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A review of the effects of colour and light on non-image function in humans

Stephen Westland,* Qianqian Pan and SooJin Lee

School of Design, University of Leeds, Leeds, LS2 9JT, UK
Email: s.westland@leeds.ac.uk

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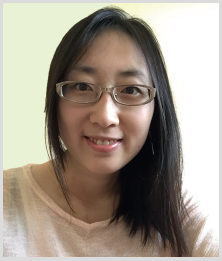
This paper reviews current knowledge on non-image-forming aspects of vision. Developments in the last 20 years have included the discovery of a fifth class of human visual pigment (melanopsin), in addition to the three classes of photopsin to be found in the cones and rhodopsin in the rods in the human retina. Melanopsin is found in a small number of retinal ganglion cells which then, in addition to receiving input from rods and cones, are intrinsically photosensitive. These retinal ganglion cells send their input primarily to the hypothalamus, where they help to regulate the circadian system (daily rhythms of sleep patterns, body temperature, heart rate, etc.). The discovery of the anatomical basis of non-image-forming vision has led to a great deal of research into the effects of light on sleep, depression and mood, retinal photodamage and well-being, amongst other factors. Given that recent technological innovations in LED lighting now give us greater control over environmental lighting, it is timely to review the non-visual effects of light in humans in order to inform lighting design in the future.

Editor-in-Chief's recommendation: *This Feature article gives a fascinating account of how colour impacts upon people's lives in ways which readers may find surprising and startling. Industry and commerce exploit colour routinely in a direct fashion to warn, to attract and to sell. Use of coloration in the belief that it manipulates mood, appeal and decision-making is not new. However, this review reveals that coloured light wields less obvious, yet still powerful, effects in numerous diverse spheres of life. Some of these aspects have only recently been established. Others form part of a dawning realisation that colour exerts potentially more far-reaching influences on health and quality of life than had previously been considered. The authors of this paper, among whose number is the SDC's President-elect, discuss the manner in which human body is affected not just by the luminance of ambient light, but also its hue. Indirect consequences of such interference, which leads to deviations in the body's natural daily rhythms, could include changes to the incidence of life-altering and -threatening disorders and diseases. The increasing prevalence of LED-based illumination and the ever lengthening amounts of time during which people receive exposure to emissive electronic display screens mean that research seeking to understand the body's responses to artificial light sources – particularly those which are blue-rich – assumes even greater importance. Concerns arising from such work are already being acted on. For example, certain smart phones and computers feature an option that automatically regulates the intensity and colour of light emitted by their displays according to the time of day or night. In several fields though, the jury is still out: findings remain ambiguous or controversy accompanies conclusions. Nevertheless, this Feature article clearly makes the case for colour having more to it than meets the eye.*

Prof Stephen Westland *received BSc and PhD degrees from the University of Leeds. He has published over 150 refereed papers in areas of colour physics, colour vision, imaging, psychophysics and colour design. He is Professor of Colour Science and Technology at the University of Leeds where he leads the Experience Design research group. In 2017 he was appointed President Elect of the Society of Dyers and Colourists.*

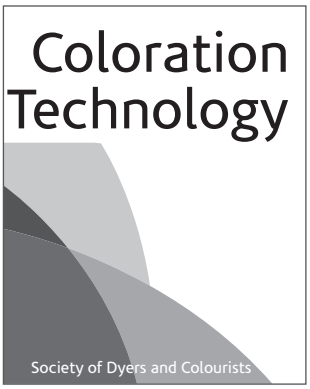


Dr Qianqian Pan *obtained a BSc in Textile Engineering (Jiangnan University) and an MSc in Advanced Textiles and Performance Clothing (University of Leeds). She was awarded a PhD from the University of Leeds where she now works as a Research Fellow. Her interests are colour appearance, colour measurement, lighting, psychophysical methods and computational aspects of colour.*

Ms Soojin Lee *obtained a first degree in Interior Architecture in Korea and an MA Design from the University of Leeds. She is currently a postgraduate researcher in the School of Design at the University of Leeds. Her interests include user experience, lighting, and environmental colour.*

*After first online publication, this article was selected as a Feature Article, and the Editor-in-Chief's recommendation has been added.

A review of the effects of colour and light on non-image function in humans



Stephen Westland,* Qianqian Pan and SooJin Lee

School of Design, University of Leeds, Leeds, LS2 9JT, UK
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Introduction

It is now known that the eyes perform two functions, involving, respectively, image-forming (IF) and non-image-forming (NIF) vision. Whereas the IF visual system allows us to see and is primarily mediated by the cones and rods in the human retina and four classes of photoreceptor (three photopsins in cones and rhodopsin in rods), the NIF function of the eye is primarily activated by a fifth photopigment, melanopsin, which is found in retinal ganglion cells (RGCs) located within a different layer of the retina from that of rods and cones. Although rods and cones mainly send signals via the laterate geniculate nuclei to the back of the brain (specifically, the visual cortex), RGCs that contain melanopsin transmit signals to the hypothalamus, where they help to regulate the circadian system that controls, amongst other things, our sleeping and waking periods. Given the increased interest in the effects of light and colour on aspects of human performance beyond vision, recent progress in understanding the NIF visual system, and technological innovations that now give us greater control over environmental lighting at home and in the workplace, it is timely to review the non-visual effects of light in humans.

This review paper will first summarise the NIF visual system and its relationship with the more widely understood IF visual system, and then review the available literature on the effects of light and colour on aspects of health and performance. Under health issues, the topics discussed are sleep and alertness, age-related macular degeneration (ARMD), cancer, anti-bacterial activity, heart rate and blood pressure, and reading, learning and other disorders. Under performance issues, the topics discussed are learning and productivity, impulsivity and creativity, jet lag, and mood and well-being. The material is presented under several headings summarised in Table 1, in which the effects included in this review are listed.

