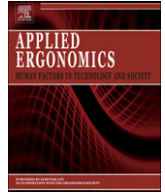




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Visual stress, its treatment with spectral filters, and its relationship to visually induced motion sickness

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ABSTRACT

We review the concept of visual stress and its relation to neurological disease. Visual stress can occur from the observation of images with unnatural spatial structure and an excess of contrast energy at spatial frequencies to which the visual system is generally most sensitive. Visual stress can often be reduced using spectral filters, provided the colour is selected with precision to suit each individual. The use of such filters and their effects on reading speed are reviewed. The filters have been shown to benefit patients with a variety of neurological conditions other than reading difficulty, all associated with an increased risk of seizures.

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1. Introduction

Q1 Critchley (1964) cited a case of a dyslexic child who was unable to read words printed on white card but could read words on coloured card. Nearly 20 years later, Meares (1980) described a syndrome of symptoms (visual perceptual distortions, eye-strain and headache) that some people experience when reading and that can be alleviated by using coloured card or coloured filters. Irlen (1983, 1991) developed a proprietary treatment system for this syndrome, which later became known as Meares–Irlen Syndrome or Visual Stress. Irlen claimed that the coloured filters need to be prescribed with great precision and different people need different colours. This attracted considerable controversy, especially because she claimed that the filters **Q2** could only be obtained from her organisation. Wilkins et al. (1997) developed an instrument, the Intuitive Colorimeter, which facilitated a double-masked randomised placebo-controlled trial of the use of precision tinted lenses in

Meares–Irlen Syndrome (Wilkins et al., 1994). The randomised controlled trial demonstrated that sufferers do indeed need different colours, and that the required colour needs to be defined with precision. The findings were replicated in another double-masked randomised placebo-controlled trial, conducted by Robinson and Foreman (1999a, b). The mechanisms that underlie the benefit from coloured filters remain uncertain (Evans, 2001) although recently the weight of evidence has turned in favour of an explanation given in the paragraphs that follow.

2. Unpleasant images and stripes

Fernandez and Wilkins (2008) asked individuals to rate the pleasantness of a range of coloured non-representational images from contemporary art. They undertook a Fourier analysis of images and discovered that the images that were rated as pleasant showed the 1/f² decrease in contrast energy with increasing spatial frequency typical of that in natural scenes. The uncomfortable images, on the other hand, showed an excess of contrast energy at spatial frequencies within two octaves of three cycles per degree.

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Fernandez and Wilkins then used images constructed from filtered random noise and demonstrated that, once again, those images filtered so as to have an excess of contrast energy near three cycles per degree were rated as least comfortable. Next they exchanged the phase and amplitude spectra of grey level images of comfortable and uncomfortable art, and showed that ratings of discomfort were dependent on the amplitude and not the phase spectra. Filtering the images so that the amplitude spectra decreased in energy with spatial frequency as $1/f^2$ made uncomfortable images comfortable. In the above experiments the energy was radially filtered. If the energy in an image is concentrated in one orientation so as to resemble a grating, the discomfort can increase.

3. Individual differences in susceptibility to pattern glare

Some people find images such as that in Fig. 1 very aversive, other people are relatively unaffected. In a few people stripes with this spatial frequency can trigger migraines or epileptic seizures (Wilkins et al., 1980, 1984). People who find stripes unpleasant tend to have frequent headaches. They see many perceptual distortions involving motion, shape and colour, collectively known as pattern glare. Migraineurs are particularly affected (Marks and Ehrenberg, 1993; Wilkins, 1995). Not only do people who suffer frequent headaches tend to see more distortions, they are particularly susceptible to the distortions in the 24 h before headache onset. If the headaches occur on one side of the head the distortions predominate in one lateral visual field in between headaches (Wilkins, 1995; Nulty et al., 1987). The link between perceptual distortions and headaches occurs only for patterns that can induce seizures in patients with photosensitive epilepsy. The links are therefore consistent with five other independent lines of evidence to support the idea that in migraine the visual cortex is hyper-excitable. The evidence is reviewed elsewhere (Wilkins et al., 2007).

