Visual stress: origins and treatment

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Abstract

The statistical characteristics of visual images that provoke discomfort generally differ from those of images found in nature. Computational models of the cortex suggest that uncomfortable images are processed inefficiently, a suggestion consistent with the large electrical and haemodynamic cortical response such images induce. The response is greater in individuals who customarily experience visual discomfort, such as those with migraine. Text provides an unnatural image and can be uncomfortable when small and closely spaced. It can provoke illusions of color, shape and motion, just as do patterns of stripes, and these illusions can disturb reading and reading acquisition. Changing the lighting chromaticity can sometimes reduce these illusions, particularly in patients with migraine aura, thereby facilitating reading.

KEYWORDS: VISUAL STRESS, FLICKER, STRIPES, LIGHTING, MIGRAINE, AURA, DISCOMFORT

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> The human visual system evolved to process images from nature. Natural images include images of jungles, deserts and woodlands, but despite the very obvious differences in the image content, all such images have in common three important properties. First, there is little flicker; second, there is a characteristic luminance structure, which can be expressed in terms of the Fourier amplitude spectrum; third, the lighting chromaticity lies on the Planckian locus (red when the sun is setting, white at mid-day and blue when the sunlight is scattered). We will consider each of these characteristics in turn and show that the properties of scenes from the modern urban environment often differ from those in nature, and that when they do, the scenes are associated with discomfort, particularly for individuals who experience migraine with aura.

Flicker

There is little flicker in natural scenes – the variation in luminance is circadian or the result of movement. In marked contrast flicker is pervasive in the modern urban environment. Flicker at frequencies in the range 4–70Hz can evoke seizures in patients with photosensitive epilepsy (Harding & Harding 2010). Flicker at these frequencies is provided when switch-start compact fluorescent lamps are ignited. The lamps are often used in toilets and turned on by occupancy sensors, and so people (including those who are photosensitive) have no opportunity of avoiding the flicker. Flicker from fluorescent lamps occurs not only when they are first ignited, but continues after ignition. The frequency of the flicker depends on the circuitry controlling the lamp. When the lamps are controlled by magnetic ballast, as was typically the case until recently, the flicker is mainly at twice the frequency of the AC supply (100Hz or 120Hz). At this frequency the flicker is usually too rapid to be seen, but it is nevertheless resolved by the human retina and appears in the electroretinogram (Berman et al. 1991). The flicker interferes with eye movements across text, enlarging saccades (Wilkins 1986). It causes headaches and eyestrain under double-masked conditions in which office occupants are unaware of the flicker (Wilkins et al. 1989). It increases heart rate in individuals with agoraphobia, again under double-masked conditions (Hazell & Wilkins 1990). Finally, it impairs visual performance (Veitch & McColl 1995). Although fluorescent lamps can now be controlled by electronic ballasts that increase the frequency of the flicker to a visually harmless 20-30kHz, the old magnetic ballasts remain widely in use: in a survey in 2009, 80% of UK classrooms were still lit with fluorescent lighting that flickered at 100Hz (Winterbottom & Wilkins 2009).

The advent of LED lighting has not resolved the flicker problem. Although it is possible to operate LED lamps without flicker, it is (slightly) more complicated and expensive to do so. As a result, many LED lamps flicker at twice the AC supply frequency and the variation in light level (modulation depth) can be greater than that typical of fluorescent lighting. As with fluorescent lighting, it is possible to operate the lamps at higher frequencies but a problem with flicker remains, even at frequencies in the kilohertz range. This is because flicker creates a pattern when a rapid eye movement (saccade) sweeps the image of the luminaire across the retina. The eyes move at up to about 700 degrees per second during a large saccade, and in consequence a few individuals can see the perisaccadic pattern at frequencies as high as 11kHz (Brown et al. 2019). These individuals tend to report symptoms of eye-strain in everyday life, raising the possibility that some of the visual discomfort they experience is attributable to the high frequency flicker. The IEEE has introduced guidelines to reduce the adverse effects of flicker. These restrict the modulation depth to 0.08 times the frequency of the flicker at frequencies above 90Hz; below 90Hz the restrictions are more stringent (IEEE Power Electronics Society 2015). The current guidance permits 100% modulation at 3kHz, however, which means that the perisaccadic pattern can sometimes be seen.