The IF and NIF visual responses

Human colour vision is mediated by three classes of light-sensitive cones, each of which has broadband spectral sensitivity, but peak sensitivity at the short (420 nm), medium (530 nm) and long (560 nm) wavelengths, respectively. The cones are active under so-called photopic levels of illumination. At lower (scotopic) levels, cones are unresponsive and human vision is mediated by the rods, which have peak sensitivity at about 498 nm. Under photopic conditions colour vision results from two opponent processes alongside a luminance response. The yellow–blue opponent system is common in species with dichromatic vision. In evolutionary terms the yellow–blue system is though to be 800 milion years old, whereas the red–green opponent system evolved much later, perhaps 40 million years ago, in Old World monkeys [1]. Today, humans and Old World monkeys are unique in being trichromats, whereas the majority of mammals are dichromats and most birds and fish are tetrachromats.

The notion of trichromacy in humans was postulated in the nineteenth century by Thomas Young and is the basis, of course, of the CIE (Commission Internationale de l'Eclairage) system developed in 1931 [2], although actual measurements of photopigments in humans were not confirmed until the second half of the twentieth century [3,4]. The rods and cones are located in the retina and generate signals that activate the bipolar layer of cells, which then activate the RGCs, the signals of which leave the eye via the optic nerve. Whereas most humans are trichromatic, a small number of people are dichromatic and possess colour-defective vision [5]. However, more recently it has been determined that some females are tetrachromatic [6].

Until the latter part of the twentieth century, the retina in trichromatic human observers was assumed to contain four photopigments and IF vision was thought to be the only function of the eye. The three cone-based photopigments in humans are based on the protein photopsin and the rod-based photopigment is based on the protein rhodopsin. A fifth human photopigment, based on the protein melanopsin, was discovered in humans at the turn of the century [7,8], having been found earlier in frogs and mice [9]. Melanopsin is found in some RGCs, which then are

Table 1 Areas of impact of exposure to light

Circadian disruption and entrainment	Age-related macular degeneration	Mood and well-being	Cancer	Heart rate and blood pressure	Reading, autism and headaches	Office and learning environments	Other medical effects
Sleep disorders	Blindness	Seasonal affective disorder	Skin damage	Heart rate	Meares–Irlen syndrome	Preference	Wound treatment
Melatonin suppression	Retinal damage	Mood	Skin and breast tumours	Blood pressure	Dyslexia	Impulsivity, reaction times, creativity	Burn treatment
Alertness		Colour, emotion	Colorectal cancer	Skin conductance	Migraine	Flicker	Tinnitus
Mood and well-being					Autism	Alertness and attention	Vestibular dysfunction
						Dynamic lighting	
						Relaxation	
						Headaches and eyestrain	
						Problem solving and performance	

intrinsically photosensitive (in addition, RGCs are responsive to light by the normal route through signals received from rods and cones via the bipolar cells). Intrinsically photosensitive RGCs (ipRGCs) mainly send their output to the suprachiasmatic nuclei of the hypothalamus (the so-called retinohypothalmic tract), whereas rods and cones send their signals to the visual cortex via the lateral geniculate nuclei. We now know that the eyes – like the ears, which give us the twin functions of hearing and balance – perform two functions by providing IF vision and NIF vision (Figure 1). The ipRGCs are primarily responsible for this NIF function, regulating the circadian system – the cycle that is approximately 24 h in duration and which controls our sleep and waking periods – but are also known to regulate pupil size. The existence of a diurnal cycle was first discovered in 1958 in plankton [10], but was not thought to exist in humans in a way that is entrained by light until much later [11].

However, it may not be so straightforward that the rods and cones contribute towards IF vision and the ipRGCs contribute towards the NIF system [12]. For example, under low light conditions, rods can regulate the circadian system and ipRGCs may contribute towards IF vision [12]. Mice without functioning rods and cones have been shown to be able to discriminate between spatial patterns in visual tests [13]. The ipRGCs combine input from rods and cones with their own, more sluggish, melanopsin-mediated response to transmit signals to various regions of the brain involved in both IF and NIF vision [14].

Melanopsin is the fifth photopigment in humans and has peak absorbance at about 480 nm (Figure 2) [15]. Like the photopigments in rods and cones, it is isomerised on light absorption, converting 11-*cis* retinal to all-*trans* retinal [16], although it may regenerate by a mechanism that differs from that established for rod and cone photopigments [9]. The human retina contains about 120 million rods and 6 million cones, but only about 3000 ipRGCs [9]. Cones can respond to temporal modulations in luminance of 100–200 ms [17]; by contrast, the response of ipRGCs has a slow onset and sustained depolarisation that can last as long as 30 s after the light is turned off [14]. Despite the fact that melanopsin can respond to a single photon of light, it is less sensitive than the photopigments in rods and cones; it is believed that this is because there is a low probability of photon capture [14]. It is now established that retinal light exposure elicits non-visual responses in humans that include the modulation of alertness and cognition [18–20].

This paper reviews the effects of light on aspects of human performance beyond colour vision. It is not clear, in many cases, whether these effects result from the IF or the NIF visual function of the eye (i.e. from cones or ipRGCs), or both.