4. Stripes in text

Text is striped partly because of the successive lines. The lines have a spatial frequency within the range that causes discomfort (Wilkins et al., 2004). Individual words are also striped because of the neighbouring letter strokes. The stripes from the vertical strokes of letters have a spatial frequency within the range that causes discomfort, and for this reason striped words (e.g. mum) take longer to read, even for fluent readers. Reducing the periodicity of the stripes by varying the inter-stroke spacing can increase reading speed in poor readers (Wilkins et al., 2007). Some people see distortions not only in stripes but also in text (Irlen, 1991). Sensitivity to striped patterns (pattern glare) plays a key role in producing these symptoms (Evans and Stevenson, 2008).

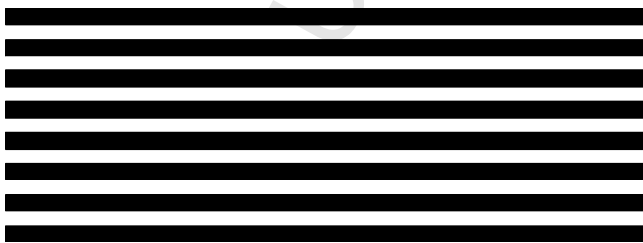


Fig. 1. A grating with square-wave luminance profile, spatial frequency close to 3 cycles per degree. **DO NOT LOOK AT THIS PATTERN IF YOU HAVE EPILEPSY OR MIGRAINE – IT MIGHT PROVOKE AN ATTACK.**

5. Coloured filters

Coloured filters can reduce the distortions seen in stripes and text. Reports of distortions are obviously subjective but they are associated with a measurable impairment of reading speed that can be measured objectively (Jeanes et al., 1997; Wilkins, 1994, 2002; Wilkins and Lewis, 1999; Wilkins et al., 1996, 2001). In addition to direct evidence implicating pattern glare in the aetiology of visual stress (Evans et al., 1994, 1995, 1996a, b), several studies have excluded other potential mechanisms (Evans et al., 1996a; Simmers et al., 2001a,b). Although these studies suggest that optometric anomalies are not causes of visual stress in the majority of cases, a thorough eye examination is important in the differential diagnosis (Evans, 2005).

6. Individual differences in colour

There is no one colour that helps everyone: the best colour needs to be individually selected. This statement is supported by both single masked clinical trials (Bouldoukian et al., 2002; Evans and Joseph, 2002; Kriss, 2002; Kriss and Evans, 2005, Singleton and Henderson, 2007; Singleton and Trotter, 2005; Swanson et al., 1993; Wilkins et al., 2001) and also by double-masked randomised placebo-controlled trials (Robinson and Foreman, 1999a, b; Wilkins et al., 1994, 2002), in which filters of similar colour were offered as control. Additionally, a recent experiment studied reading speed at a large range of chromaticities and thereby directly addressed the issue of the precision with which the coloured filters need to be prescribed so as to suit an individual (Wilkins et al., 2007). People who read more quickly with their chosen coloured overlay see more distortions in striped patterns (Hollis and Allen, 2006). These people can be identified objectively by the decrease in search speed that occurs when the search task is surrounded by a pattern of stripes (Singleton and Henderson, 2007; Allen et al., 2008).

7. Colour choice

In order for susceptible individuals to obtain an effective filter, it is important to sample a large number of colours. The Intuitive Overlays, see Fig. 2, are coloured transparencies that are placed over the page when reading. They are available in colours that sample the CIE Uniform Chromaticity Scale (Hunt, 1991, p. 61) diagram efficiently. They are designed so that 30 evenly spaced chromaticities can be obtained systematically by using the overlays singly or in pairs with the same or similar chromaticity, one on top of another. Another range of overlays, the Cerium overlays, have similar properties but some other systems have had a range of colours insufficient to increase reading speed effectively (Smith and Wilkins, 2007).

