

Origins of Visual Stress

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The mathematics of uncomfortable images

The comfort with which visual images can be viewed depends in part on simple physical properties of the image, quite independently of what the images represent. This is the implication of recent studies by Juricevic et al. (2010) and by Fernandez and Wilkins (2008). Fourier analysis can be used to represent any image as a series of sine waves (Fourier components) with various frequencies, amplitudes, phases, and orientations. Most images, particularly those from nature, have a relatively high contrast of the lower spatial frequency Fourier components and the amplitude falls off as the spatial frequency increases. It falls off according to a power law, so that a graph of log amplitude (luminance contrast) against log spatial frequency is a straight line with a slope of approximately -1 . If images do not have this simple relationship between spatial scale and contrast (larger spatial scales having larger contrast) they become uncomfortable to look at. Juricevic et al. (2010) generated meaningless artificial images from random noise and from randomly disposed rectangles of various sizes. The Fourier spectra of these two types of image were similar with respect to contrast amplitude, although they differed with respect to phase. The images were rated for comfort, and the comfort was found to be maximal when the slope of the amplitude spectrum was about -1 , as it is in images from the natural world. When the curve was steeper (slopes in the range -1 to -2) the discomfort increased. When the curve was shallower (slopes in the range -1 to 0) the discomfort again increased. All of the images were novel and artificial and therefore equally unfamiliar, so the effect cannot be attributed to familiarity as such. The same result was obtained for both types of image, those from random noise and random rectangles. Evidently, images with unnatural spatial structure are uncomfortable to view, regardless of their content or meaning.

There are many ways in which the spatial structure of an image can differ from that found in images from nature, and some departures from the natural spatial structure are more uncomfortable than others. Images with unnatural Fourier spectra tend to be more uncomfortable if they have a relative excess of contrast energy at mid-range spatial frequencies, where the visual system is generally most sensitive. This has been shown by Fernandez and Wilkins (2008) who used a variety of images from works of contemporary non-representational art, photographs of everyday scenes, and artificial images generated from random noise. The images rated as comfortable had Fourier amplitude spectra similar to those for natural scenes; the uncomfortable images had the same average slope, but were not linear when plotted as log amplitude versus log frequency. They were curved,

with an excess of contrast amplitude for mid-range spatial frequencies of about three cycles per degree. In a further study, Fernandez and Wilkins showed that decreasing the relative contrast amplitude at about three cycles per degree (whilst maintaining the overall contrast amplitude) increased the image comfort, even though the spectrum remained non-linear and unnatural. Evidently images were more uncomfortable if they had an unnatural excess of contrast amplitude at mid-range spatial frequencies relative to that elsewhere in the spectrum. Fernandez and Wilkins (2008) exchanged the Fourier phase and amplitude spectra of comfortable images with those of uncomfortable images. The ratings of comfort depended upon the amplitude spectra, even though the image appearance was more affected by the phase spectra.

Very uncomfortable stimuli—visual and non-visual effects

If all the contrast in an image is concentrated only at mid-range spatial frequencies, the image becomes intensely uncomfortable, even dangerous (Wilkins, 1995). Fig. 4.1 shows a pattern of stripes in which all the energy is concentrated at mid-range spatial frequencies. It is a photograph of the stair tread of an escalator. Images of this kind can induce headaches and seizures, so you are advised to cover this figure if you have migraine or epilepsy.

Images such as the stripes in Fig. 4.1 are not only uncomfortable to look at, they induce illusions of colour, shape, and motion. The number of illusions you see is related to the number of headaches you have: (1) people who see many distortions tend to have frequent headaches; (2) they see more distortions on days when they have a headache; (3) if the headache is on one side of the head the distortions are asymmetric; (4) people with migraine have a greater aversion to the pattern than others; (5) those with aura see more distortions on the side of the aura, between headaches. The parameters of patterns that induce illusions and discomfort are similar to those that provoke photosensitive seizures (Wilkins et al., 1984; Nulty et al., 1987; Marcus & Soso, 1989).

WARNING: COVER THIS
PATTERN IF YOU HAVE
MIGRAINE OR EPILEPSY

Fig. 4.1 The stair tread of an escalator. At typical viewing distances the spatial frequency is close to 3 cycles per degree.



The listed relationships between headaches and illusions occur only with respect to patterns that can cause seizures. Other patterns show no such relationships (Wilkins et al., 1984). It is possible that the illusions reflect a hyperexcitability of the visual cortex, because there is diverse but convergent evidence that in migraine the visual cortex is hyperexcitable, even between headaches (Palmer et al., 2000; Antal et al., 2005; Bowyer et al., 2005). This possibility will be explored later.

The photoparoxysmal electroencephalogram response

The susceptibility to seizures can be estimated without actually provoking them using the electroencephalogram (EEG). The brain's electrical activity shows a distinctive change involving spiked waveforms (a photoparoxysmal response) when the patient is exposed to stressful visual stimulation. In Fig. 4.2 the solid lines show the probability of this EEG response in patients with photosensitive epilepsy when they look at a pattern of stripes. Similar functions (broken lines) describe the number of illusions of colour, shape, and motion seen by normal observers when they look at the patterns. The similarity between the parameters that induce illusions and those that induce seizures is obvious. (Note that all graphs have the same scales and that the curves have not been adjusted in vertical position.) Patterns that give rise to the illusions of motion, shape, and colour and to seizures in patients with photosensitive epilepsy are usually uncomfortable (Wilkins et al., 1984).

The relationships between illusions, discomfort, and seizures apply not only to spatial properties of visual stimulation but also to temporal properties. Diffuse flicker can also give illusions, seizures, and discomfort, and the frequency at which it does so is similar, and close to the frequency at which flicker at threshold contrast is most readily perceived in large fields.