Circadian entrainment and disruption

In the USA, approximately 30% of working adults average <6 h of sleep per night, but 50 years ago only 3% of the working population slept so little [21]. Poor sleep is associated with greater risk for obesity, diabetes, heart disease, depression and stroke [22]. One factor in the change in sleep patterns in society may be increased use of

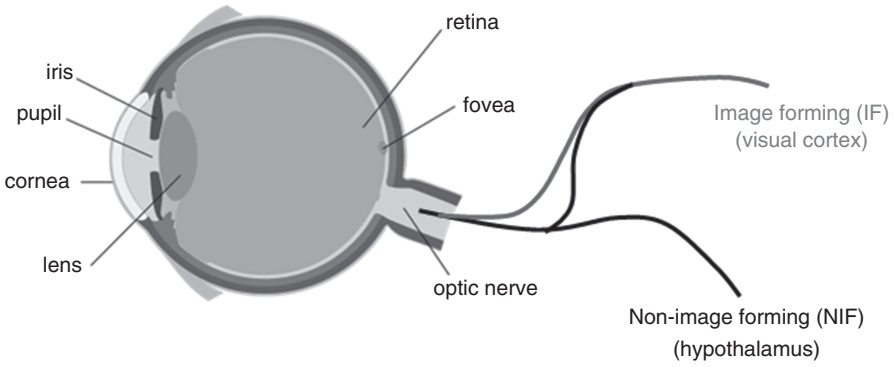

Figure 1 Schematic diagram showing image-forming and non-image-forming visual systems. The two systems may not exist in isolation, but may interact with one another

light. Between 1950 and 2000 the cost of electric light fell six-fold and usage per capita rose four-fold [21]. Use and control of light are increasingly considered as alternative non-drug-based methods to alleviate age-related sleep disturbance [23]. Light has been shown to exert strong alerting effects that depend upon several parameters such as irradiance, duration, time of day of exposure, and the spectral composition of the light [24,25].

In the morning when we wake, secretion of the hormone melatonin by the pineal gland is inhibited and the adrenal gland secretes cortisol (a hormone produced in large quantities when we are stressed, but which is also, like melatonin, part of the circadian cycle). Melatonin starts rising about 2 h prior to natural bedtime [26] and is involved in the circadian rhythms of several physiological functions, including sleep timing and blood pressure regulation [27]. Activation of ipRGCs by light after dusk inhibits sleep-promoting neurons, activates arousal-promoting neurons in the hypothalamus, and inhibits the secretion of melatonin. Light at night disrupts the circadian system, interferes with sleep and increases alertness [21]. Measurements of brain responses using functional magnetic resonance imaging have shown greater responses in the hippocampus to blue light rather than green light [18]. Blue light is most problematic because of the spectral sensitivity of the photopigment melanopsin (Figure 2). The measurement of melatonin levels in the body (usually from saliva samples) is therefore often used as a measure of alertness in various experimental paradigms. Today's lighting environment has substantially changed from that

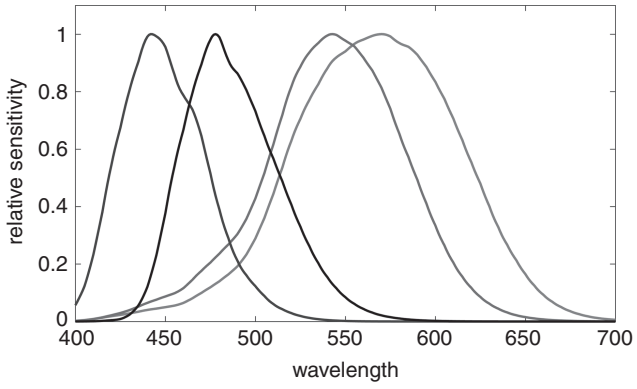

Figure 2 Relative spectral sensitivity of cones (from Stockman and Sharpe [185]) and the photopigment melanopsin [15], which is found in intrinsically photosensitive retinal ganglion cells

experienced during evolution; in most parts of the world artificial light has replaced natural sunlight during the day and artificial light at night has replaced darkness [28]. Reductions in sleep and the associated lowering of melatonin levels are associated with incidences of a great number of other illnesses, including cancer, heart disease and psychiatric disorders [21,29,30].

The ability of light to disrupt the circadian system and suppress levels of melatonin was established before the discovery of ipRGCs in humans in 2002 [31–33]. However, over the last decade or so, the role of the NIF visual system in this process has become better understood. The spectral sensitivity associated with the suppression of nocturnal melatonin in humans by light has been investigated and action spectra constructed that show distinct short-wavelength sensitivity peaking between 460 and 490 nm [34,35]. An interesting study was conducted with participants at a polar base station (where there is no access to sunlight in winter) where sleep problems and circadian misalignment are often reported [36]. A combination of measurements of melatonin levels (from saliva samples) and self-reporting was used to assess the effects of standard fluorescent white lights and blue-enriched lights in the daytime and showed that blue-enriched light resulted in substantially less delay in the onset of melatonin in the evening [36]. In another study, participants were submitted to continuous electroencephalogram (EEG) recordings and undertook a series of tests whilst exposed to light of 555 nm or 460 nm; under the blue light participants had lower subjective sleepiness and increased EEG alpha waves [37]. Significantly less melatonin suppression has been noted in elderly subjects compared with young subjects, which may reflect age-related changes in lens density in the eye [38]. This means that younger people may be at particular risk from using artificial light at night.

Although the primary concern refers to the use of light in the home, there is some concern that evening use of emissive displays (smartphones and tablets) is partly responsible for the changing sleep patterns observed [39]. Figure 3 shows the spectral emissions of two popular smartphones when white is displayed; it is clear that there is substantial radiation in the region where the NIF system is sensitive. Although there is a great deal of speculation about the negative impact of using emissive displays at night, it is likely that the increased use of room lighting at home (and the replacement of warm Tungsten light bulbs with solid-state lighting that emits more of the potentially

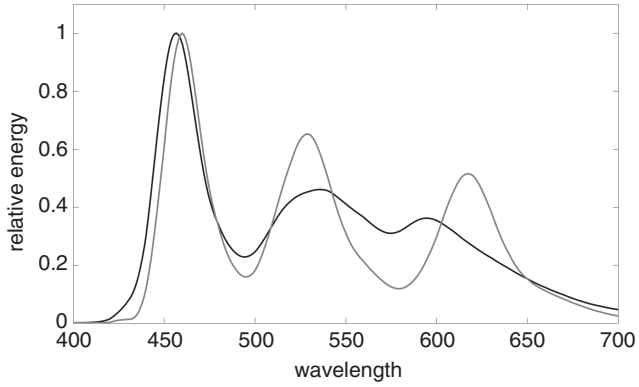

Figure 3 Relative spectral emissions from two commercial smartphones when white is displayed, demonstrating that both devices emit substantial short-wavelength light