8. Overlays examination

The overlays examination requires illumination similar to that under which the overlays will be used. Two identical passages of text of appropriate size are presented side by side. The overlays can be placed over each passage and compared. The overlays are compared in pairs, and the best of each pair retained, the other being replaced by another overlay. If the patient finds the choice difficult, the choice is repeated when all overlays have been assessed. Double overlays are used if symptoms remain (Wilkins, 2003). In six studies of normal unselected children in mainstream schools, about 20% used their chosen overlay long-term (Jeanes et al., 1997). Those that used their overlays read faster with them: 5% read more than 25% faster (Wilkins, 2002).

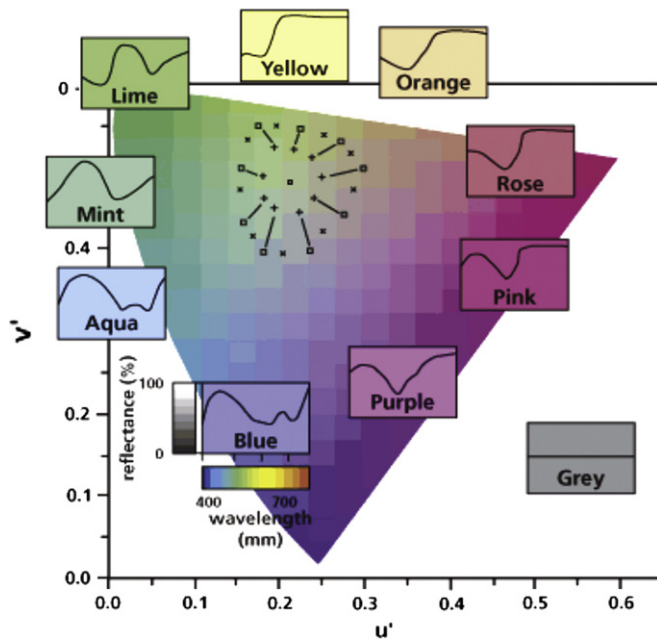


Fig. 2. The Intuitive Overlays: sheets of coloured plastic for placing over a page of text when reading. The chromaticities of the single overlays (crosses) are shown together with the chromaticities of pairs of superimposed overlays, both those pairs formed from two identical overlays (large squares) and those formed from neighbouring overlays (diagonal crosses). The chromaticity coordinates indicate that colour space has been sampled evenly with respect to hue angle. Note that when overlays having neighbouring chromaticities are combined, the chromaticity is not appreciably affected by which overlay is uppermost. The resulting pair of overlays has a chromaticity midway between the chromaticity of the component overlays. This restriction on the combination of overlays to those of neighbouring chromaticity makes the colour mixing intuitive.

9. The school environment

Lighting levels in classrooms are generally too high, according to a recent survey of lighting levels in UK classrooms (Winterbottom and Wilkins, in press). The lighting level at the work surface was more than 1000 lux in 39% of classrooms when the window blinds were down, and with the blinds up, 80% of classrooms had a lighting level greater than 1000 lux. Above 1000 lux visual discomfort starts to increase and visual performance to decrease. The recommended levels are 300 lux but the lighting levels could rarely be adjusted appropriately by switching banks of luminaires. Electronic boards were invariably mounted vertically on the wall and the projector on the ceiling, so that the gloss surface of the board directed glare from the projector into childrens' eyes. In 80% of classrooms the fluorescent lighting was operated by 50 Hz circuitry that produces 100 Hz variation in light output. Although it is imperceptible, the 100 Hz variation is resolved by the human retina (Berman et al., 1991), interferes with ocular motor control (Wilkins, 1986) and visual performance (Veitch and McColl, 1995), gives headaches and eye-strain (Wilkins et al., 1989), and possibly contributes to anxiety (Hazell and Wilkins, 1990). Given these aspects of the visual environment in schools, it is perhaps unsurprising that such a large proportion of school children benefit from coloured overlays.