Therefore the visual stimuli that at high contrasts provoke illusions in most people, and in people with photosensitive epilepsy provoke seizures, have spatial and temporal characteristics very similar to those stimuli that are most readily seen at low contrasts. They are also stimuli that at higher contrasts interfere with the perception of other stimuli. Chronicle and Wilkins (1996) presented letters at low contrast at the centre of gratings and measured the contrast required to identify the letters as the gratings varied in spatial frequency, in size (angular subtense) and in shape (ratio of bar width to bar separation). The masking of the letter was maximal for spatial parameters in the range that was most strongly associated with the induction of illusions and seizures: in particular the masking increased with the area of the visual cortex to which the pattern projected, just as does the probability of seizures in patients with photosensitive epilepsy. The stimuli that have these properties can be said to be 'strong' stimuli.

Colour contrast

The colour contrasts that occur in nature tend not to be extreme and they tend to involve contrasts of particular hues. Juricevic et al. (2010) showed that meaningless patterns are rated as comfortable to the extent that the chromatic contrast resembles that found in natural images.

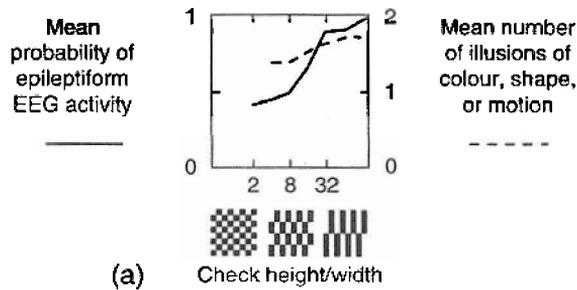
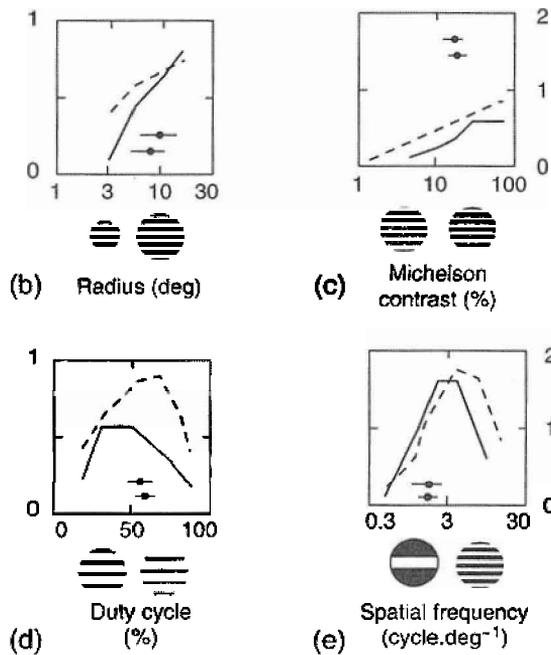


Fig. 4.2 Probability of epileptiform EEG activity in patients with pattern-sensitive epilepsy, shown as a function of several spatial characteristics of the pattern (solid curves). The broken lines show the number of illusions of colour, shape, or motion reported by normal observers. The horizontal points and bars show the mean ± 1 standard deviation of characteristics of text, when considered as a striped pattern, the lower bars for clear text and the upper bars for less clear text. Icons beneath each graph represent variation in the relevant spatial characteristic.

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If the spatial characteristics of a coloured pattern are reduced in complexity to the simplest spatial configuration—a pattern of stripes—a surprisingly simple relationship emerges between the characteristics of the pattern and how unpleasant it is. The unpleasantness depends mainly on how different the colours are—that is, how far apart their chromaticities are in the Commission Internationale de l'Éclairage (CIE) Uniform Chromaticity Scale (UCS) diagram. People were asked to judge discomfort from patterns of stripes with two alternate colours, and in four experiments a consistent correlation was found between ratings of unpleasantness and the separation of the colours (chromaticities) in the CIE UCS diagram. This relationship was obtained for gratings in which the bars had the same luminance, and also in gratings in which the bars differed in luminance (Wilkins et al., 2008).

The haemodynamic response of the visual cortex to these coloured gratings was measured in four studies (in preparation) using near infrared spectroscopy (NIRS). NIRS is a

technique in which low-power laser light is shone on the scalp, penetrates the skull, reflects from the surface of the brain, and re-emerges from the scalp, to be picked up by sensitive photodiodes. Changes in the concentration of oxyhaemoglobin and deoxyhaemoglobin can be calculated by comparing the signal reflected at two different wavelengths. Both the discomfort from patterns of stripes and the haemodynamic response in the brain increased with the difference in colour between the stripes. This finding is consistent with the idea that coding in the brain is efficient for naturally occurring stimuli, which rarely show strong chromatic contrasts (Juricevic et al., 2010).

In short, we can now describe mathematically what makes images uncomfortable to look at. We can do so for both meaningless and meaningful images. Images that are uncomfortable tend to be those that are strong visual stimuli, and that induce a large haemodynamic response in the visual cortex. When we apply the mathematics to images from the contemporary urban environment, it transpires that the environment has many 'uncomfortable' images with unnatural image statistics. One of these is text.

Text as an uncomfortable image

Text has an unnatural spatial structure with an excess of contrast energy at mid-range spatial frequencies. This is particularly true of Western text: Arabic and Chinese text have less such energy. The high-contrast energy is due to the stripes from the lines of text. They are in the critical ranges of the parameters shown in Fig. 4.2. The spatial parameters of the stripes of text are shown by the horizontal bars.

Text is clearer if it has a relatively large spacing between the words, breaking up the 'grating' structure, and if the spacing between the lines is relatively large, decreasing the spatial frequency of the grating. In an experiment by Wilkins and Nimmo-Smith (1987) books were selected by students as having 'clear' or 'less clear' text. The 'clearer' text had more space, particularly space between the lines.