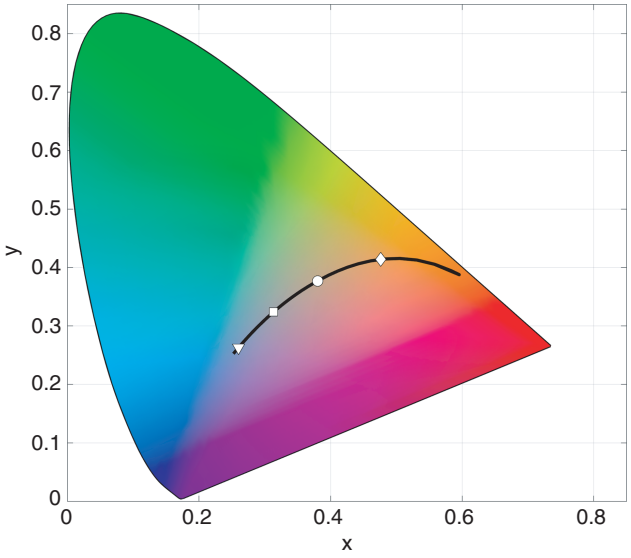

Figure 4 CIE chromaticity diagram showing the blackbody locus (solid line) and the chromaticities of light with colour temperatures of 2500 K (diamond), 4000 K (circle), 6500 K (square) and 17 000 K (triangle)

harmful short wavelengths) is an even greater problem. A recent study found that exposure to bright room light (200 lux) suppressed melatonin and resulted in later melatonin onset compared with exposure to dim light (<3 lux) [40]. Evening light levels as low as 65 lux in the home can alter circadian timing [41].

In terms of colour, light at 420 nm has a stronger effect than that at 470 nm, which, in turn, is more effective than light at 600 nm [42]. However, light at 460 nm was found to significantly suppress melatonin levels to a greater extent than light at 420 nm [43]. In a study of daytime sleeping, green light at 500 nm (administered via a light mask) was not found to inhibit sleep [44]. There is some suggestion that adolescents may be more sensitive than adults and may be at particular risk from blue light. The use of self-luminous devices for 1 h or 2 h prior to natural bedtime reduced melatonin levels in adolescents by 23% and 38%, respectively [26].

Although exposure to blue light late at night is problematic, during the day a high colour temperature (and high intensity) of lighting is actually required for synchronisation of the circadian system [45]. A study conducted in elderly patients with insomnia found that exposure to bright light in the early evening was beneficial [23]. The effect of bright light at lunchtime in a geriatric hospital resulted in clinical improvements in sleep and wakefulness [46]. Light at a correlated colour temperature (CCT) of 6500 K (40 lux for 2 h in the evening) significantly increased alertness and suppressed melatonin levels compared with light at 2500 K [47]. The CCT is a measure of the colour of light sources that refers to the closest point in CIE chromaticity space on the blackbody locus (Figure 4). Office workers exposed to either a blue-enriched light (17 000 K) or a white light (4000 K) showed increased alertness and positive mood, and decreased evening fatigue as measured subjectively after exposure to the blue-enriched light in comparison with the white light [48]. In a similar study conducted in subjects who were sleep-deprived, a dawn-simulating light (gradually increasing from 0 lux to 250 lux) in the morning resulted in enhanced mood and well-being compared with the use of a blue light (100 lux at 470 nm) [49]. Light can also have other positive effects; for example, sunlight acts via the skin to synthesise vitamin D [50].

Some questions remain. Most studies link the alerting effects of light to its ability to suppress melatonin, but at least one study has found both short (blue) and long (red) wavelengths increase alertness in the night after a period of darkness, although only the short-wavelength light significantly suppressed melatonin levels [51]. The relative contributions of rods, cones and ipRGCs to NIF responses under light conditions differing in irradiance, duration and spectral composition remain to be determined in humans [52]. In one study, subjects were exposed to blue (460 nm) or green (555 nm) light near the onset of nocturnal melatonin secretion; initially, both lights were equally effective but spectral sensitivity to 555-nm light decayed exponentially, suggesting that cones make a significant contribution to NIF vision at the beginning of light exposure [53]. A study conducted in subjects who had been deprived of quality sleep for two consecutive nights found no difference between the effects of two lights (one of which was much richer in short wavelengths) on subjective alertness, energy and mood, suggesting that when sleepiness is high, the ability of classical photoreceptors to increase alertness cannot be ruled out [54]. It has also been reported that in mice blue light causes an increase in alertness, whereas green light promotes sleep [25]. Another study showed that light can be used to increase alertness in the afternoon, but that red light is a stronger alerting stimulus than blue light [55].

Another interesting effect of light concerns alleviation of the effects of jet lag, which result from the temporary loss of synchrony between an abruptly shifted sleep period, timed in accordance with the new local day–night cycle, and a gradually re-entraining circadian system. Jet lag is often confused with travel fatigue, but the symptoms of the former do not disappear after a good night's sleep [56]. The most commonly experienced symptoms are sleep disorders, difficulty in concentrating, irritability, depression, fatigue, disorientation, loss of appetite and gastrointestinal disturbance [57]. For short stopovers, adapting the circadian system is not advised even if it were possible, but for longer stays strategies to hasten adaptation include exposure to,

and avoidance of, light [58]. However, the published research has produced inconclusive evidence so far.