10. Reading speed

Reading speed can be measured quickly and efficiently using the Rate of Reading Test in which randomly ordered common words are read aloud for 1 min (Wilkins et al., 1996). The words are high-frequency and therefore familiar to poor readers. The random word

order means that the words cannot be guessed from context but have to be seen to be read. The text is meaningless so readers are unaware of their errors. The text is small to increase fatigue. The benefit from overlays can be rapidly ascertained as an increase in reading speed, as measured by this test. Although the Rate of Reading Test is not a typical reading task it has been shown to predict performance when text is read silently for comprehension (Wilkins, 2002). An overlay needs to be of a size sufficient to cover the text, but it does not have to cover the surround (Waldie and Wilkins, 2004). Individuals who find coloured overlays helpful usually prefer coloured lenses (Evans et al., 1999). The optimal colour for lenses is not the same as for overlays (Lightstone and Evans, 1995), and it can be selected with far greater precision. Coloured lenses also have practical advantages over overlays, because lenses are easier to use when writing, reading a white board in class, and using a computer. Coloured overlays are therefore used for screening, with the precision tinted lenses representing the preferred treatment.

11. Coloured lenses

The colour for lenses can be selected while the eyes are colour-adapted using the Intuitive Colorimeter, an instrument that illuminates a page of text with coloured light, allowing the hue, saturation and luminance to be varied independently (Wilkins and Sihra, 2000; Wilkins et al., 1999; Fig. 3). The optimal tint can then be matched in coloured trial lenses. Under conventional lighting the lenses result in a spectral power distribution almost identical to that in the Intuitive Colorimeter (Wilkins and Sihra, 2000), allowing observers with colour vision anomalies to be tested. The Intuitive Colorimeter system will provide lenses that closely approximate any chromaticity (Fig. 4). The lenses have a smoothly varying spectral transmission that minimises metamerism under different types of lighting (Wilkins, 2003). Each person reads most quickly with a particular individual optimal chromaticity. Departures from this optimum, whether in hue or saturation, result in slower reading. The greater the difference in chromaticity the slower the reading, unless the CIE colour difference (ΔE^*) exceeds about 100, in which case the speed is similar to that under white light. Despite this specificity, calculations suggest that most tints offer at least some benefit under most types of lighting (Wilkins et al., 2005). Several different tinting systems are available, but most have only a few tints. Indications are that at least 1000 tints are needed to provide sufficient precision to increase reading speed optimally (Wilkins et al., 2005). An audit of people using coloured lenses prescribed with the Intuitive Colorimeter system indicates that over 80% were still using them regularly at least a year after the last clinical contact (Evans et al., 1999; MacLachlan et al., 1993).

12. Examination with the Intuitive Colorimeter

With the Intuitive Colorimeter system the typical examination and prescription has six stages, usually taking a total of 20–30 min: (1) The optimal chromaticity is selected using the Intuitive Colorimeter. Initially, 12 hues are compared. Saturation is optimised at those hues that improve perception, and these are then compared. The eyes remain colour-adapted while hue and saturation are alternately adjusted by small amounts to find the best chromaticity. (2) The matching combination of tinted trial lenses is calculated using a computer program. (3) The trial lenses are offered to the patient and the combination adjusted, if necessary. (4) The combination of lenses constitutes the (calibrated) colour prescription which is sent to a dyeing company. (5) Spectacle lenses are dipped into two dyes to obtain the appropriate spectral transmission. (6) A spectroradiometer and computer program check the