Reducing the luminance and contrast of the lines of text you are *not* reading, using a mask, can make the text you *are* reading clearer to see. Masks of this kind are known as *typoscopes* and they cover the lines below and above the lines that are being read. The mask can reduce eye strain (Wilkins & Nimmo-Smith, 1984) and also reduce seizures in photosensitive patients (Wilkins & Lindsay, 1985). People who report improvements in clarity with a typoscope tend to be those who report more illusions in patterns of stripes (Wilkins & Nimmo-Smith, 1984).

Stripes in letter strokes

In text it is not only the lines of words that are spatially repetitious, the strokes of letters can also form stripes. These stripes can interfere with reading as well, so much so that words such as *mum* take longer to read than words such as *dad* (Wilkins et al., 2007a). The stripes can be measured in terms of the first peak in the horizontal autocorrelation function. The first peak measures the extent to which the neighbouring strokes of letters resemble each other. The peak is far greater for the striped word *mum* than for the more rounded word *dad*. There are several possible reasons why spatially periodic words take

longer to read. One is due to the adjustments in the alignment of the two eyes that occur when reading. When you read, your eyes make a series of jerks from left to right called saccades. After each saccade the alignment of the eyes has to be re-adjusted to bring the retinal images of the word into correspondence. The readjustment has to be more accurate when the eyes land on a word with a high autocorrelation perhaps because of the potential for false alignment of similar letter strokes, and this requirement for greater accuracy takes extra time. The above effects are not seen when reading is monocular. In any event, the time taken to fixate a striped word is greater, and reading takes longer (Jainta et al., 2010). The effect on ocular motor control may not be the only reason: the effect on reading speed is large relative to the increase in fixation duration. Be that as it may, the interference with ocular motor control as a result of spatial periodicity would be likely to increase the neural computation involved in reading, consistent with the proposal that strong excitation results in discomfort.

Font design

The average of the first peak in the horizontal autocorrelation of 1000 words was measured in various fonts. Times New Roman was among those with the highest spatial periodicity and Verdana among those with the least. Sassoon, a font widely used in primary education was similar to Times New Roman with respect to its high spatial periodicity. Studies comparing the reading speed for various fonts generally show that the fonts with higher spatial periodicity are read more slowly. One such study compared children's speed of reading passages printed in Sassoon with those printed in Verdana and found that children read more quickly with Verdana even though they were more familiar with Sassoon (Wilkins et al., 2010).

One way of reducing the effects of stripes, and decreasing the destructive effects of small errors of alignment of the eyes, is to increase the size of the letters. Increasing the size of the typeface has dramatic effects on children's reading speed, comprehension, and general reading ability. This is generally recognized to be the case, and text for young children is therefore printed in a large typeface. The height of the central body of the letters, known as x-height, begins at about 4 mm at age 5 and decreases to the adult size of about 2 mm over the course of the subsequent 5 years or so. Hughes and Wilkins (2000) created meaningless passages of randomly ordered common words that they asked children to read aloud as quickly as they could. The speed of reading the passages was measured for text with a variety of x-heights. Surprisingly, the speed of reading was *not* greatest with text of a size that the children were normally required to read and with which they were familiar. Instead the children (aged 5–9 years) read more quickly with text of a size normally used by younger children. In other words, text for children decreases in size at too early an age.

These findings have been replicated with more meaningful material. Wilkins et al. (2010) measured the speed with which 7–8-year-olds could silently read short sentences and classify them as true ('Fish live under the water') or false ('People have two noses'). The speed of comprehension (sentence verification) increased by 9% when the x-height was increased by 10%.

Wilkins et al. (2010) then made a version of the Salford Sentence Reading Test in which the text remained at the size of the initial sentences instead of decreasing in size as the test progressed, as is usual. The reading age increased by an average of 4 months when assessed by the version of the test in which the text remained large throughout. Evidently reading speed, comprehension speed, and reading age are all increased by increasing the size of text young children are required to read.

Environmental concerns

The task of classroom reading is made more difficult than it needs to be not only by the small size of text but by the way in which classrooms are lit. In a recent survey, 80% of UK classrooms were found to be lit with conventional fluorescent lighting that flickers 100 times per second (Winterbottom & Wilkins, 2007). The flicker is imperceptible but is resolved by the human retina (Berman et al., 1991), interferes with the control of eye movements (Wilkins, 1986), impairs visual performance (Veitch & McColl, 1995), and causes headaches (Wilkins et al., 1989). It is regrettable that low-frequency fluorescent ballasts, which are unhealthy and more expensive to operate than electronic ballasts, continue to be fitted into new school buildings because of their lower initial cost.

Typical classroom lighting not only flickers, but it is excessively and wastefully bright: in 84% of classrooms lighting levels exceed those at which visual discomfort starts to increase (Winterbottom & Wilkins, 2007).

In summary, we have seen that images with an unnatural spatial, temporal, and chromatic structure are more uncomfortable to look at, and that text is intrinsically an uncomfortable image. We have reviewed some of the consequences of the design of (Western) text. We now turn to the physiological reasons for the discomfort.

Neurological response to uncomfortable visual stimuli

It has long been held that visual systems are suited to the tasks they are required to carry out (e.g. Barlow, 1989) and that their resources are efficiently used. It has been shown that principal component filters (which sensory processes have been shown to emulate, e.g. Buchsbaum & Gottschalk (1984)) result in a sparse coding of natural scenes in which few neurons are active at any one time, conserving energy (Willmore & Tolhurst, 2001). It is quite possible that natural images are coded sparsely, and that unnatural images result in inefficient processing and excessive neuronal activity, as reflected in the haemodynamic response in the visual cortex (Juricevic et al., 2010). The excessive neuronal activity may have little consequence for most people, but may have adverse consequences for the 10% or so of the normal population whose cerebral cortex is already hyperexcitable (Aurora et al., 1999), a proportion that includes individuals who suffer migraine.

