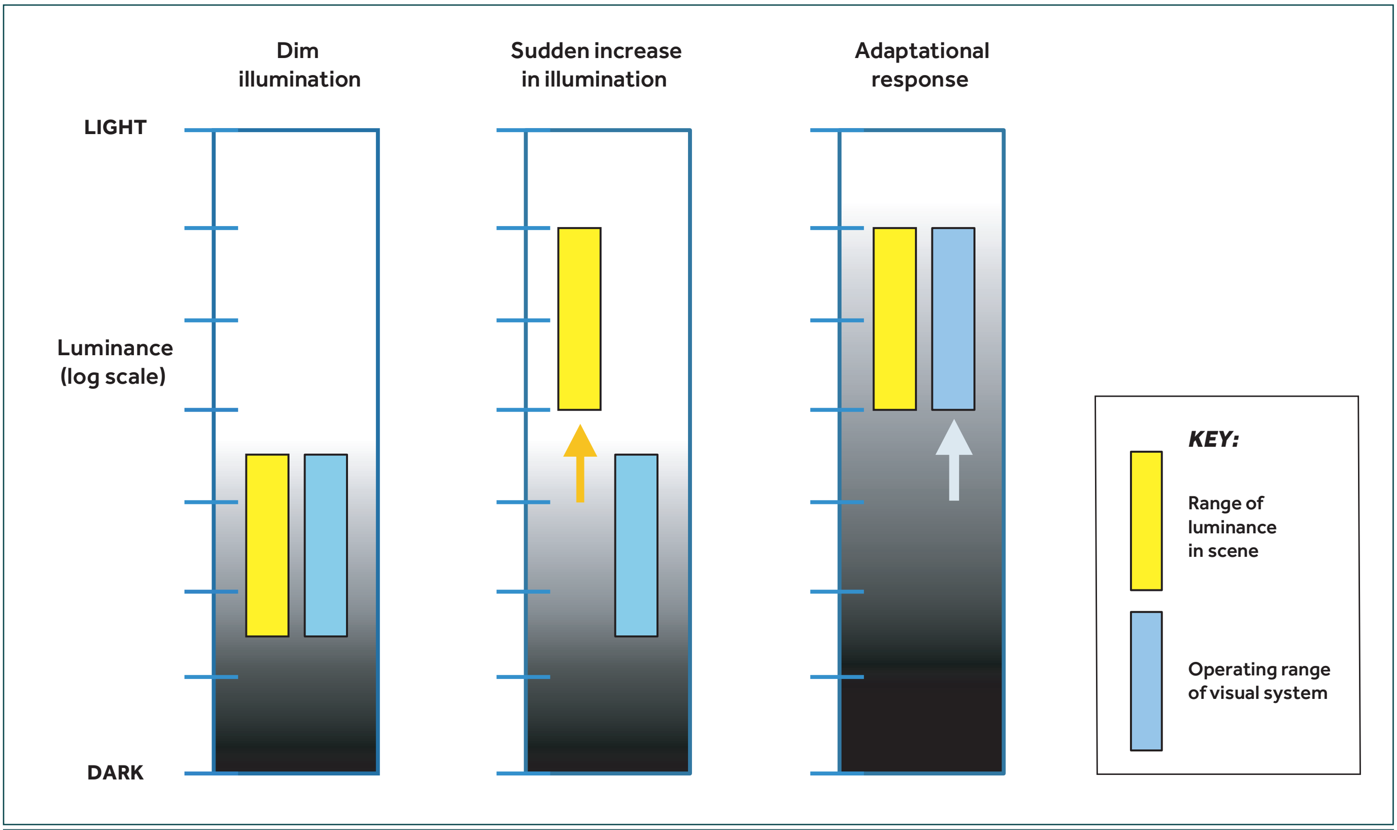

FIGURE 3: The response of our dynamic range when the illuminance is increased in the environment[7]

Carpenter R and Reddi B. Neurophysiology - A conceptual approach. 5th ed. London: CRC Press, 2012: p.127

However, in dark adapted scotopic conditions, the rod cells dominate to support our perception of dark environments with achromatic (*without colour*) vision. This can easily be observed at night when you are in an environment with no artificial lighting; approximately 30 minutes after the rhodopsin in the rod cells regenerates, and the visual system becomes dark-adapted[11], subjects will be able to perceive their environment more in the periphery of their field of view compared to their central field of vision.