In the 1990s, laboratory simulations, in which sleep was advanced by 6–8 h and subjects were exposed to 3–4 h of bright light for several days, were not at all conclusive [59]. One possible reason for this is that jet lag is associated with other factors, such as stress and tiredness, in addition to the time shift, and therefore that simulations do not replicate real-world conditions. In an early study conducted in a realistic setting, four subjects underwent light treatment before and after a flight from Tokyo to San Francisco; two of them received 3 h of bright light at 11.00 h (San Francisco time) for 3 days after arrival and showed enhanced sleep efficiency compared with the other two, who received dim light treatment [60]. However, in a later study in 20 subjects who flew from Zurich to New York, light treatment showed significantly larger phase delays in melatonin onset but little behavioural benefit [61]. These studies are promising but limited by their small sample sizes. A review of the literature concluded that laboratory studies do not unequivocally support the hypothesis that bright light alleviates jet lag and the scarcity of field studies does not allow for a clear judgement on the beneficial effect of bright light treatment on jet lag [62].

Most studies have looked at light treatment after arrival in a new time zone. However, one study considered the use of light treatment to advance circadian rhythms prior to travelling eastwards and found greater (although not statistically significant) advancement with bright light than with dim light [63]. Although not directly related to jet lag, an interesting study looked at psychological and physiological indicators of time perception when subjects were exposed to various monochromatic light environments [64]. Psychological indicators showed that time was perceived to run faster in red light than in light of any other colour and were supported to some extent by EEG measurements also taken [64].

Age-related macular degeneration

Age-related macular degeneration (ARMD) is the leading cause of irreversible blindness in the developed world and usually affects people over 50 years of age [65]. It is ironic that the very light we require to see by is highly damaging to our visual systems. ARMD is caused by damage to the macula of the retina and results in blurred vision or, in extreme cases, no vision at all in the centre of the visual field (Figure 5). The macula is the central area of the retina, contains the highest density of photoreceptors and is responsible for high-resolution spatial acuity. Photoreceptors are susceptible to damage by light, particularly short-wavelength light [66,67]; free retinal (an essential element in the photochemical process of vision) is phototoxic [68]. Short-wavelength light is a particular threat because photons at this wavelength are high energy and can damage the cellular structure and function of photoreceptors [68]. Blue light has been described as 50–80 times more effective at causing photoreceptor damage [69]. Most ultraviolet (UV) radiation of <295 nm is blocked by the cornea, whereas much UVA (315–400 nm) and UVB (280–315 nm) light is absorbed by the lens. However, some radiation of <400 nm does reach the retina [68]. The macula area is naturally yellow as a result of the presence of various xanthophyll carotenoids (such as lutein), which may give protection against blue light [67] and are also free-radical scavengers [68]. The lutein or macula pigment has been described as 'nature's notch pigment' [70].

Figure 5 Simulation of vision in moderate age-related macular degeneration. (Reproduced with permission from the University of Cambridge Inclusive Design Toolkit [http://www.inclusivedesigntoolkit.com/betterdesign2/simsoftware/simsoftware.html])

It has long been suggested that exposure to blue and white light (especially in later life) may be a contributory factor in ARMD [71], although much of the research has been based on animal experiments. Experiments in rats, for example, found photoreceptor apoptosis after exposure to light of 400–480 nm [72]. Using narrowband radiation, blue (403 nm) light was found to severely damage rat photoreceptors, whereas green (550 nm) light of the same energy did not [73]. However, animal data and models may not be relevant to human pathology [74]. A review conducted in 2004 indicated that the evidence suggests, but does not yet confirm, that blue light is a risk factor for ARMD in humans [75]. More recently, it has been suggested that eye protection should be worn in very bright outdoor conditions to protect against the risk for ARMD [76].

In the European Union, the sale of incandescent light bulbs has been phased out over the last 10 years and estimates indicate that the use of white LEDs to replace all other light sources will reduce carbon dioxide emissions by 270 million tons per year [75]. However, the replacement of Tungsten light with LED lights that are rich in short-wavelength light represents a potential health hazard. Disruption of circadian rhythm, loss of sleep and early onset of ARMD are three serious risks that may rise with the increased use of light (and blue light in particular) in homes and workplaces. A recent review by the French Agency for Food, Environmental and Occupational Health and Safety noted that serious effects of chronic day-long lifetime exposure to blue light could not be ruled out [74]. A 2014 study conducted in albino rats subject to illumination by white LEDs to simulate typical domestic light showed evidence of retinal damage and cell death after just 9 days of exposure [77]. However, blue light is not without virtue [78]. Indoor light that is deficient in short-wavelength light may be detrimental in terms of myopia [79] and is required during the day for entrainment of the circadian system. Insufficient blue light during the day can also negatively affect mood and lead to depression [80].

Mood and well-being

A long history of research shows that colour can have an effect on mood [81,82]. Although there is now a huge number of publications on this topic, these are not included in full in this review as most of this research is arguably about the visual effects of colour. However, this section will present a very brief overview of some ideas in colour emotion, along with some effects that are likely to be associated with the NIF visual process and seasonal affective disorder (SAD).

Colours have strong associations and can affect mood and emotion. Many associations [83] are almost certainly the result of the IF visual process and fall outside the remit of this paper; however, it is not clear whether the emotional effects of colour result from the IF or NIF visual systems. The effects of colour and light on emotion have been referred to in the recent literature as colour emotion [84–87], although there is some confusion in the literature between the emotional effect of a colour and a simple association of a colour with a concept or idea. Much of the recent research in colour emotion uses scaling techniques to assign colours to bipolar scales such as masculine–feminine or warm–cold. Some work has attempted to find principal factors or dimensions for colour emotion. For example, Kobayashi developed three main dimensions of colour emotion (warm–cool, soft–hard and clear–greyish) [88], and Sato *et al.* described the dimension of warm–cool, the potency and activity of which were found to be associated with attributes of the appearance of the colour such as hue, lightness and chroma [89]. More recently, Xin *et al.* and Ou *et al.* developed models for single- and two-colour stimuli and discussed the relationship between colour emotion and colour preference [84–86].

Some studies have found that mood in a living or workplace environment can be affected by colour [90], although others have found environmental colour to have no effect on mood [91,92]. A study conducted in a light laboratory that aimed to simulate perceptions of participants in an aircraft cabin when exposed to different lighting conditions found that room temperature was perceived differently depending on the colour of the lighting; in yellow light, room temperature was felt to be warmer than in blue light [93]. Subjects felt more alert in blue light [93]. There is currently great interest in dynamic lighting and its effects on mood and perception [94].