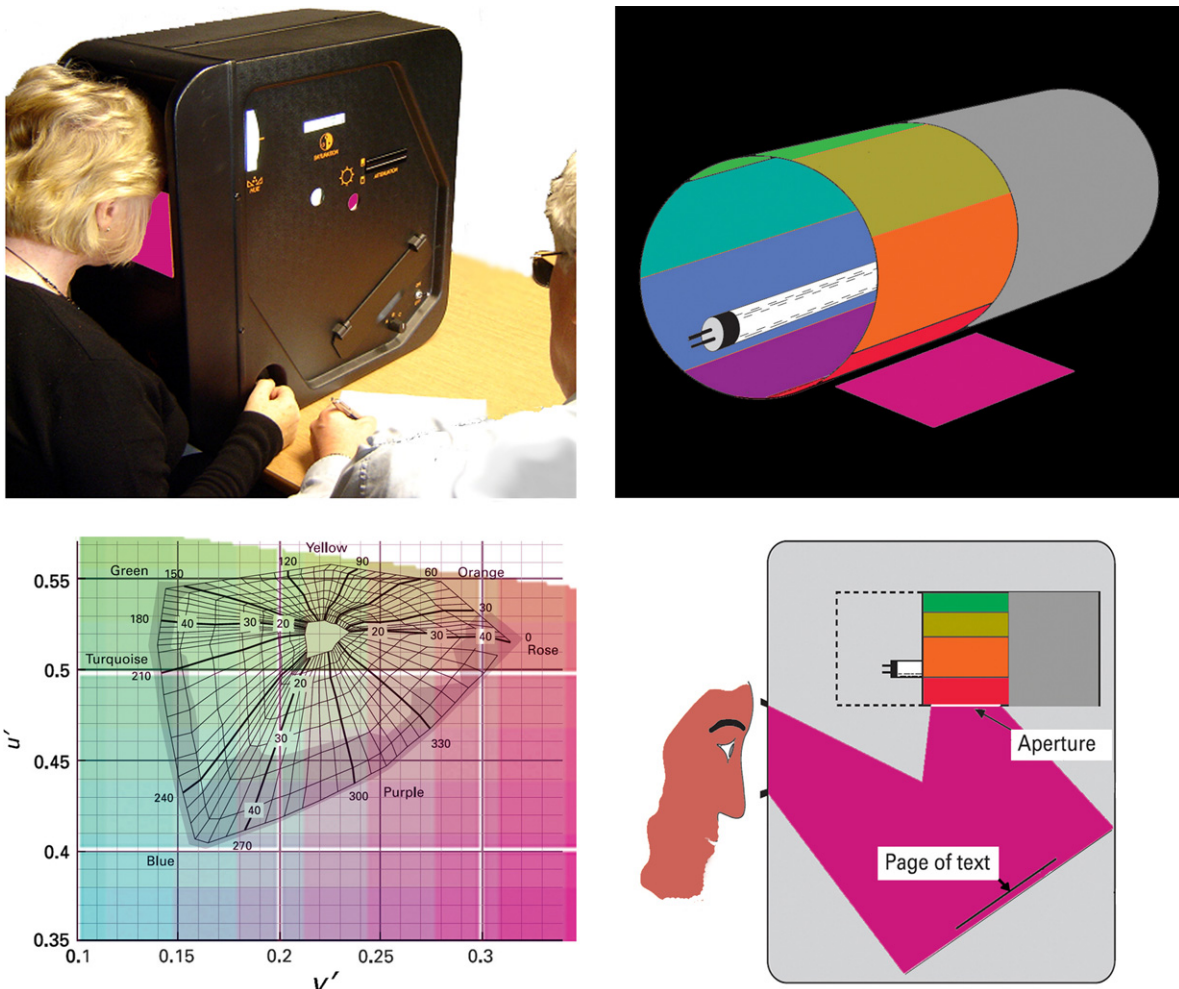


Fig. 3. The Intuitive Colorimeter. The upper left panel shows the colorimeter in use, and the panel below, the chromaticities available in the instrument. The concentric contours are the loci of chromaticities obtained by rotating the hue control, and the radial lines the loci obtained by changing saturation control. The upper right panel shows the light source and filter arrangement. The filters can rotate about the axle of the cylinder changing hue and the cylinder can slide along its axle, changing saturation. The light enters the viewing chamber (lower right) through the square aperture, where it is mixed by multiple reflection.