Colour discrimination in low light will also be difficult, with the peak colour sensitivity shifting towards the blue wavelengths (known as the *Purkinje Shift*), and with totally dark-adapted scenes being perceived without colour and with poorer acuity[7,11,12].

Rod cells also have a high level of neural convergence, with an average of 120 rod cells pooling their inputs into one ganglion cell (as opposed to the low neural convergence of cone cells with an average of six cone cells to one ganglion cell)[7,11]. Whilst this results in poorer spatial resolution and acuity, this convergence greatly increases light sensitivity.

There is a functional overlap in the sensitivity ranges in which both cones and rods operate and contribute to our light perception, and this is described as **mesopic** conditions (shown as the orange region in **Figure 4**).

Pathologies affecting the rod cells, or the production of rhodopsin within those cells, will have a significant impact on the patient's light perception thresholds. Retinitis pigmentosa, for example, results in progressive rod cell death as the condition develops. As a consequence, night blindness (nyctalopia) is one of the most frequent symptoms typically associated with this condition[15,16].

This can be understood when considering the luminance ranges shown in **Figure 4**; atrophy of rod cells will prevent any perception of scotopic levels of vision, and significantly impact the mesopic perceptual range. Vitamin A deficiency impairing rhodopsin production also affects the functional performance of the rod cells and again can lead to symptoms of night blindness[17,18].

Differences between the absolute measured luminance and the perceived brightness can also be seen in our perception of colour. If we viewed a red, green, and blue lamp of **equal** luminous intensity (i.e. the photon output is the same) in photopic conditions, most observers would perceive the green lamp as being brighter, with the red and blue lamps dimmer[19].

The functional combination of short (S), medium (M), and long (L) wavelength cone cells results in our visual system being more sensitive to medium wavelength light of 555nm (yellow-green) in photopic conditions, so light around this wavelength will appear more luminous (though, with the aforementioned Purkinje shift, this sensitivity shifts towards the blue-end of the spectrum under scotopic conditions)[3,12].

Whilst it makes sense that an absence of light stimulation produces no response in the visual system, this is not quite true. Much like an electrical sensor, spontaneous neural changes within photoreceptor cells and cortical processing areas can introduce 'noise' or *dark light* into the visual system, even when there is no light stimulus[7,19-21].

This visual noise is generally ignored in our perceptual processing in normal viewing conditions, although it can be perceived in pitch black dark-adapted