Fluorescent lamps and some LEDs rely on fluorescence to create part of the light spectrum, converting ultraviolet radiation into visible light. When fluorescent lamps flicker, they can vary not only in brightness but also in color, due to the persistence of the phosphors used (Wilkins & Clark 1990). For example, the halophosphate coating of some early fluorescent lamps continued to glow with long wavelength light in the interval between successive gas discharges. It was therefore possible to reduce the modulation depth of the flicker from these lamps with spectacle lenses (FL41) that transmitted light mainly at the long wavelength end of the visible spectrum (Wilkins & Wilkinson et al. 1991). When the more efficient television phosphors superseded halophosphate coatings this was no longer an option.

Both the halophosphate coatings and the more recent television phosphors in fluorescent lamps result in a continuous variation in spectral power throughout the cycle of the AC power supply. Individuals with migraine are particularly susceptible to flicker (Karanovic et al. 2011; Thabet et al. 2013).

Luminance structure

Despite their vast differences in appearance, scenes from nature share a surprising number of statistical regularities. One of the most notable regularities is evident in the Fourier amplitude spectrum. The amplitude decreases with increasing spatial frequency f, as the reciprocal of frequency (i.e. the amplitude is proportional to wavelength). When plotted on a log-log scale, and averaged over orientations, this distribution falls on a line with slope of about −1. The slope typically ranges from around −0.8 to −1.5 (Tolhurst et al. 1992). Several studies have shown that people are best able to discriminate images with a slope close to −1, compared to images with slopes outside the natural range (Hansen & Hess 2006; Knill et al. 1990; Tadmor & Tolhurst 1994). More recently it has also been shown that images with these natural statistics are more comfortable to look at (Fernandez & Wilkins 2008; Juricevic et al. 2010). Departures from $1/f$ are uncomfortable, and if the departure involves a relative excess of energy at mid spatial frequencies, i.e. those at which the visual system is generally most sensitive, then the discomfort is enhanced (Fernandez & Wilkins 2008).

Most early studies considered the amplitude averaged across orientations, but, as Penacchio & Wilkins (2015) pointed out, discomfort from two-dimensional repetitive patterns, such as checks and plaids, is usually less than that from one-dimensional patterns such as stripes, suggesting that it is important to take orientation into account. Penacchio & Wilkins analysed the two-dimensional Fourier amplitude spectrum, taking account of orientation. They characterized the two-dimensional log amplitude as a cone with slope of −1, and allowed for meridional anisotropies by varying the surface of the cone, using fixed parameters. They obtained the cone with amplitude that best fitted each image, and weighted the residuals by a contrast sensitivity function obtained from the literature, so that mid spatial frequencies were given greater weight. Then they analysed images from seven collections ranging from works of art, to photographs of nature and urban scenes, to abstract geometric designs. The model had no free parameters yet the weighted residuals accounted for more than 25% of the variance in judgments of discomfort from the images: the further the statistics of an image departed from those of images from nature, the greater the discomfort. Le et al. (2017) used the model to predict the discomfort from images of building frontages. They showed that the images that the model classified as "uncomfortable" by virtue of the large residuals were indeed rated as uncomfortable, and evoked a larger haemodynamic response.