Individuals with migraine differ from matched controls in that their physiological response to sensory stimulation is abnormally large. Individuals with migraine: (1) see more illusions of colour, shape, and motion when they look at gratings, particularly gratings that would induce seizures in patients with photosensitive epilepsy (Wilkins et al., 1984); (2) they show a larger amplitude haemodynamic response to these gratings, as

measured using functional magnetic resonance imaging (fMRI) blood oxygen level-dependent (BOLD) (Huang et al., 2003); (3) when measured using NIRS, the haemodynamic response can be shown to have a shorter latency (Cou tts et al., in preparation); (4) the amplitude of the evoked potential fails to show the usual reduction in amplitude with repeated stimulation (Schoenen, 1996) and (5) when the occipital cortex is stimulated with a magnetic pulse the threshold current at which spots of light (phosphenes) first appear is lower (Aurora & Welch, 1998).

The over-responsiveness to sensory stimulation may reflect a cortical hyperexcitability because (1) the sensory stimulation to which patients with migraine are particularly susceptible is similar to the stimulation that induces seizures in patients with photosensitive epilepsy; (2) migraine and epilepsy are comorbid conditions (Brinciotti et al., 2000); (3) four antiepileptic drugs have been shown to prevent migraine in double-masked trials (Tfelt, 1996); and (4) DC-magnetoencephalography during visual stimulation reveals large-amplitude signals, reduced by the anticonvulsant, sodium valproate (Bowyer et al., 2005).

Coloured filters and reading

There is now considerable evidence that coloured filters can improve reading speed, although the reasons have proved to be elusive. There is no single colour that is generally beneficial, but each person seems to need their own individually selected colour (Wilkins & Neary, 1991; Wilkins et al., 1991, 1992a; 1992b, 1994, 1996, 2005a, 2005b, 2007b; Wilkins, 1992, 2003; Maclachlan et al., 1993; Evans et al., 1995, 1996a, 1996b, 1999, 2002; Tyrrell et al., 1995; Jeanes et al., 1997; Wilkins & Lewis, 1999; Bouldoukian et al., 2002; Scott et al., 2002; Huang et al., 2004; Waldie & Wilkins, 2004; Ludlow et al., 2006; Newman Wright et al., 2007; Smith & Wilkins, 2007; Allen et al., 2010).

Hollis and Allen (2006) separated individuals into two groups: those who reported many illusions when they looked at a striped pattern (a grating with spatial frequency close to three cycles/degree) and those who reported few. The former group reported an improvement in clarity of text with a coloured overlay, and read more quickly with the overlay. The latter group showed no such effect. The illusions reported in response to a striped pattern predicted the increment in reading speed better than the reports of visual discomfort in a symptom questionnaire.

Many individuals who use overlays for reading find that it is more convenient to use coloured lenses. The lenses have the advantage that they can be used for writing and for reading at distance. The colour optimal for use in overlays differs from that optimal for use in lenses, perhaps because the eyes are adapted to coloured light when coloured lenses are worn (Lightstone et al., 1999).

The *Intuitive Colorimeter* is an instrument that allows the colour that suits an individual to be selected. It shines coloured light on text and permits the separate manipulation of hue, saturation, and brightness. The chosen chromaticity is matched using combinations of tinted trial lenses. The combinations of trial lenses enable the tint to be tried out in natural viewing conditions and they guide the dyeing of spectacle lenses. The prescription is made up by dipping spectacle lenses into two dyes with hue similar to

that of the desired tint. One advantage of the colorimeter is that the entire visual field is coloured so the eyes are adapted to coloured light. This is the simplest method of studying colour and its effect is similar to a coloured lens, not an overlay.

To check on the specificity and reliability of the optimal colour, Wilkins et al. (2005b) asked five observers who had used coloured lenses to read without their lenses. They read randomly ordered words repeatedly under light of different colours (Wilkins et al., 2005b). A computer algorithm was used to plot iso-reading speed contours in the CIE UCS diagram. The contours were similar from one test session to the next a few weeks later, and they showed no evidence of colour opponency. Although reading was usually slowest with white light and there was a large change in reading speed with colour, each individual had a different optimum. Despite the differences in optimal colour, the functions for all participants were similar when the data were plotted in terms of the difference in colour between the colour of light the individual was using for reading and the colour at which the text was perceived to be clearest. The reading speed decreased progressively with the difference in colour until the separation in CIE UCS chromaticity was about 0.06 when reading speed became similar to that under white light (Wilkins et al., 2005b).

These findings help predict how many different tints are necessary in an ophthalmic tinting system. To achieve an increment in reading speed within 95% of that obtainable with an optimum tint, about 6000 tints are necessary (Wilkins et al., 2005a). It is not necessary to offer 6000 trial lenses. Trial lenses can be placed one upon another to create different colours, and so it is not necessary to have more than about 35 trial lenses to achieve the requisite number of tints, provided the spectral transmissions are appropriately chosen.

Clinical indications

Tinted spectacles have shown clinical benefits in a variety of disorders. These disorders include not only reading difficulty, but photosensitive epilepsy (Wilkins et al., 1999, 2003), migraine (Wilkins et al., 2002), autism (Ludlow et al., 2006), and multiple sclerosis (Newman Wright et al., 2007). In all these disorders there is evidence (direct or indirect) for a hyperexcitability of the brain, particularly the visual cortex. There is direct evidence for a hyperexcitability in migraine, described earlier. In both autism and multiple sclerosis, the evidence is indirect: these disorders are comorbid with epilepsy (Sullivan, 1975; Kinnunen & Wikstrom, 1986; Levinson, 2007) and migraine (Gee et al., 2005; Casanova, 2009), and there is electrophysiological evidence for a hyperexcitability of the (motor) cortex in multiple sclerosis (Reddy et al., 2002; Caramia et al., 2004).