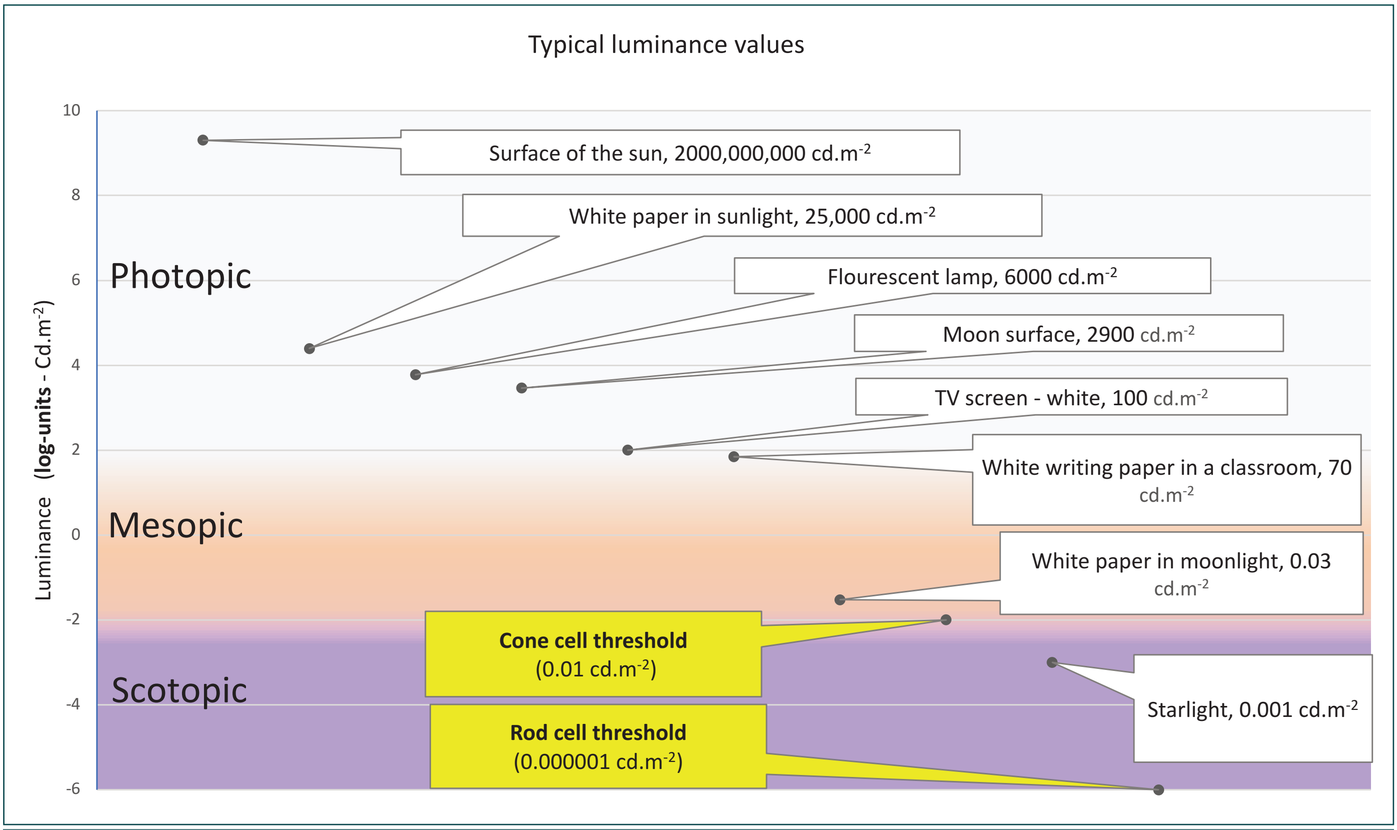

FIGURE 4: Typical luminance values[1,3,7,13,14] – note that the vertical scale is *logarithmic*; i.e. 2 log units = 100, 4 log units = 10,000)

conditions as a fluctuating grey percept. This signal noise also affects the sensitivity threshold limits of our vision, as the brain has to decide which signals from the photoreceptors represent actual stimulus-driven activation, and which are merely noise.

Whilst neuro-electrical signal output from cone and rod cells are dependent on their thresholds, further visual processing takes place at low levels by the retina[22,23] and higher levels by the visual processing areas of the brain, and are interpreted to form our perception. Thus, our perceptual experience derives, in part, from a neural analysis of differences in light levels between the stimulus and the background to help construct our perceptual model of the environment[2,7,11].

The dynamic response of our visual system to environmental illuminance can create some seemingly paradoxical issues; for example, consider a dark sheet of paper, with a reflectance of five per cent, illuminated in bright sunlight of 100,000 lux. The luminance can be calculated as 5000 cd.m^{-2}. Now a white piece of paper, with a reflectance of 90 per cent, can produce the **same** luminance as the dark sheet if it is illuminated by 5555.56 lux of illumination (for example, illuminance in the evening).

Although both these sheets of paper have the same luminance, and should therefore appear the same shade, they will appear to be different shades in their respective visual environments. This reinforces the fact that our visual system is based on comparative analysis of the variation of luminance in the visual scene (part of a process known as ***lightness constancy***) rather than a direct translation of objective luminance values[24].