Figure 1 shows an example of one of the most unnatural images, as defined by the Fourier amplitude spectrum. It is also one of the most uncomfortable. This image is shown at the end of this article because it is known to provoke seizures in patients with photosensitive epilepsy (Soso et al. 1980). It also provokes discomfort and headaches in patients with migraine (Marcus & Soso 1989; Harle et al. 2006; Haigh et al., 2012). The pattern evokes a variety of perceptual phenomena: illusions of color shape and motion, first described by the Czech anatomist and physiologist Jan Purkyně (1787–1869). These phenomena are related to the occurrence of headaches – individuals who see many perceptual phenomena tend to be those who are susceptible to headaches (Wilkins et al. 1984). The phenomena increase in the 24 hours before headache onset (Nulty et al. 1987). Individuals who experience unilateral headache tend to see the phenomena more on one side of the pattern (Wilkins et al. 1984). Huang et al. (2003) measured the blood oxygenation level dependent (BOLD) response of the visual cortex. They showed that the BOLD response was maximal at those spatial frequencies to which people are generally most sensitive (the low frequency peak in the response was consistent with the low luminance they used). Huang et al. (2003) also showed that the BOLD response to the patterns was greater for individuals with migraine than for healthy controls, and the difference between the groups was greatest for the uncomfortable patterns.

Other studies have similarly shown that migraine sufferers are particularly susceptible to visual discomfort, and that this susceptibility is associated with an abnormally large haemodynamic response. Martín et al. (2011) compared 19 patients with migraine and 19 controls. Patients with migraine showed a larger number of activated occipital voxels than the controls. Cucchiara et al. (2015) found that in patients with migraine who experienced aura, the number of self-reported symptoms of discomfort was positively correlated with the amplitude of the BOLD response to visual stimulation.

The relationship between discomfort and the magnitude of the haemodynamic response appears to be quite general. Alvarez-Linera Prado et al. (2007) compared 20 photophobic patients with 20 controls who viewed a light source at various intensities. The size of the BOLD response increased with stimulus intensity, and the cortical reactivity was higher in the photophobic patients. Bargary et al. (2015) compared healthy participants with high and low discomfort glare thresholds while they identified the orientation of a Landolt C surrounded by peripheral sources of glare. The group that was sensitive to discomfort glare had an increased BOLD response localized at three discrete bilateral cortical locations: in the cunei, the lingual gyri and in the superior parietal lobules. Finally, the physiological response to uncomfortable stimuli has also been studied with the EEG. Haigh et al. (2017) has shown a greater reduction in alpha power with uncomfortable visual stimuli.

In summary, images that are uncomfortable tend to increase the electrical and the blood oxygenation response of the visual cortex to a greater extent than those images that are comfortable. Further, people who are particularly susceptible to discomfort, such as those with migraine, have a greater cortical response.

Computation and metabolism

Two studies (Hibbard & O'Hare 2015; Penacchio et al. 2015) have reported the behaviour of computational models of the visual cortex, the first based simply on the centre-surround antagonism of visual neurons and the second involving their interconnections. When the models process uncomfortable patterns, the distribution of "neural activity" in both models increases and becomes less sparse. This change in the "neural activity" is consistent with the studies reviewed above that have shown a larger haemodynamic response to uncomfortable images; it suggests that uncomfortable images are processed inefficiently with greater metabolic demand. The human brain weighs about 2% of the body's weight but consumes about 20% of the body's energy. Most of the energy is used in generating action potentials (Attwell & Laughlin 2001). The energy is conserved by a sparse neural code in which few neurons are active at any one time. Uncomfortable patterns decrease the sparseness, (defined in terms of the kurtosis of the distribution of firing rates; Hibbard & O'Hare 2015). Wilkins et al. (2014) have proposed that the discomfort is a homeostatic mechanism that acts to reduce the metabolic demand by reducing exposure to stressful visual stimuli.

Text as an uncomfortable stimulus

One of the most commonly encountered unnatural patterns is that provided by text. Text has a spatial periodicity from the horizontal lines formed by rows of words and also from the vertical lines formed by combinations of neighbouring letter strokes. Text evokes perceptual distortions similar to those seen in striped patterns (Wilkins & Nimmo-Smith 1987). As we have seen, striped patterns are perhaps the most unnatural of all images, and are among the most uncomfortable. The discomfort and distortions they evoke depend on the spatial frequency of the pattern, independently of viewing distance, suggesting that accommodative mechanisms play little role (Monger et al. 2016). The discomfort depends on the size of the pattern according to the area of the visual cortex to which the pattern projects (Wilkins et al. 1984).