Strong stimulation

High-contrast stripes may be assumed to stimulate neurons strongly. Most visual neurons are responsive to the moderate contrasts found in natural scenes (Clatworthy et al., 2003) and their firing rate is likely to be close to maximal at contrasts above about 10%. With high-contrast stripes, the responsive neurons are likely to be firing strongly.

Stripes will stimulate columns of neurons with the appropriate orientation specificity, and the resulting excitation will presumably be concentrated within limited regions of the visual cortex, that is, the columns in which cells with the appropriate orientation

specificity are to be found. There are at least two reasons for supposing that such a dense firing of neurons within the cortical network is detrimental: (1) when neurons fire, the concentration of ions in the extracellular space increases and excitatory effects can cause activation of adjacent neurons (Jefferys, 1991); (2) the orientationally selective pyramidal neurons are interconnected by inhibitory interneurons which are responsible for orientation tuning, and may help to prevent any strong excitation spreading through the cortical network. Because the interneurons are shared between pyramidal neurons, strong firing of neighbouring neurons might deplete the local availability of an inhibitory neurotransmitter such as gamma-aminobutyric acid, decreasing the inhibition and allowing a discharge to spread within the network (Meldrum & Wilkins, 1984).

Any spread of excitation might cause neurons to fire inappropriately, giving illusions of motion, shape, and colour. (The visual patterns that produce such illusions are curiously similar to the patterns seen as hallucinations when viewing bright (epileptogenic) flickering lights. The patterns can be inferred to arise as a result of lateral connectivity when the resting state of the visual cortex becomes unstable, see Bressloff et al. (2002).)

In rhesus monkeys the neurons in V2 show a topographic representation of colour. Neurons that respond to a red–black grating are found in areas that are next to areas in which the neurons respond to yellow–black gratings, and these in turn are next to areas in which the neurons respond to green–black gratings and so on. The colour selectivity is distributed across the cortex in much the same way as colours are distributed within the CIE UCS diagram (Xiao et al., 2003). For this reason, coloured filters are likely to redistribute the cortical excitation that results from a visual stimulus, at least in V2, one of the visual areas in which migraineurs show an abnormally large fMRI BOLD response (Huang et al., 2011). Colours that make visual stimuli more comfortable may be those that result in a redistribution of activity that avoids areas that are hyperexcitable.

We have already seen that the BOLD response is abnormally large in patients with migraine and this abnormality is most pronounced in visual areas V2 and V3 (Huang et al., 2011). With the appropriately coloured filter, the abnormal response in V2 and V3 is reduced in size and is normalized in terms of its spatial frequency tuning. There is no effect of the coloured filters in controls (Huang et al., 2011).

The latency of the haemodynamic response to visual stimuli can also be measured using a different technique, near infrared spectroscopy. With this technique it is evident that the response has an abnormally rapid decline in individuals with migraine. The decline is lessened (normalized) with filters selected to improve visual comfort. There is no such increase with control colours (Coutts et al., in press).

The imaging studies referred to previously indicate that (1) the over-responsiveness of the visual cortex seen in migraine is reduced with coloured filters, and (2) the reduction is dependent on the colour of the filters in a different way for each individual.

Peripheral consequences of central effects?

The effects of coloured filters are not exclusively central. Indeed, the individuals who respond to coloured filters show an underfocusing of the eyes (a lag of accommodation) that is greater than that seen in controls. The underfocusing is reduced by a coloured

filter, one with a colour that individuals report as improving comfort, but is unaffected by other colours. There is no association between the focusing error and the particular colour that has this effect, as might be expected if the reduction in accommodative lag were due to the chromatic aberration of the eye. Instead it is possible that the underfocusing acts to slightly blur the retinal image so as to reduce the extent of cortical activation, thereby improving visual comfort (Allen et al., 2010).

Individual differences

The large individual differences in the therapeutic colour are difficult to explain. It is possible that they reflect differences in the distribution of hyperexcitability across the cortex in anterior cortical areas. It is also possible that the differences reflect peripheral effects. They may be a consequence of differences between individuals in the proportion of long-, middle-, and short-wavelength cones (L, M, and S cones) in the retina. The differences are large (the ratio of L:M cones can be as great as 16:1 (Hofer et al., 2005; Roorda & Williams, 1999)), but they do not appear to give rise to large perceptual differences between people. Perhaps the perceptual normalization that occurs is the result of a larger 'gain' being applied to the less numerous cones, and if so, the greater gain may have greater 'noise' associated with it. It is possible that the chosen filter colour acts to reduce the effects of the noise by increasing the relative activation of the less numerous cone type. However, the S cones are the least numerous (about 1 for every 20 L or M cones) and the large individual differences that have been observed pertain mainly to the ratio of L to M cones. We would therefore expect the individual differences to occur mainly along the L–M confusion line, and the differences do not appear to favour any particular axis of confusion (Wilkins et al., 2005b).

A synthesis

It is now possible to bring the very disparate components of this discourse together. It is possible to conceive of visual stress as arising from strong sensory stimulation. When the cortex is normally excitable, this strong stimulation is without adverse consequence. When, however, the cortex is hyperexcitable, visual illusions are experienced, together with discomfort. The discomfort can be seen as providing for homeostasis: individuals will avoid sensory stimulation that is bad for them. *In extremis*, the neural discharge that usually results in no more than visual illusions has more adverse consequences, resulting in a large discharge that may trigger migraine, or end in a seizure.