OTHER FACTORS AFFECTING LIGHT PERCEPTION

As with processes such as depth perception, our visual system utilises the context of the visual scene to create our perceptual experience. Luminance cues within the scene, such as surface orientations, shadows, atmosphere, and surface albedos, will all influence the perceived brightness of the scene[5,24-26]. Our visual system, using lightness constancy, attempts to disentangle the actual lightness of an object (a fixed property based objectively from reflectance) from the brightness of an object (based on the perceived luminance of the object)[5,27]. Whilst this analysis is important to allow us to see shades of objects the same regardless of the illuminance, it can, in some situations, lead to illusionary percepts, as exampled in **Figure 5 - page 24**.

Pupil size is another physiological process that impacts on the perception of brightness. Photographers know this only too well; to increase the exposure of an image and let more light into the camera, photographers increase the size of the camera aperture. The physiology of the eye also adapts to light levels in the same way; as light levels drop, our pupils dilate to let more light in, enhancing our perception of brightness.

Whilst it is estimated that pupil dilation in dim conditions increases light entering the eye by 17x compared to outdoor sunlight, the perceptual increase is relatively minor in comparison to the aforementioned dynamic light adaption mechanism[2,3,7,28].

As well as influencing our perception of light, it should be recalled that pupillary dilation will also cause optical aberrations to impact on the quality of vision as the visual system diverges from a pin-hole system; patients with any uncorrected refractive error will notice their acuity and depth of focus is better