As you read, your eyes make a succession of rapid jerks (saccades) along the row of words. The eyes lose their alignment during each saccade and have to be re-aligned when a word is fixated. The process of re-alignment (vergence) is more precise and takes longer when the word has a spatially repetitive striped pattern. This pattern arises from the neighbouring strokes of letters, as is the case with words such as "mini" (Jainta et al. 2010). The striped properties of words can be measured using the horizontal autocorrelation of the image of the word. The height of the first peak in the autocorrelation (a simple measure of the striped charactertistics of the letter strokes) actually predicts the length of time required to read the word (Wilkins et al. 2007; Jainta et al. 2010). Evidently, considerable neural processing is involved simply to move the eyes across the page, and yet this complexity never reaches our awareness.

In the section on flicker above, we explained how the rapid flicker from lighting creates a pattern on the retina during a saccade, and this pattern can sometimes be perceived. Even when not seen, it is possible that it interferes with the neural processing involved in aligning the eyes after each saccade. As described above, we are unaware of vergence adjustment and yet it is adversely affected by the spatial repetitiveness in text. Perhaps the intrasaccadic pattern supplements that from text and interferes still further with the processes that control vergence.

The striped characteristics of letter strokes were compared for a wide variety of common fonts (Wilkins et al. 2020). Times New Roman had one of the highest first peaks in the autocorrelation, and is therefore one of the most striped, and in principle the most difficult to read, even though the most familiar. In general, serif fonts had a higher spatial periodicity, not because of the serifs themselves but because of the effect of the serifs in giving rise to a regular spacing of vertical letter strokes.

Earlier we described an algorithm by Penacchio and Wilkins (2015) that predicted discomfort from images. The prediction was based on the residuals obtained when a cone was fitted to the two-dimensional Fourier amplitude spectrum. Images with high residuals were more uncomfortable to look at. This algorithm has now been applied to images of text, and is successful at discriminating those iBook texts that are selected as comfortable for reading (Wilkins et al. 2020). The algorithm was more successful at prediction than any of the conventional typographic variables, such as x-height and font, taken individually. There were large differences between fonts with regard to the residuals obtained, which were due in part to the *weight* of the font (the average thickness of the letters). But the largest effect on the residuals came from the line spacing. The larger the line spacing, the lower the residuals, and the more the image of the text resembled natural images. This provides a neurological explanation as to why it is more comfortable to read text when it is widely spaced.

Reading difficulty and visual stress

The text children are required to read is inappropriately designed, being unnecessarily striped (Wilkins et al. 2009). It gets too small too early in life, compromising reading speed (Hughes & Wilkins, 2000). Some 10–30% of individuals who have difficulty with reading report perceptual distortions of a page of print (Singleton & Trotter 2005). The distortions include apparent movement of the letters and colored halos in and around the words. The distortions are similar to those reported by healthy observers in patterns of stripes such as Figure 1 (Wilkins & Nimmo-Smith et al. 1987).

Curiously, some individuals report that when the text has a colored background the distortions abate. But the color that is effective in reducing the distortions differs from one individual to another (Wilkins 2003). (The above observations were first made by Olive Meares and Helen Irlen in the 1980's.) Most of the studies of the effects of color on reading use colored plastic sheets placed over a page of text when reading, known as overlays. The Intuitive Overlays (Wilkins 1994) are a set of 9 colored filters designed to sample hue (CIE 1976 h_{uv}) systematically. They can be superimposed in pairs of neighbouring chromaticity to provide a total of 30 chromaticities. The overlays have been used in some 20 studies of children's reading. Individuals with reading difficulty who report perceptual distortions of printed text can usually find an overlay or pair of overlays with a color that reduces the distortion, and when they do, their reading speed is generally increased. Reading speed has usually been measured by the Rate of Reading Test (Wilkins et al. 1996) in which a paragraph of randomly ordered closely spaced common words is read aloud for one minute. The test is precise and reliable, and an increase in rate of more than 15% exceeds that from chance variation (Wilkins et al. 2016).