There is some evidence that performance and mood are adversely affected by non-visual flicker in some fluorescent lights [95]. In office environments, subjects reported a more positive mood under 2000 lux than under 300 lux [96]. Findings in countries north of the equator show significant variation in mood over the year that does not occur in countries closer to the equator, and indicate that mood is lowest when it is dark and best when there is optimal brightness [82].

Seasonal affective disorder is a form of recurrent depressive or bipolar disorder in which episodes vary in severity and normally occur annually [80,97]. Most cases are associated with winter depression and are thought to be aggravated by low light levels, although SAD cases associated with other seasons (such as summer depression) are also noted [80]. For winter-based SAD, exposure to light in the morning is a common treatment and preliminary experiments with light were carried out in the 1980s [80,98,99]. It was suggested that an effective treatment (usually measured by improvements in scores on the Hamilton Rating Scale for Depression) should include 2500 lux of artificial light exposure in the morning at least twice per day for 1 week [100]. Early treatments were effected using a viewing cabinet fitted with a 4000-K fluorescent tube [101]. Illumination of different areas of the human retina generates different amounts of melatonin suppression [102]. Such findings suggest a non-homogeneous distribution of ipRGCs in the human retina so that the geometric relationship of any lighting with the observer may be an important factor. The use of a light above eye level in contexts in which the eyes look downwards towards a work surface is supported by studies that show enhanced melatonin suppression with directional illumination of the lower retina [102]. Currently, there is interest in light-emissive visors known as dawn simulators that can mimic the gradual twilight transitions found outdoors naturally [101].

Although initial treatments used broadband white light, increased understanding of the NIF visual process has led to interest in treatments using shorter wavelengths, but the various studies reported have produced quite contradictory findings. One early study found that white light was more effective than either red or blue light [103], whereas another suggested that broadband white light was more effective than green light [104]. A further study found that green light was more effective than red light [105]. Both bright white light and dim red light were also found to be effective with no statistical difference between them [106]. In a later study, narrowband blue light (468 nm) from LEDs was shown to be more effective than red light (654 nm), although the red light used in this study was also dimmer than the blue light [107]. The inclusion of UVA wavelengths within treatment protocols has been shown to be ineffective [108]. Since the 1990s, treatment with light of 10 000 lux has been commonly recommended [109], although it has also been suggested that the recommended dose may be too high if narrowband short-wavelength light is used [110]. Some mild side effects of light treatment, including headaches, eye strain and feeling 'wired' have been reported [108,109].

The slightly confusing issue of whether short-wavelength light is more effective than broadband white light may have arisen because the relative contributions of cones, rods and ipRGCs to NIF visual function may depend upon various parameters such as illuminance level, time of day and duration. Many published studies on the use of light therapy in mood disorders failed to meet certain criteria, but a meta-analysis of published studies that did meet these criteria concluded that treatment with bright light has a level of efficacy equivalent to that of treatment with anti-depressant drugs [111]. Whether light therapy is effective in the treatment of non-seasonal depression is less clear, but some efficacy has been noted when it is used in conjunction with anti-depressants [112,113]. Some effect of light therapy has also been found in the treatment of bulimia nervosa that worsens in winter [101,114] and in elderly dementia [113].

Cancer

The most familiar human photochemical damage is skin cancer [115]. UV radiation in sunlight is the most prominent and ubiquitous physical carcinogen in the natural environment [116], but does not penetrate deeper than the skin. The relationship between skin cancer and sun exposure was suspected in the late nineteenth century and confirmed experimentally in the early part of the twentieth century [116]. Both UVA (315–400 nm) and UVB (280–315 nm) radiation play important roles in conditions such as premature skin ageing, eye damage (including cataracts) and skin cancers [117]. Some concern has been expressed that indoor lighting could be harmful. Compact fluorescent lamps used in desk or task-lighting applications could result in overexposure of the skin to UV light [118], although this has recently been contested [119,120]. Other researchers have argued that TVs, tablets and computers pose no UV risk to humans when used at a safe distance [121].

There is also the possibility that UV, visible and infrared radiation can cause skin damage other than cancer [122]. Visible and infrared radiation can raise the temperature of the skin (and of the cornea of the eye) and can, with sufficient elevation in temperature, result in burning. The Illuminating Engineering Society of North America Recommended Practice 27 sets out a system for classifying light sources according to the level of radiation risk they represent [122]. Meanwhile the Commission Internationale de L'Eclairage has published a biological safety standard that may be used to assess LED lighting [123].

There has been some suggestion that exposure to blue light, in particular, during the late evening or at night may represent a risk factor for cancer because it reduces the amount of melatonin in the body. A number of animal studies have shown melatonin to be effective against cancer. It is a powerful anti-oxidant and free radical scavenger. For example, in hundreds of investigations, melatonin has been documented to ameliorate the oxidative injuries to tissue caused by ionising radiation [124]. That melatonin has significant atoxic, apoptotic, oncostatic, angiogenetic, differentiating and anti-proliferative properties against all solid and liquid tumours is beyond doubt [125]. It has also long been known that the risk for breast cancer is higher in industrialised societies than in non-industrialised areas [126]. As exposure to light at night can decrease production of melatonin by the pineal gland, and melatonin has been shown to suppress mammary tumorigenesis in some animals, it was suggested that the use of light at night (and hence nightshift work itself) may be a contributory factor to the high rates of breast cancer in industrialised areas. Some studies have suggested that exposure to light at night may be associated with risk for breast cancer in humans [127,128] and that nurses who work nightshifts may be at greater risk for colorectal cancer [129]. Indeed, a World Health Organization review concluded that shift work involving circadian disruption is probably carcinogenic to humans [130]. Recently, however, a meta-analysis of seven studies (involving a total of 1.4 million women) looked at shift work and incidences of cancer and concluded that nightshift work has little or no effect on breast cancer incidence [131].