Reading can be a stressful activity—it is one for which the visual system was not designed. Text can be improved in design to reduce visual stress, but where individual susceptibility is extreme it may be helpful to use appropriately coloured filters that appear to act to reduce an overexcitation of the visual cortex. The reasons for the individual differences in the colour optimal for achieving this reduction remain an enigma.

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References

- Allen, P.M., Hussain, A., Usherwood, C., & Wilkins, A.J. (2010). Pattern-related visual stress, chromaticity and accommodation. *Investigative Ophthalmology and Visual Science*, 51, 6843–9.
- Antal, A., Temme, J., Nitsche, M.A., Varga, E.T., Lang, N., & Paulus, W. (2005). Altered motion perception in migraineurs: evidence for interictal cortical hyperexcitability. *Cephalalgia*, 25, 788–94.
- Aurora, S.K., Cao, Y., Bowyer, S.M., & Welch, K.M. (1999). The occipital cortex is hyperexcitable in migraine: experimental evidence. *Headache*, 39, 469–76.
- Aurora, S.K. & Welch, K.M. (1998). Brain excitability in migraine: evidence from transcranial magnetic stimulation studies. *Current Opinion in Neurology*, 113, 205–9.
- Barlow, H.B. (1989) Unsupervised learning. *Neural Computation*, 1, 295–311.
- Berman, S.M., Greenhouse, D.S., Bailey, I.L., Clear, R., & Raasch, T.W. (1991). Human electroretinogram responses to video displays fluorescent lighting and other high frequency sources. *Optometry and Vision Science*, 68, 645–62.
- Bouldoukian, J., Wilkins, A.J., & Evans, B.J.W. (2002). Randomised control trial of the effect of coloured overlays on the rate of reading of people with specific learning difficulties. *Ophthalmic and Physiological Optics*, 22, 55–60.
- Bowyer, S., Mason, K.M., Moran, J.E., Tepley, N., & Mitsias, P.D. (2005). Cortical hyperexcitability in migraine patients before and after sodium valproate treatment. *Journal of Clinical Neurophysiology*, 22, 65–7.
- Bressloff, P.C., Cowan, J.D., Golubitsky, M., Thomas, P.J., & Wiener, M.C. (2002). What geometric visual hallucinations tell us about the visual cortex. *Neural Computation*, 14, 473–91.
- Brinciotti, M., Di Sabato, M., Matricadi, M., & Guidetti, V. (2000). Electroclinical features in children and adolescents with epilepsy and/or migraine, and occipital epileptiform EEG abnormalities. *Clinical Electroencephalography*, 31, 76–82.
- Buchsbaum, G., & Gottschalk, A. (1984). Chromaticity coordinates of frequency-limited functions. *Journal of the Optical Society of America*, 1, 885–7.
- Caramia, M.D., Palmieri, M.G., Desiato, M.T., Boffa, L., Galizia, P., and Rossini, P.M. (2004). Brain excitability changes in the relapsing and remitting phases of multiple sclerosis: A study with transcranial magnetic stimulation. *Clinical Neurophysiology*, 115, 956–65.
- Casanova, M.F. (2009). The minicolumnopathy of autism: a link between migraine and gastrointestinal symptoms. *Medical Hypotheses*, 70, 73–80.
- Chronicle, E., & Wilkins, A.J. (1996). Gratings that induce perceptual distortions mask superimposed targets. *Perception*, 25, 661–8.
- Clatworthy, P.L., Chirumuta, M., Lauritzen, J.S., & Tolhurst, D.J. (2003). Coding of the contrasts in natural images by populations of neurons in primary visual cortex (V1). *Vision Research*, 43, 1983–2001.
- Coutts, L., Cooper, C., Elwell, C., & Wilkins A.J. (in press). The haemodynamic response to visual stimulation in migraine measured using near infrared spectroscopy *Cephalalgia*.
- Evans, B.J.W., Busby, A., Jeanes, R., & Wilkins, A.J. (1995). Optometric correlates of Meares-Irlen syndrome: a matched group study. *Ophthalmic and Physiological Optics*, 15, 481–7.
- Evans, B.J.W., Wilkins, A.J., Brown, J., Busby, A., Wingfield, A., Jeanes, R., et al. (1996a). A preliminary investigation into the aetiology of Meares-Irlen syndrome. *Ophthalmic and Physiological Optics*, 16, 286–96.
- Evans, B.J.W., Wilkins, A.J., Busby, A., & Jeanes, R. (1996b). Optometric characteristics of children with reading difficulties who report a benefit from coloured filters. In: I.J.C.M. Dickinson, Murray, & D. Garden (Eds.) *John Dalton's Colour Vision Legacy*, pp. 709–15. London: Taylor and Francis.
- Evans, B.J.W., Lightstone, A., Eperjesi, F., Duffy, J., Speedwell, L., Patel, R., et al. (1999). A review of the management of 323 consecutive patients seen in a specific learning difficulties clinic. *Ophthalmic and Physiological Optics*, 19, 454–66.