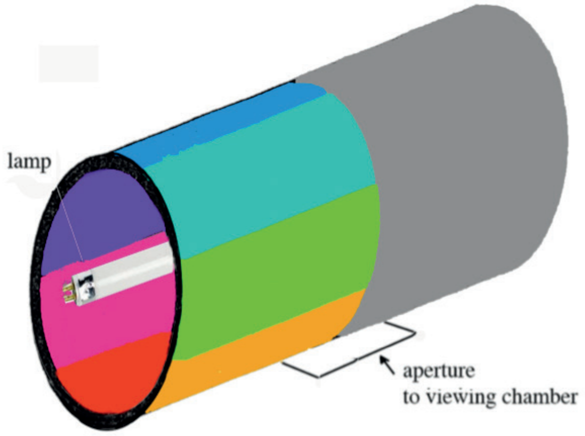
It is difficult to assess the role of placebo effects in these studies, although a variety of motivational controls has been used. For example, in one study children were given a grey overlay labelled "Scientific prototype" and told that it was new, that it combined all the colors, they were one of the first children to use it and they were expected to do as well as they could. These motivational instructions had little effect on reading speed, whereas the color chosen for comfort had a relatively large effect. Studies of the Intuitive Overlays have been consistent in finding that colored overlays are superior to both clear overlays (another placebo control) and grey overlays that reduce the contrast similarly to the colored overlays. Quite different colors can be beneficial, although the color chosen for clarity increases reading speed the most, and more than a complementary color, or one chosen as aversive, see reviews by Wilkins (2002) and Evans and Allen (2016). Overall, 18 out of 22 studies (82%) using the Intuitive Overlays have found statistically significant improvements in reading continuous or discontinuous text with colored filters. Of the four studies that did not find such an improvement, two found a significant reduction in symptoms and a third found a significant improvement with one reading test (Wilkins Rate of Reading Test); but not another (Neale Analysis of Reading) (Evans and Allen 2016).

Nevertheless reviews of the literature that consider colored filters as a treatment for dyslexia usually fail to find any benefits. The most thorough review of this kind is by Griffiths et al. (2016). It is important to realize that colored filters are *NOT* a treatment for dyslexia but for the visual discomfort and anomalous perceptual effects that sometimes accompany the condition. Only a minority of dyslexic children benefit, and it is important to select them appropriately (cf Ritchie et al. 2011).

Intuitive Colorimeter

The need for tints with a precise and individual choice of color was initially demonstrated using the Intuitive Colorimeter (Figure 2). This instrument illuminates a passage of text with colored light. It enables the hue (CIE 1976 UCS h_{uv}) and saturation (CIE 1976 UCS s_{uv}) of the light to be varied continuously and independently, while keeping luminance constant. The variation therefore involves the separate manipulation of the three intuitive dimensions of color: hue, saturation and brightness. An initial version of the instrument, Mark 1, (Wilkins et al. 1992) was later superseded by versions Mark 2 and Mark 3 (Wilkins & Sihra 2001) that provided a spectral power distribution of light similar to that obtained with ophthalmic tints under typical office lighting. The most recent version uses LEDs and is computer-controlled.

Figure 2. The principle of color mixing used in the Intuitive Colorimeter Mark 2. White light passes through a cylinder on which are mounted colored and gray filters of similar transmission. The light then passes through a square aperture into a viewing chamber (not shown) where it is mixed by multiple reflection. Rotation of the cylinder changes the color of the mixed light, and movement of the cylinder along its axle changes the saturation.