Heart rate and blood pressure

Although much of the popular media assume that colour affects heart rate and blood pressure, a review in 1984 found inconclusive data [132]. However, Kaiser [132] noted one study in which systolic blood pressure was higher when observers viewed the colour red than when they looked at white and that both responses were higher than for blue, although this finding was reported in an unpublished PhD thesis written in 1958 [133]. Nevertheless, studies in rats have shown the heart to be under the control of the suprachiasmatic nucleus (which is at the centre of the circadian system) and findings in humans indicate a time-of-day-dependent simulation of resting heart rate by moderate light intensities [134,135]; typically, heart rate is about 6 beats per min faster at noon than during sleep. Experiments have shown that bursts of bright light can raise heart rate compared with resting heart rate in the dark [135]. Illumination at 1000 lux has also been shown to increase heart rate compared with similarly coloured (4000 K) illumination at 250 lux [136].

A number of studies using coloured light and environments have been carried out since 1984. A study with 60 participants exposed to red, white and blue light, respectively, found no differential effects of light colour on heart rate or skin conductance [137]. A later study found that participants' blood pressure fell when they relaxed in a pink room; however, the study was not fully controlled and therefore, for example, blood pressure may also have fallen had the participants relaxed in a white room [138]. Recently, study participants were placed in environments with coloured lighting in which it was found that, relative to the white condition, heart rate increased in the red condition and decreased in the blue and green conditions; however, the differences were not statistically significant [139]. Recently, in a study in which students were presented with differently coloured learning environments, heart rate was increased in red and yellow environments and decreased in a blue environment, and these differences in effect were significant [140]. In a sleep study in which participants were exposed to light during the late evening, light at 460 nm led to significantly higher heart rates than light at 550 nm (or the no-light control condition) [24]. However, whereas the effect of light intensity on heart rate is quite well established, the evidence for an effect of colour (whether of light or environment) on heart rate and blood pressure accumulated over the 30 years since Kaiser's 1984 review [132] is still not entirely convincing and more work is required before any definitive conclusions can be drawn.

Reading and learning disorders, autism and headaches

Some people experience stress and headaches whilst reading (Meares–Irlen syndrome) and about 375 000 children in the UK have dyslexia [141]. It has long been believed that the use of coloured overlays can reduce the distortion experienced by children with reading difficulties (and others who suffer from eye strain) and alleviate symptoms, although the effectiveness of different colours varies amongst subjects [142,143]. The rate of reading (assessed using the Wilkins Rate of Reading Test) for some participants with learning difficulty

was found to be significantly faster when a coloured overlay was used [144]. Coloured glasses can also be beneficial, although the optimal colours can differ from those when an overlay is used [145]. However, the efficacy of coloured overlays in Meares–Irlen syndrome and indeed the validity of the syndrome itself have been questioned [146]. Recent analyses have also criticised many of the studies carried out in subjects with dyslexia and concluded that the use of coloured overlays and lenses is unlikely to be effective [141,147].

However, the exacerbating effect of light on migraine headaches in about 80% of subjects with migraine, a condition known as photophobia, is well known [148]. A surprising study found that even some blind subjects (in whom blindness resulted from retinal damage or eye removal, but in whom the optic nerve remained intact) experienced their worst headaches in conditions of bright light [149]. It has now been shown that narrowband green light can actually alleviate headaches in migraine sufferers, contrary to the action of other colours, and this is leading to some interesting ideas about light therapy [148].

Autism is a condition characterised by impaired social interaction, verbal and non-verbal communication, and restricted and repetitive behaviour that is usually noticed within the first 2 years of a child's life [150]. Some research has indicated that colour overlays may be effective in helping autistic children to read more easily [151]. There has been some concern that the flicker from fluorescent lights may have an adverse effect on some repetitive behaviours. A study conducted in six children with autism showed that they spent significantly more time engaged in repetitive behaviour when illuminated by a fluorescent light than by an incandescent light source [152]. However, a study performed in five children with autism and five children with intellectual disabilities found no differential effects of fluorescent or incandescent light on behaviour [153].

Learning, productivity and alertness in indoor spaces

The luminous environment in a space is one of the key factors affecting the occupants' work performance and mood [154]. Current concerns about sustainability may lead to a reduction in illuminance levels in office light; in the commercial sector, lighting accounts for up to 40% of energy costs in a typical UK office [155]. However, users require lighting that does not limit visual performance, does not cause visual discomfort and meets expectations [156]. Illuminance of 500 lux is an accepted standard, but it has been suggested that lower light levels may be possible without compromising the user experience [156]. The effects of illuminance (300 lux or 500 lux) and colour temperature (4000 K or 6500 K) were measured in mock office rooms [157]; observers preferred the 500 lux and warmer (4000 K) lighting. Some effects of spectral power distribution (rather than simple CCT) were also observed. Although there are standards for lux level in office environments, the same is not true for CCT [154]. Some, although not all, studies have shown that higher CCTs appear brighter to people than lower CCTs.

High CCT lighting has shown significant improvements in self-reported measures of concentration in office workers compared with standard office lighting [158]. A study involving different types of space (such as the office and living room) showed that people preferred different CCTs for different activities and suggesting changeable CCTs would be better than a fixed CCT [154]. Environmental workspace colour was varied to determine performance in low- and high-demand tasks [91]. Over time, performance worsened most in the blue environment in subjects performing a low-demand task, but declined most in the red environment in subjects performing a high-demand task [91]. Participants exposed to 460-nm light have been found to show decreased auditory reaction times and fewer attentional failures than when exposed to 555-nm light [158].