- Evans, B.J.W., Patel, R., & Wilkins, A.J. (2002). Optometric function in visually sensitive migraine before and after treatment with tinted spectacles. *Ophthalmic and Physiological Optics*, 22, 130–42.
- Fernandez, D., & Wilkins, A.J. (2008). Uncomfortable images in art and nature. *Perception*, 37, 1098–113.
- Gee, J.R., Chang, J., Dublin, A.B., & Vijayan, N. (2005). The association of brainstem lesions with migraine-like headache: An imaging study of multiple sclerosis. *Headache*, 45, 670–7.
- Hofer, H., Carrol, J., Neitz, J., Neitz, M., & Williams, D.R. (2005). Organization of the human trichromatic cone mosaic. *Journal of Neuroscience*, 25, 9669–79.
- Hollis, J., & Allen, P.M. (2006). Screening for Meares-Irlen sensitivity in adults: can assessment methods predict changes in reading speed? *Ophthalmic and Physiological Optics*, 26, 566–71.
- Huang, J., Cooper, T.G., Satana, B., Kaufman, D.I., & Cao, Y. (2003). Visual distortion associated with hypervisual neuronal activity in migraine. *Headache*, 43, 664–71.
- Huang, J., Wilkins, A.J., & Cao, Y. (2004). Mechanisms whereby precision spectral filters reduce visual stress: an fMRI study. Tenth Annual Meeting of the Organization for Human Brain Mapping, June 13–17, 2004, Budapest, Hungary.
- Huang, J., Zong, X., Wilkins, A.J., Jenkins, B., Bozoki, A., & Cao, Y. (2011). A neurological basis for reducing cortical hyperactivation in migraine with precision ophthalmic tints. *Cephalalgia*, 31, 925–36.
- Hughes, L.E., & Wilkins, A.J. (2000). Typography in children's reading schemes may be suboptimal: evidence from measures of reading rate. *Journal of Research in Reading*, 23, 314–24.
- Jainta, S., Jaschinski, W., & Wilkins, A.J. (2010). Periodic letter strokes within a word affect fixation disparity during reading. *Journal of Vision*, 10(13), 2.
- Jeanes, R., Busby, A., Martin, J., Lewis, E., Stevenson, N., Pointon, D., et al. (1997). Prolonged use of coloured overlays for classroom reading. *British Journal of Psychology*, 88, 531–48.
- Jefferys, J.G.R. (1991). Non-synaptic modulation of neuronal activity in the brain: electric currents and extracellular ions. *Physiological Reviews*, 75, 689–723.
- Juricevic, I., Land, L., Wilkins, A.J., & Webster, M.A. (2010). Visual discomfort and natural image statistics. *Perception*, 39, 884–99.
- Kinnunen, E., & Wikstrom, J. (1986). Prevalence and prognosis of epilepsy in patients with multiple sclerosis. *Epilepsia*, 27, 729–33.
- Levinson, P.M. (2007). The autism-epilepsy connection. *Epilepsia*, 48, 33–5.
- Lightstone, A., Lightstone, T., & Wilkins, A. (1999). Both coloured overlays and coloured lenses can improve reading fluency, but their optimal chromaticities differ. *Ophthalmic and Physiological Optics*, 19, 279–85.
- Ludlow, A.K., Wilkins, A.J., & Heaton, P. (2006). The effect of coloured overlays on reading ability in children with autism. *Journal of Autism and Developmental Disorders*, 36, 507–16.
- Maclachlan, A., Yale, S., & Wilkins, A.J. (1993). Open trials of precision ophthalmic tinting: 1-year follow-up of 55 patients. *Ophthalmic and Physiological Optics*, 13, 175–8.
- Marcus, D.A., & Soso, M.J. (1989). Migraine and stripe-induced visual discomfort. *Archives of Neurology*, 46, 1129–32.
- Meldrum, B.S., & Wilkins, A.J. (1984). Photosensitive epilepsy: integration of pharmacological and psychophysical evidence. In P. Schwatzkroin & H.V. Wheal (Eds.) *Electrophysiology of Epilepsy*, pp. 51–77. London: Academic Press.
- Newman Wright, A., Wilkins, A., & Zoukos, Y. (2007). Spectral filters can improve reading and visual search in patients with multiple sclerosis. *Journal of Neurology*, 254, 1729–35.
- Nulty, D., Wilkins, A.J., & Williams, J.M. (1987). Mood, pattern sensitivity and headache: a longitudinal study. *Psychological Medicine*, 17, 705–13.
- Palmer, J.E., Chronicle, E.P., Rolan, P., & Mulleners, W.M. (2000). Cortical hyperexcitability is cortical under-inhibition: evidence from a novel functional test of migraine patients. *Cephalalgia*, 20, 525–32.