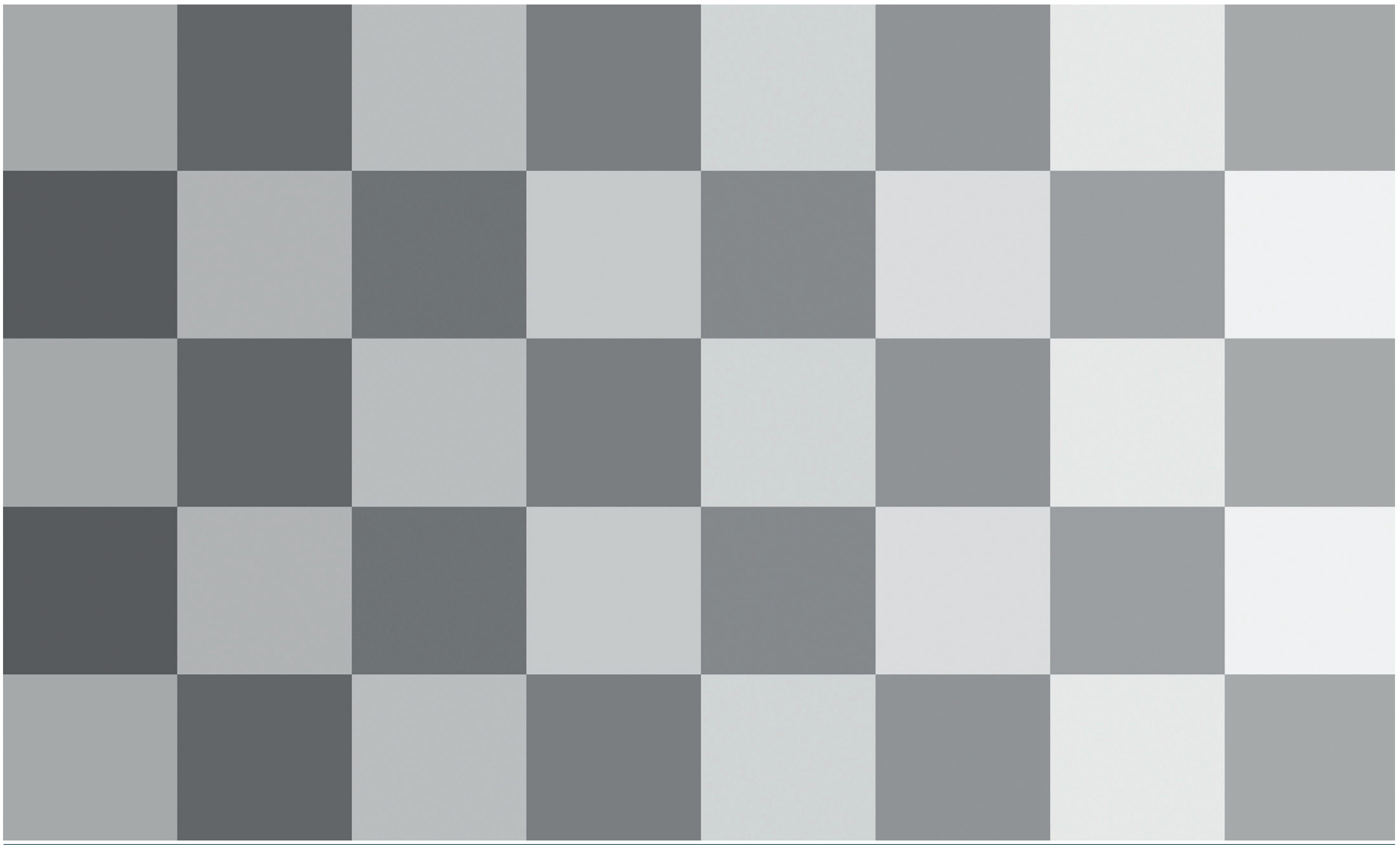

FIGURE 5: Light perception illusion; the four corner squares of this checkerboard have the same luminance; however, perceptually the two corner squares on the left are commonly perceived lighter than the two on the right of the board. Factors, such as the apparent shadow on the right-hand side, are misleading our perceptual analysis of the scene

in bright light, as their pupil size moves towards a pin-hole system, and worse in darker environments with dilation[7,29].

For our perceptual system to organise and segregate objects within the visual scene, objects must stand out from their background; this perceptual property is known as ***visual salience***, and can be affected by a number of factors, including brightness, colour, and motion[11,30].

In relation to light perception, contrast plays a significant role in enhancing the visual salience of a percept, and thus helps the observer discriminate objects, texts, and the like. Contrast is fundamentally linked with luminance; when viewing scenes, differences in luminance are utilised within receptive fields of retinal ganglion cells and neurons in the visual cortex (V1), within the early stages of visual processing, to detect edges and orientations of a stimulus[11,23].

Michelson contrast[28,31] is one of the ways we can numerically express contrast as a percentage, expressed by:

$$C = \frac{(L_{max} - L_{\min})}{(L_{max} + L_{min})} \times 100\%$$

Thus, increasing the difference between the background luminance and the object luminance will increase contrast, and the healthy visual system generally requires a one per cent threshold in contrast for discrimination[7].

SUPPORTING PATIENTS WITH A VISUAL IMPAIRMENT

Due to this central role in visual processing, consideration of contrast and illuminance control is essential to help visually impaired patients with a range of ocular conditions.

Pathologies, such as macular degeneration, cause retinal cells to atrophy and result in a reduction in contrast sensitivity and perceived brightness[32]. Increasing the lighting illuminance for such patients can improve the patient's visual performance, and studies have found increasing illuminance to around 1000 lux can provide optimal conditions to improve visual tasks[31].

Recalling the inverse-square law earlier, patients should be advised to either use brighter lighting or to bring light sources closer to their reading material, in order to increase illuminance when required. Moreover, advice on contrast enhancement within the home and working environments should also be incorporated into low vision care plans.

Recommending the use of household objects and decor with high contrast differences will help increase the visual salience of stimuli (**Figure 6**); for example, having stairs which have step nosing and bannisters that use strong contrast differences to help define their structure.

It should be noted that too much illuminance in the visual scene can negatively affect vision; recalling the dynamic range of luminance, bright lighting and glare can create a shift in this dynamic range and make stimuli with lower luminances harder to perceive (as with the mobile-phone analogy earlier).

Extremely bright light sources can produce scotomatic glare by bleaching the cone photopigment, temporarily reducing their function and briefly blinding the eye[3]. Even with the healthy eye, excessive illumination can also be uncomfortable, causing discomfort glare, or even detrimental to visual function, resulting in disability glare[33].