The use of 100-Hz fluorescent lighting has been shown to cause headaches and impair visual performance [159]. A study of 50 students undertaking a simple visual search task revealed better performance in light with low modulation (flicker) than in light with high modulation [160]. The speed of production of workers assembling electronic devices was higher under 1200-lux lighting than in an 800-lux environment, but there was no impact of light level on error rate [161]. It is not at all clear whether full-spectrum fluorescent lights (with a colour temperature of about 5000 K) can support better performance than cool-white (4100 K) or warm-white (3000 K) fluorescent lighting [162].

Bright light can have particularly strong alerting effects at night [163]. Such alerting effects have also been measured during the day. For example, illumination at 1000 lux has been shown to increase subjective assessments of alertness and sustained attention to tasks compared with illumination at 250 lux [136].

Recently, there has been much focus on dynamic lighting, or lighting that varies in illuminance and colour over time [164]. Dynamically coloured lighting, for example, has been shown to decrease boredom and increase relaxation in people in a waiting environment [165]. Office workers, when assessed using a questionnaire, showed no effect of dynamic lighting (compared with static lighting) on alertness, headache and eyestrain, psychiatric health, sleep quality or subjective performance, although employees were more satisfied with the dynamic lighting [166].

A study on the effects of lighting on short-term memory and problem solving revealed better performance in warm lighting than in cool or artificial daylight lighting [92]. An earlier study found that cognitive performance may be related to the effects of lighting on mood [167]. That 'colour is one of the least studied aspects of the physical environment, but [. . .] nonetheless remains the topic of some of the most optimistic claims about morale and efficiency' has been noted previously [168,169].

The colour of ambient light in a simulated car interior has been shown to have a positive effect on participants' perceptions of space, quality and safety [170].

The physical environment of an office space has been shown to affect creativity, although some findings with regard to colour are contradictory. One study concluded that cooler colours were more conducive to creativity [171], whereas another claimed that warmer colours were more effective [172]. A third study found no effect of colour on creativity [173]. The level of light has also been shown to have no effect [172]. Generally, the physical environment is

thought to be less important than the social–organisational environment and the creative personality of the individual [174].

Hyperactive children are thought to be more easily under-stimulated than non-hyperactive children and the addition of extra stimulation to a task to improve performance in hyperactive children has been proposed [175]. The addition of colour to an otherwise black-and-white task has been effective in this regard [175]. Over the last 10 years, blue lights have been installed on many railway station platforms in Tokyo in an attempt to reduce suicides and have been found to be effective [176,177], although such effectiveness has been recently questioned [178].

Other medical applications

Low-level light therapy, or photostimulation, has been suggested as an attractive alternative to enhance wound healing [179]. The use of low-level lasers was introduced in the 1970s as a treatment for wound healing [180]; low doses of laser were found to stimulate the regeneration of mechanically induced wounds and burns. Wounds generated by laser (long-wavelength and infrared) surgery have been shown to heal more quickly than similar wounds generated by conventional surgery [181]. However, a study using infrared lasers in wound healing in rats found no beneficial effect [182]. Many studies are performed using red or infrared radiation, but blue light (470 nm) has been shown to be able to significantly influence biological systems. Blue light decreased wound size in rats and both red and blue light decreased keratin-1 mRNA [179].

Low-level laser therapy using red or infrared radiation has been used to treat various diseases involving musculoskeletal and neurological structures [183]. For example, it has been shown to be effective in the treatment of vestibular dysfunction and tinnitus. More recently, coloured lights have been suggested as a treatment for tinnitus [184].

Summary and future outlook

Technology for lighting and light luminaires is rapidly changing. For the consumer, this is manifested mainly in terms of the range of products now available for home lighting, in which Tungsten bulbs are being replaced by solid-state lighting in Europe, and in smartphones and tablets, in which new technologies are producing brighter, flatter and more colourful displays. It is becoming possible and inexpensive to illuminate homes and offices in such a way that the colour (and possibly even the spectrum) of the lighting can be changed instantly. This, however, raises interesting questions concerning which colours of lighting are most appropriate for different applications and tasks. This is leading to increased research into the effects of colour, of lighting in particular, on health, well-being, mood and performance. The proliferation of inexpensive coloured lighting is also leading to new uses of lighting to, for example, bring about faster healing of wounds, reduce the symptoms of migraine and tinnitus, and alleviate reading disorders. Whereas, for example, only the intensity of light used to treat SAD was previously considered to be important, there is now renewed interest in the colour and spectrum of the lighting. Coloured lighting is being installed in various public places with the aim of reducing certain behaviours such as suicide and anti-social activities, but further research exploring the effectiveness of these installations is required. It is widely believed that light and colour can affect heart rate and blood pressure. However, the evidence for this is not very convincing and further work to confirm these effects and the precise conditions under which they occur is warranted.

Although light clearly has great potential to positively affect health and performance, there is no doubt that it also presents a potential health threat. There is growing evidence that short-wavelength light in particular can increase the risk for ARMD, although much of the underlying research carried out to date has been conducted in animals. There is still no conclusive proof that bright short-wavelength light increases risks in humans. It remains to be seen whether increased use of emissive displays, changing working habits, and the replacement of warm interior lighting in the home with light of a much higher CCT present real risks in terms of retinal damage and ARMD. Exposure to blue light at night is another potential health risk. Excess light at night is probably partly responsible for poor sleep experiences and also carries some associated health risks with reference to diabetes and heart disease. Insufficient light in the day can lead to depression and myopia. A sensible way forward, however, involves using plenty of high-CCT light in the day and not very much at night (the scenario in which we evolved for millions of years). There is also substantial potential for the better use of dynamic lighting to illuminate homes, workplaces and cities. It is clear that reference to the spectral power of light (rather than its CCT) may be required in many cases in order to properly assess levels of risk and benefit. The biggest risk associated with light exposure today, however, probably remains skin cancer.

Colour and light undoubtedly affect mood and our perceptions of our environment. However, research to explore the effects of colour and light on learning, autism, reading and creativity still has a long way to go before any definitive conclusions can be drawn.

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