- Reddy, H., Narayanan, S., Woolrich, M., Mitsumori, T., Lapierre, Y., Arnold, D., *et al.* (2002). Functional brain reorganisation for hand movement in patients with multiple sclerosis: Defining distinct effects of injury and disability. *Brain*, 125, 2646–57.
- Roorda, A., & Williams, D.R. (1999). The arrangement of the three cone classes in the living human eye. *Nature*, 397, 520–2.
- Schoenen, J. (1996). Deficient habituation of evoked cortical potentials in migraine: a link between brain biology, behavior and trigeminovascular activations? *Biomedicine and Pharmacotherapy*, 50, 71–8.
- Scott, L., McWhinnie, H., Taylor, L., Stevenson, N., Irons, P., Lewis, E., *et al.* (2002). Coloured overlays in schools: orthoptic and optometric findings. *Ophthalmic and Physiological Optics*, 22, 156–65.
- Smith, L., & Wilkins, A. (2007). How many overlay colours are necessary to increase reading speed? A comparison of two systems. *Journal of Research in Reading*, 30, 332–43.
- Sullivan, R. (1975). Hunches on some biological factors of autism. *Journal of Autism and Childhood Schizophrenia*, 5, 177–86.
- Tfelt, H.P. (1996). Drug treatment of migraine: acute treatment and migraine prophylaxis. *Current Opinion in Neurology*, 9, 211–13.
- Tyrrell, R., Holland, K., Dennis, D., & Wilkins, A.J. (1995). Coloured overlays, visual discomfort, visual search and classroom reading. *Journal of Research in Reading*, 18, 10–23.
- Veitch, J.A., & McColl, S.L. (1995). Modulation of fluorescent light: flicker rate and light source effects on visual performance and visual comfort. *Lighting Research and Technology*, 27, 243–56.
- Waldie, M., & Wilkins, A. (2004). How big does a coloured overlay have to be? *Ophthalmic and Physiological Optics*, 24, 55–60.
- Wilkins, A. (1986). Intermittent illumination from visual display units and fluorescent lighting affects movements of the eyes across text. *Human Factors*, 28, 75–81.
- Wilkins, A. (1992). *A System for Precision Ophthalmic Tinting: Manual for the use of the Intuitive Colorimeter and Trial Lenses*, p. 27. Kent: Cerium Visual Technologies.
- Wilkins, A.J. (1994). Overlays for classroom and optometric use. *Ophthalmic and Physiological Optics*, 14, 97–9.
- Wilkins, A.J. (1995). *Visual Stress*. Oxford: Oxford University Press.
- Wilkins, A.J. (2003). *Reading Through Colour. How coloured filters can reduce reading difficulty, eye strain, and headaches*. Chichester: John Wiley and Sons.
- Wilkins, A.J. & Lewis, E. (1999). Coloured overlays, text and texture. *Perception*, 28, 641–50.
- Wilkins, A.J. & Lindsay, J. (1985). Common forms of reflex epilepsy: physiological mechanisms and techniques for treatment. In Pedley, T.A., & Meldrum, B.S. (Eds.) *Recent advances in epilepsy II*, pp. 239–71. Edinburgh: Churchill Livingstone.
- Wilkins, A.J. & Neary, C. (1991). Some visual, optometric and perceptual effects of coloured glasses. *Ophthalmic and Physiological Optics*, 11, 163–71.
- Wilkins, A., & Nimmo-Smith, I. (1984). On the reduction of eye-strain when reading. *Ophthalmic and Physiological Optics*, 4, 53–9.
- Wilkins, A.J., & Nimmo-Smith, M.I. (1987). The clarity and comfort of printed text. *Ergonomics*, 30, 1705–20.
- Wilkins, A.J., Nimmo-Smith, M. I., Tait, A., McManus, C., Della Sala, S., Tilley, A., *et al.* (1984). A neurological basis for visual discomfort. *Brain*, 107, 989–1017.
- Wilkins, A.J., Nimmo, S.I., Slater, A.I., & Bedocs, L. (1989). Fluorescent lighting, headaches and eyestrain. *Lighting Research and Technology*, 21, 11–18.
- Wilkins, A.J., Nimmo-Smith, I., & Jansons, J.E. (1991). A colorimeter for the intuitive manipulation of hue saturation and brightness. *Ophthalmic and Physiological Optics*, 12, 381–5.

- Wilkins, A., Milroy, R., Nimmo-Smith, I., Wright, A., Tyrrell, R., Holland, K., *et al.* (1992a). Preliminary observations concerning treatment of visual discomfort and associated perceptual distortion. *Ophthalmic and Physiological Optics*, 12, 257–63.
- Wilkins, A.J., Nimmo-Smith, I., & Jansons, J.E. (1992b). Colorimeter for the intuitive manipulation of hue and saturation and its role in the study of perceptual distortion. *Ophthalmic and Physiological Optics*, 12, 381–5.
- Wilkins, A.J., Evans, B.J.W., Brown, J.A., Busby, A.E., Wingfield, A.E., Jeanes, R.J., *et al.* (1994). Double-masked placebo-controlled trial of precision spectral filters in children who use coloured overlays. *Ophthalmic and Physiological Optics*, 14, 365–70.
- Wilkins, A.J., Jeanes, R.J., Pumfrey, P.D., & Laskier, M. (1996). Rate of Reading Test: its reliability, and its validity in the assessment of the effects of coloured overlays. *Ophthalmic and Physiological Optics*, 16, 491–7.
- Wilkins, A.J., Baker, A., Smith, S., Bradford, J., Zaiwalla, Z., Besag, F.M., *et al.* (1999). Treatment of photosensitive epilepsy using coloured glasses. *Seizure*, 8, 444–9.
- Wilkins, A.J., Patel, R., Adjamian, R., & Evans, B.J.W. (2002). Tinted spectacles and visually sensitive migraine. *Cephalalgia*, 22, 711–19.
- Wilkins, A., Huang, J., & Cao, Y. (2003). Visual stress theory and its application to reading and reading tests. *Journal of Research in Reading*, 27, 152–62.
- Wilkins, A., Sihra, N., & Nimmo-Smith, I. (2005a). How precise do precision tints have to be and how many are necessary? *Ophthalmic and Physiological Optics*, 25, 269–76.
- Wilkins, A., Sihra, N., & Myers, A. (2005b). Increasing reading speed using colours: issues concerning reliability and specificity, and their theoretical and practical implications. *Perception*, 34, 109–20.
- Wilkins, A.J., Smith, J., Willison, C.K., Beare, T., Boyd, A., Hardy, G., *et al.* (2007a). Stripes within words, reading speed and reading difficulty. *Perception*, 36, 1788–803.
- Wilkins, A.J., Huang, J., & Cao, Y. (2007b). Prevention of visual stress and migraine with precision spectral filters. *Drug Development Research*, 68, 469–75.
- Wilkins, A.J., Tang, P., Irabor, J., Banningham, L., & Coutts, L. (2008). Cortical haemodynamic response to coloured gratings. *Perception*, 37, 144.
- Wilkins, A.J., Cleave, A., Grayson, N., & Wilson, L. (2010). Text for children may be inappropriately designed. *Journal of Research in Reading*, 32, 402–12.
- Willmore, B., & Tolhurst, D. (2001). Characterising the sparseness of neural codes. *Network*, 12, 255–70.
- Winterbottom, M., & Wilkins, A. (2007). Lighting and visual discomfort in the classroom. *Journal of Environmental Psychology*, 29, 63–75.
- Xiao, Y., Wang, Y., & Felleman, D.J. (2003). A spatially organized representation of colour in macaque cortical area V2. *Nature*, 421, 535–9.