FIGURE 6: An example of using contrast to aid visual impairment. This chopping board has different overlays that can be used to aid contrast when cutting dark or light food

The presence of ocular pathologies can significantly worsen unwanted glare; some examples[31] include:

- **Cataracts:** opacities in the crystalline lens can cause light to scatter, resulting in discomfort glare
- **Congenital achromatopsia:** a rare condition which results in the eye only containing rod cells. Vision will be hindered by rhodopsin bleaching under bright photopic lighting conditions
- **Aniridia:** malformation or absence of the iris, increasing light entering the eye and associated with photophobia and discomfort glare

Though there is a clear disparity between measured light levels and our perception of light, the impressive complexity of our visual physiology and dynamic processing allows us to experience a wide variety of visual environments and stimuli. Consideration of illumination and lighting design is important in various artificial environments, from general shop lighting to sports-stadium lighting, to improve visual performance of subjects interacting within those settings, and to meet health and safety standards.

With an ever-growing elderly population, along with the associated senescent pathologies, it is important to consider lighting for patients, especially when pathologies limit the visual performance for low vision patients. Whilst possible low vision solutions often tend to primarily evoke consideration of magnification, discussion of luminance should also be incorporated into the care plan as part of a holistic approach to supporting such patients' needs.

REFERENCES: ***References for this article are published with the online version in the ABDO CPD portal.***

MARK HICKTON BSc (Hons) Cert Ed, FBDO, FHEA has been a lecturer in ophthalmic dispensing at Bradford College for more than 14 years, and is a practising dispensing optician with over 24 years of experience. An established CPD author, Mark is module leader for Bradford's Optics and Ophthalmic Lenses modules, and his college scholarly activity revolves around visual and audio-visual perception.

LEARNING OUTCOMES FOR THIS CPD ARTICLE

DOMAIN: Communication

1.8: *Consider patients environmental lighting circumstances and any ocular pathology present to enable the provision of appropriate advice to support patients in caring for themselves and making appropriate lifestyle changes.*

DOMAIN: Clinical Practice

5.3: *Develop a greater understanding of human light perception and a range of factors that may influence individual experiences and consider how this may impact the care you provide*

PLAN YOUR CPD TODAY

For all the latest available CPD from ABDO, visit ***www.abdo.org.uk.*** *All online and face-to-face interactive CPD events open for booking can be found on the Events pages. CPD articles and recorded lectures can be accessed in your personal membership area. Resources to help you plan and reflect on your CPD are available in the Professional Development Toolbox. GOC registrants are now responsible for submitting their own CPD and points are no longer uploaded by providers.*

On successful completion of this CPD session, log into your MyGOC account and follow the steps to submit this session using your certificate of completion as evidence. For more information on the new GOC CPD scheme, visit www.optical.org

References

1. Tunnacliffe AH and Hirst JG. *Optics.* 2nd ed. Canterbury: ABDO, 1996.

2. Bruce V, Green PR and Georgeson MA. *Visual Perception: Physiology, Psychology, and Ecology.* 4th ed. Hove: Psychology Press, 2003.

3. Tunnacliffe AH. *Introduction to Visual Optics.* 4th ed. Canterbury: ABDO, 2004.

4. Hecht E. *Optics*. 5th ed. Global edition. London: Pearson, 2016.

5. Gilchrist A. *Seeing Black and White*. Oxford: Oxford University Press, 2006.

6. Kunkel T and Reinhard E. A reassessment of the simultaneous dynamic range of the human visual system'. In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization* 2010:17-24.

7. Carpenter R and Reddi B. *Neurophysiology – A conceptual approach.* 5th ed. London: CRC Press, 2012.

8. Stabell B and Stabell U. *Duplicity Theory of Vision – From Newton to the Present*. New York: Cambridge University Press 2012.

9. Kalloniatis M and Luu C. Light and Dark Adaptation. 2007. In: Kolb H, Fernandez E and Nelson R. *Webvision: The Organization of the Retina and Visual System* [Internet]. University of Utah Health Sciences Center; 2020:1089-1100.