In early studies using the first version of the instrument, children selected colors that eliminated the distortions of text they habitually experienced. The range of colors that did so was often small (Wilkins et al. 1992a; 1992b). These findings were corroborated in a double-masked study in which 26 children who used colored overlays for reading were asked to select a color of light that reduced the distortion. The hue angle was then increased or decreased until the children first reported the return of the distortion. The chromaticity of the light that eliminated the distortion, and the chromaticity of the light when the distortion first returned were separated in the CIE 1976 UCS diagram by an average distance of 0.065 (Wilkins et al. 1994). (Although this color difference would normally be expressed as delta *E**, the calculation of delta *E** assumes an adapting luminance (a reference white), so we have adopted the simpler measurement.) The specificity was again corroborated in a double-masked trial of adults with migraine. The patients selected an optimal hue and saturation of light and were given tinted spectacles that provided this color under white fluorescent lighting. They were also given control spectacles that provided a chromaticity differing by an average of 0.06 in the CIE 1976 UCS diagram. They were unable to distinguish which pair of spectacles had the chosen color. Although the sample size was small, the active tints reduced headaches and eyestrain significantly more than the control, suggesting that a separation of 0.06 in chromaticity was sufficient to reduce clinical benefit.

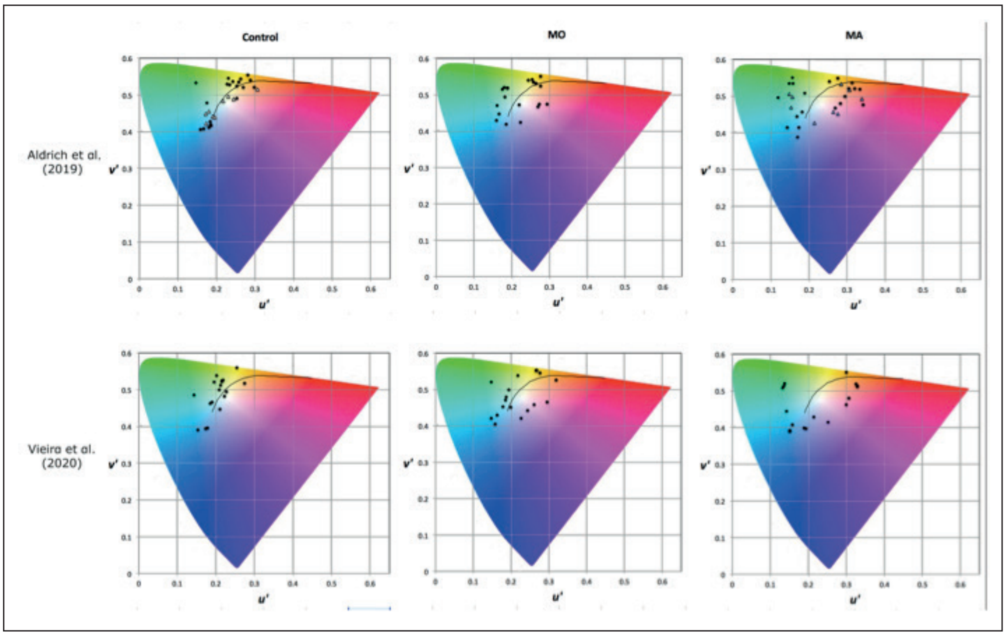
The importance of selecting the appropriate chromaticity precisely has also been shown in two studies that have measured the haemodynamic response to gratings when colored tints were worn (Huang et al. 2011; Coutts et al. 2012). Huang et al. demonstrated that in migraine patients the abnormally large BOLD response in visual areas V2, V3, V3a and V4 was normalized by wearing lenses tinted to provide a color of light previously selected in the Intuitive Colorimeter as optimal for comfort. There was no reduction with tints having a CIE 1976 UCS chromaticity that differed by 0.07. Broadly similar findings, again with migraine patients, were obtained by Coutts et al. (2012) using near infrared spectroscopy.