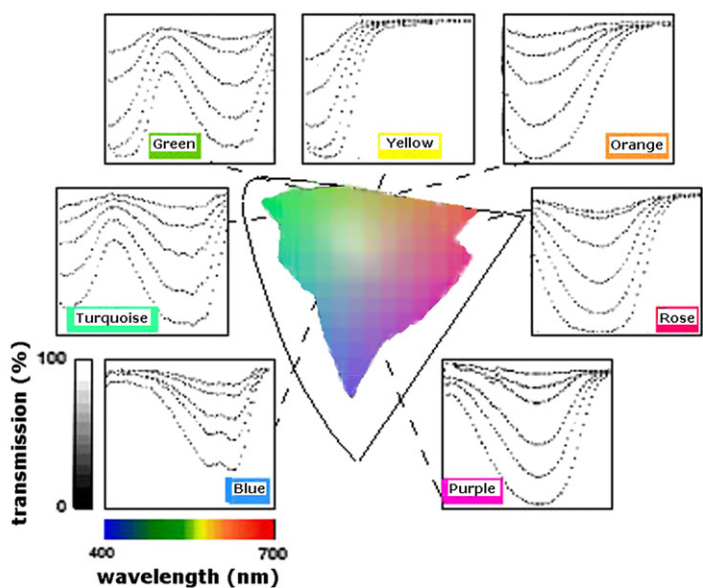


Fig. 4. Left panel, tinted trial lenses. Right panel, graphs of their spectral transmission (periphery) and (centre) the gamut of colours they provide.

transmission and supply individual information for the prescribing practitioner and patient (Wilkins, 2003). (7) Using trial lenses the practitioner carries out a visual check of the colour of the supplied spectacle lenses.

13. Clinical protocol

The Intuitive Colorimeter was patented by the MRC in 1994 and there are now over 250 of the instruments in use in the UK, mostly by community optometrists and a few by hospital orthoptists. A clinical protocol was published over 10 years ago (Lightstone and Evans, 1995) and is widely followed by colorimeter users. A Society for Coloured Lens Prescribers was established in 2007 to oversee the administration of a code of conduct to which members of the society subscribe. Evidence-based practice is codified and ratified by the society.

14. Neurological disorders involving visual stress

The patients who benefit from precision spectral filters include those with:

- reading difficulty (double-masked trial of lenses) (Wilkins, 2003);
- photosensitive epilepsy (open trial of lenses) (Wilkins et al., 1999);
- migraine (small-scale double-masked trial of lenses) (Wilkins et al., 2002);
- autism (open trial of overlays) (Ludlow et al., 2006);
- multiple sclerosis (double-masked trial of overlays) (Newman Wright et al., 2007).

All these disorders (with the possible exception of reading difficulty) are associated with an increased risk of seizures, suggesting cortical hyper-excitability. There is good convergent evidence for cortical hyper-excitability in migraine (Welch, 2002, 2003); there is an increased but variable risk of epilepsy in autism (Tuchman and Rapin, 2002), and there is also an increased risk of seizures in patients with multiple sclerosis (Koch et al., 2008). Pattern glare, one possible consequence of cortical hyper-excitability (Harle and Evans, 2004; Harle et al., 2006), has been found to be the strongest visual correlate of the use of precision tints (Evans et al., 1995, 1996a, b, Hollis and Allen, 2006).

15. Strong visual stimulation

The visual stimulation responsible for visual stress is generally of high contrast with a large visual subtense. The spatial parameters are generally those that, at threshold contrasts, would render the visual stimulus maximally visible. They are stimuli that at high contrasts interfere with the visibility of small low contrast target stimuli, masking them effectively (Chronicle and Wilkins, 1996). The stimuli evoke high-amplitude electrical signals from the scalp (Plant et al., 1983) and large blood oxygenation dependent signals during functional magnetic resonance imaging (Huang et al., 2003). They induce perceptual distortions (Wilkins et al., 1984) and, in those who are susceptible, migraine (Huang et al., 2003) and seizures (Wilkins et al., 1980).

