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A neurological basis for visual stress and its treatment with coloured filters☆

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ABSTRACT

The perceptual distortions and discomfort that some individuals experience when they read has a recent literature. A review of this literature leads to the conclusion that the distortions and discomfort can have their basis in an excitability of the visual cortex. Tinted lenses of an individually selected hue and saturation reduce the discomfort, possibly because the resulting change in the cortical distribution of activation avoids locally excitable tissue. The above conclusion is reached as follows. Images from nature, despite their heterogeneity, have in common certain statistical features that enable them to be encoded efficiently by the human visual system. Certain images that have an un-natural spatial and chromatic structure (including text) can be uncomfortable to look at. They can give rise to a large cortical haemodynamic response, consistent with indications from computational neurology that they are processed inefficiently. There are large differences between people in susceptibility to discomfort from images. These differences reflect differences in medical history. When the spatial and chromatic structure of images deviates maximally from those found in nature, susceptible individuals are liable to discomfort, migraine and/or seizures, a liability that individually coloured filters can sometimes reduce.

1. Background

It is well known that certain individuals with epilepsy (about 5 %) are liable to seizures triggered by flashing light (Harding & Jeavons, 1994). It is less well known that about one third of these patients are also liable to seizures triggered by stable continuously illuminated patterns, particularly patterns of stripes (Wilkins, Binnie, & Darby, 1980). The patterns responsible have been studied in detail using EEG control and the risk of seizures is known to depend on the following pattern parameters: (1) spatial frequency (about 3 cycles per degree has the greatest risk of seizures); (2) retinal subtense of the pattern (the risk increases linearly with the area of the visual cortex to which the pattern projects); (3) luminance contrast and (4) space-averaged luminance (the risk increases approximately linearly with the logarithm of each of these variables) (Wilkins, 1995). Healthy observers find epileptogenic patterns uncomfortable to look at, and report perceptual distortions (Wilkins et al., 1984). The perceptual distortions in healthy individuals and the seizure risk in patients with photosensitive epilepsy are both similarly dependent on the above parameters (Wilkins et al., 1984). The number of distortions seen is greater in individuals who experience frequent headaches (Wilkins et al., 1984).

In susceptible people, reading can induce seizures, thought to arise primarily from language processing (Miller, Razvi, & Russell, 2010). However, printed text has parameters that are similar to those of epileptogenic and uncomfortable patterns (Wilkins and Nimmo-Smith, 1987; Wilkins et al., 2020). Text forms patterns of stripes from the horizontal lines of text but also from the vertical strokes of neighbouring letters (Wilkins et al., 2020; Wilkins et al., 2007). The periodicity of the vertical strokes can be measured from the first peak in the horizontal autocorrelation of words or pages. This is known to predict the speed of reading (Wilkins et al., 2007) and, in a patient reported by Weaver (Weaver, 2014), to predict seizures. The patient had seizures when reading material printed in fonts with high horizontal autocorrelation (Times and Palatino) but not when reading the same material printed in less periodic fonts (Arial and Verdana).

Some fonts and text layouts have far greater spatial periodicity than others (Wilkins, Smith, & Penacchio, 2020). Children's fonts are often too small (Hughes, Wilkins, & Arnold, 2000) and spatially repetitive (Wilkins, Cleave, Grayson, & Wilson, 2009) for rapid reading.

The above review suggests that the patterns formed by the lines of text and the strokes of letters can be aversive, and even epileptogenic.

In the 1980s there were anecdotal reports of children who

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experienced perceptual distortion of text. Their reading sometimes improved when using coloured filters (Meares, 1980; Irlen, 1983). The anecdotes had a certain credence because of the isolated reports of individuals with photosensitive epilepsy who have been successfully treated using variously coloured glasses (Newmark & Penry, 1979).