10. Zele AJ and Cao D. Vision under mesopic and scotopic illumination. *Frontiers in psychology* 2015;5(1594):1-15.

11. Goldstein EB and Brockmole JR. *Sensation and Perception*. 10th ed. Boston: Cengage Learning, 2016.

12. Kelber A, Yovanovich C and Olsson P. Thresholds and noise limitations of colour vision in dim light. *Philosophical Transactions of the Royal Society B: Biological Sciences* 2017;372(1717):20160065.

13. Stockman A and Sharpe LT. Into the twilight zone: the complexities of mesopic vision and luminous efficiency. *Ophthalmic & Physiological Optics* 2006;26(3):225-239.

14. Kolb H. Facts and Figures Concerning the Human Retina. 2007. In: Kolb H, Fernandez E and Nelson R. *Webvision: The Organization of the Retina and Visual System* [Internet]. University of Utah Health Sciences Center; 2020:1817-1825

15. Senthil MP, Khadka J and Pesudovs K. Seeing through their eyes: lived experiences of people with retinitis pigmentosa. *Eye* 2017;31(5):741-748.

16. Kanski JJ and Bowling B. *Clinical Ophthalmology - A Systemic Approach*. 7th ed. London: Elsevier, 2011.

17. Clifford LJ, Turnbull AM and Denning AM. Reversible night blindness – A reminder of the increasing importance of vitamin A deficiency in the developed world. *Journal of Optometry* 2013;6(3):173-174.

18. Abbott-Johnson W and Kerlin P. Vitamin A, Zinc, Dark Adaptation, and Liver Disease. In: Preedy, V. R. (eds.) *Handbook of Nutrition, Diet, and the Eye.* Oxford: Elsevier; 2014:301-310.

19. Gregory RL. *Eye and Brain: The psychology of seeing*. 5th ed. Oxford: Princeton University Press, 2015.

20. Pugh EN. The discovery of the ability of rod photoreceptors to signal single photons. *Journal of General Physiology* 2018;150(3):383-388.

21. Chen G and Gong P. Computing by modulating spontaneous cortical activity patterns as a mechanism of active visual processing. *Nature Communications* 2019;10(1):1-15.

22. Sinha P, Crucilla S, Gandhi T, Rose D, Singh A, Ganesh S, Mathur U and Bex P. Mechanisms underlying simultaneous brightness contrast: Early and innate. *Vision Research* 2020;173:41-49.

23. Fulcher C and Strong S. Low-level processing and visual illusions. *Optometry Today* 2018;58(6):64-67.

24. Adelson EH. Lightness Perception and Lightness Illusions. In: Gazzaniga, M. (eds.) *The New Cognitive Neurosciences*. 2nd ed. Cambridge, MA: MIT Press; 2000:339-351.

25. Hung CP, Callahan-Flintoft C, Walker AJ, Fedele PD, Fluitt KF, Odoemene O, Harrison AV, Vaughan BD, Jaswa MS and Wei M. A 100,000-to-1 high dynamic range (HDR) luminance display for investigating visual perception under real-world luminance dynamics. *Journal of Neuroscience Methods* 2020:108684.

26. Strong S and Fulcher C. High-level processing and visual illusions. *Optometry Today* 2018;58(7):64-68.

27. Gilchrist AL. Lightness and brightness. *Current Biology* 2007;17(8):R267-R269

28. Stone JV. *Vision and Brain – How we perceive the world*. Cambridge: Massachusetts Institute of Technology, 2012.

29. Schwartz SH. *Geometrical and Visual Optics: A Clinical Introduction.* 3rd ed. New York: McGraw Hill Education, 2019.

30. Poltoratski S, Ling S, McCormack D and Tong F. Characterizing the effects of feature salience and top-down attention in the early visual system. *Journal of Neurophysiology* 2017;(118):564-573.

31. Dickinson C. *Low Vision: principles and practice*. Edinburgh: Butterworth-Heinemann, 2003.

32. Xiong YZ, Kwon M, Bittner AK, Virgili G, Giacomelli G and Legge GE. Relationship between acuity and contrast sensitivity: differences due to eye disease. *Investigative Ophthalmology & Visual Science* 2020;61(6):1-7.

33. Harsant R. Low vision: categories and strategies. *Dispensing Optics* 2016;31(9):18-21.