Binnie et al. (1985) showed that, in patients with photosensitive epilepsy, gratings that drift continually towards fixation can be fixated stably, but do not evoke epileptiform paroxysmal EEG activity: they are not epileptogenic. In comparison, gratings can be highly epileptogenic if their bars move at the same velocity as those of a drifting grating but repeatedly alternate their direction of drift, vibrating in a direction orthogonal to that of the bars. Binnie et al.

(1985) attributed the differences to a synchronization of cortical activity when populations of neurons sensitive to one direction of motion are caused to fire alternately with neurons tuned to the opposite direction of motion, arguing that synchronization was necessary for epileptogenesis, and that the vibrating gratings provided the synchronization whereas drifting gratings did not.

Although the differences in the epileptogenic potential of drifting and vibrating gratings are extreme, recent unpublished studies by the first author and colleagues using near infrared spectroscopy to measure the oxygenation of the cortex have shown a similar oxygenation in response to both types of grating motion (continuous drift and vibration), and greater oxygenation than in response to stationary gratings. Aversion to the gratings is as great for those that drift as for those that vibrate, and greater than for stationary patterns. This would suggest that aversion to gratings is dependent on the excitation that the patterns evoke, independently of its synchronization, as might be expected if it is the metabolic consequences of the excitation that are responsible for the aversion.

16. A hypothesis

Pyramidal neurons share inhibitory interneurons. Strong sensory stimulation may lead to a local depletion of inhibitory neurotransmitter. The local impairment of inhibition may result in a spread of excitation (Meldrum and Wilkins, 1984). It is hypothesised that this spread of excitation results in the inappropriate firing of cortical neurons and the perception of illusions/distortions. By virtue of the topographic encoding of chromaticity in the cortex, and the large variation in spectral sensitivity of cortical neurons (Xiao et al., 2003), colours redistribute excitation. Colours that are comfortable may reduce excitation in hyper-excitability areas.

17. Evidence

Blood oxygenation in the visual cortex (as evidenced by the fMRI BOLD signal) shows an increase in response to stripes with spatial frequencies in the aversive range (Huang et al., 2003). In migraines this increase is abnormally large at similar spatial frequencies. In a preliminary study the abnormal increase has been shown to be reversed in V3 when precision tints are worn, but not when control tints are worn (Wilkins et al., 2007a).

18. Visual fatigue from VDTs

The above theory of visual stress conceives the symptoms of visual stress as resulting when the neurological processes that subserve vision place an excessive metabolic demand on the visual cortex. Within this conception it is possible to interpret the visual fatigue that results when normal visual processing is compromised, as, for example, when normal eye movement control is compromised by rapid and imperceptible screen flicker (Wilkins, 1986).

19. Visually induced motion sickness

The dizziness that accompanies visually induced motion sickness has a superficial resemblance to that which can accompany visual stress. Visual stress results from strong sensory stimulation, and such stimulation may be more effective at evoking motion sickness as well. In general, the larger the visual field receiving stimulation the greater the likelihood of both visually induced motion sickness (DiZio and Lackner, 1997) and visual stress (Wilkins, 1995, p. 40). The spatial frequency tuning of visual stress is three cycles per degree \pm one octave (half height) for gratings drifting at 7° per second (Wilkins, 1995, p. 40) as well as for

stationary gratings (Wilkins, 1995, p. 46) and complex images (Fernandez and Wilkins, 2008). The spatial frequency tuning for motion sickness is lower, maximal at about 0.067 cycles per degree for gratings drifting at 60° per second (Hu et al., 1997), and in complex scenes the spatial frequency components and scene velocity combine as spatial velocity to determine motion sickness (So et al., 2001). It seems likely that although visual stress and visually induced motion sickness are different conditions, they share some mechanisms in common that further work will be needed to elucidate.

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