A further study investigated the effects of colored light on reading speed and again showed the importance of precision when selecting the color (Wilkins et al. 2005). Five volunteers who had previously used tinted lenses viewed text in the Intuitive Colorimeter (without their lenses) and selected the hue and saturation of colored illumination optimal for clarity. Then they repeatedly read paragraphs of randomly-ordered common words as quickly as possible, both under illumination of the color chosen as optimal and under a wide range of other colors chosen in random succession. On average, the optimal color of illumination doubled the reading speed relative to that under white light. As the color of the illumination departed from this optimum, so reading speed decreased, and it did so consistently in two sessions separated by at least two weeks. Although there were only five participants, the way in which the reading speed decreased with the change in color was similar for all. When the chromaticity of the illumination differed by 0.07 in the CIE 1976 UCS diagram there was little residual benefit to reading speed.

In all the above studies, involving participants with and without experience of the use of colored lenses, a separation from the optimal chromaticity of 0.06–0.07 in the CIE UCS diagram was sufficient to eliminate most of the beneficial effects of the tint. Interestingly, in a recent investigation of the repeatability of the choice of color in the Intuitive Colorimeter, Aldrich et al. (2019) showed that the standard deviation of u′ and v′ coordinates was 0.02, so a difference of 0.07 is about 3 standard deviations.

Of course, the light reaching the eyes is dependent not only on the tint but on the source of illumination. The tints were designed for use under "white" fluorescent lighting, the most ubiquitous of the many sources of artificial light. Some difference in the color of light reaching the eyes occurs when the tinted lens is worn under other sources of illumination, particularly incandescent lighting, which is more yellow, and daylight, which is more blue in color. When the changes are taken into account, the chromaticity of light reaching the eyes does not differ from the chosen optimum by more than to 0.06, except in the case of purple tints, which exaggerate the differences in light energy at each end of the visible spectrum (Wilkins et al. 2005).

Figure 3. Chromaticities of light chosen as comfortable for viewing text. Each point represents a choice of chromaticity, and the Planckian locus is shown by a continuous line. Individuals who experience migraine with aura (MA) chose strongly saturated colors mostly distant from the Planckian locus. Healthy controls chose chromaticites close to the locus. The studies by Aldrich et al (2019) and Vieira (2020) used different samples of volunteers and were conducted by different investigators.



Controversy

The use of colored filters to aid reading continues to arouse skepticism although there has been an average year-on-year increase in the use of overlays in UK schools over the last six years (personal communication from Crossbow Education). Practical guidelines for clinical use have been set out (Evans et al. 2017) but if precision tinted lenses are ever to be provided as part of a health service, good evidence for their efficacy will be necessary. This will involve a double-masked randomized controlled trial. The Intuitive Colorimeter facilitates such masking because observers adapt to the color of lighting and are often unaware how strongly saturated is the color they have chosen. As mentioned earlier, an initial study with a double-masked design was conducted in 1993 when the Intuitive Colorimeter was first introduced into optometric practice in the UK (Wilkins et al. 1994). This study has been criticized for its high attrition and because the data were not analysed on an intention-to-treat basis (Griffiths et al. 2016).

Preference for lighting chromaticity in migraine

Although the use of colored filters to treat reading disorders continues to be controversial, two independent studies confirm the view that color can treat the visual discomfort with which reading is sometimes associated (Aldrich et al. 2019; Vieira et al. 2020). Healthy individuals, and individuals who experienced migraine with and without aura were shown a page of text in the Intuitive Colorimeter. The examiners varied the saturation and hue according to a standard routine designed to find the optimum chromaticity incrementally. Healthy individuals chose a chromaticity close to the Planckian locus, that is, they chose a color of lighting they would normally experience in everyday life. Individuals who experienced migraine with aura, however, chose a strongly saturated color, mostly well away from the Planckian locus, see Figure 3. When individuals with aura were given tinted spectacles that provided the chosen chromaticity the speed at which they undertook a visual search task improved by more than 40%. The participants were recruited simply on the basis of their neurological diagnosis (International Headache Society criteria), and without consideration of any reading difficulty or perceptual distortion. Individuals with migraine tend to be more susceptible than others to the discomfort from flicker and patterns described above. Indeed, the first open trial of precision tints was conducted with many children who had a family history of migraine (Maclachlan et al. 1993).

Conclusion

The spatial and temporal characteristics of uncomfortable images tend to differ from natural images, so it is curious that migraine patients (who are particularly susceptible to visual discomfort) choose unnatural colors of lighting as comfortable. This might be because of the effects of adaptation to rapid flicker from artificial light, which can vary continually not only in brightness but also in color. Another possibility is that the tint reduces the color contrast in images. Images with high color contrast are uncomfortable (Haigh et al. 2017). The tint would reduce some contrasts and increase others, and therefore its effects would depend on the component colors in the scene.

Yet another possibility is that the color redistributes the excitation in visual areas of the cortex so as to avoid local areas of hyperexcitability. The cortex is hyperexcitable in photosensitive epilepsy and there is a long history of the use of colored filters to reduce seizures, with a succession of case reports over the years and a small-scale open trial of precision tints (Wilkins et al. 1999). The cortex is also hyperexcitable in migraine (Aurora & Wilkinson 2007), and there is normalization of the hyperneuronal BOLD response with tints (Huang et al. 2011), reviewed above. A small-scale randomized controlled trial of tints in migraine prophylaxis is suggestive of some limited benefit (Wilkins et al. 2002). There is also recent evidence that green light can reduce photophobia (Noseda et al. 2016).

Other neurological disorders exhibit a high co-morbidity with epilepsy, suggestive of a hyperexcitability. These include autism spectrum disorder, Tourette's syndrome, stroke, head injury and multiple sclerosis. In all these five conditions there are suggestions that colored filters may benefit reading subjectively or in terms of reading speed (Ludlow et al. 2006; Whitaker et al. 2016; Ludlow & Wilkins 2016; Beasley & Davies 2013; Fimreite et al. 2016, Newman Wright et al. 2007, respectively). In autism, tints have also been shown to improve the perception of facial emotion (Ludlow et al. 2020; Whitaker et al. 2016). In contrast, precision tints do not seem to be of value in retinal disorders, even though more conventional tints may sometimes help (Eperjesi et al. 2004).

Taken together, these results are suggestive of a role of cortical hyperexcitability. If hyperexcitability is indeed the explanation, it is quite possible that the excitability is not uniform. Evidence for a non-uniformity comes from cases of pattern-sensitive epilepsy in which the seizures are triggered by striped lines only when in a particular orientation (Soso et al. 1980). Presumably in these patients the excitability was local and confined to a limited range of orientationally coded cells.

Optical recording in macaque area V2 of intrinsic signals in response to differently colored gratings has revealed an organized representation of color. Colors are spatially organized in the same way as colors occur in perceptual color maps such as CIE 1976 UCS (Xiao et al. 2003). The representation of perceptual color dimensions also occurs in the posterior inferior temporal cortex (V4 complex; Bohon et al. 2016). Thus it is likely that tinted lenses act to redistribute the excitation in the cortex that results from a visual scene. If the tints are comfortable, it is possible that the redistribution avoids local regions in which the cortex is hyperexcitable. This hypothesis is quite consistent with the effects of neuroimaging thus far observed, but it will require improvements in imaging techniques before it can be disproved. For now, it draws together a range of disorders in which precision tints have been found to be beneficial.

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Figure 1. A pattern of stripes. WARNING: This pattern can induce migraine and seizures in patients who have photosensitive epilepsy. Do not observe for more than a few seconds. The visual effects are neural and unrelated to accommodation (Haigh et al. 2013)