The literature on the perceptual distortion and discomfort that can interfere with reading is now extensive. The condition is known variously as Scotopic Sensitivity Syndrome/SSS/Irlen syndrome/Meares-Irlen syndrome/visual stress/pattern-related visual stress. Initially Irlen named the perceptual disorder *Scotopic Sensitivity Syndrome* (but with no evidence that the condition was due to rod vision). She later used the term *Irlen syndrome*. She developed a set of tests and ophthalmic filters marketed by Irlen diagnosticians from the Irlen centres she set up largely independently of conventional ophthalmic care. Irlen's techniques are proprietary. They have not been fully described in the scientific literature, and they remain controversial (Ritchie, Della Sala, & McIntosh, 2011). Attempts to evaluate her treatment have had mixed findings, largely negative (Robinson and Foreman, 1999; Griffiths et al., 2016).

As the various names might suggest, there is disagreement as to the nature of any pathophysiology, and even its existence. SSS was conceived as visual disturbance of reading whereas visual stress refers to visually-induced distortion and visual discomfort more generally.

Irlen's reports (Irlen, 1983) prompted Wilkins to invent a means of investigating the effects of colour on perceptual distortion. He designed the *Intuitive Colorimeter* in 1990 (Wilkins et al., 1992); initially as a research tool. It has undergone development since 1990 and now provides a spectral power distribution of light similar to that when tinted lenses are worn under conventional lighting (Wilkins & Sihra, 2001). It illuminates text with coloured light and allows the separate control of hue and saturation at one of three constant luminance levels. Some individuals with reading difficulty and perceptual distortion of text were able to find a chromaticity of illumination that reliably reduced the distortions they habitually experienced under white light (Wilkins, Nimmo-Smith, & Jansons, 1992). Filters were developed that provided the chosen chromaticity under conventional lighting (Wilkins, 1996). Following preliminary observations (Wilkins et al., 1992; Wilkins et al., 1992) a double-masked trial was conducted in 1993 (Wilkins, Jeanes, Pumfrey, & Laskier, 1996). Ophthalmic filters designed to match the optimal colorimeter setting were compared with others matching a suboptimal setting (differing in CIE Uniform Chromaticity Scale (UCS) chromaticity by an average of 0.06) and the optimal filters were shown to be associated with a greater reduction in the incidence of headaches and eyestrain. The colorimeter and filters were then introduced into clinical practice, initially in the UK and subsequently worldwide. They were used to treat a condition initially termed *Meares-Irlen syndrome* and later *visual stress*. To quantify the effects of the filters on reading, Wilkins introduced a Rate of Reading test (Gilchrist et al., 2021; Evans and Allen, 2016) in which a paragraph of randomly ordered common words is read aloud. The test demonstrated an increase in reading speed with specific individually chosen colours (Wilkins et al., 1996). The test is sensitive to the visual demands of reading but does not measure comprehension (Gilchrist, Allen, Monger, Srinivasan, & Wilkins, 2021).

The use of coloured filters in the treatment of reading difficulty remains contentious, with systematic reviews arriving at opposite conclusions (Griffiths et al., 2016; Evans and Allen, 2016). The Irlen method seems likely to over-diagnose. In a study by Richie et al. (Ritchie et al., 2011); 61 children with reading difficulties aged 7–12 were examined by an Irlen diagnostician who diagnosed Irlen syndrome in 44 (72 %). It is now thought that only a minority of individuals with reading difficulty have visual stress (Wilkins, Allen, Monger, & Gilchrist, 2016). The Irlen diagnosis therefore differs importantly from that of visual stress, which is recognised by a set of criteria listed in a Delphi study (Evans, Allen, & Wilkins, 2017). The criteria include an increase of at least 15 % in reading rate with the chosen colour (Evans et al., 2017). These criteria are under evaluation in a randomised controlled trial (in preparation).

There are many studies that have used various attempts at placebo control (Evans & Allen, 2016); but none is wholly satisfactory. Grey tints are generally ineffective but can be readily distinguished from those of other colours and are therefore unlikely to be a convincing control. Other colours may not be inactive, as placebos are required to be. One approach has been to use the Intuitive Colorimeter and to find a colour of light for each individual that is reliably associated with a reduction of perceptual distortion of text, preferably under conditions in which the eyes are colour-adapted and the patient is unaware of the saturation (Wilkins et al., 1994). In symptomatic patients such adjustments are quite repeatable (Aldrich, Lovell-Patel, Allen, & Wilkins, 2018). Tints with this colour can be compared with another colour with which distortions just appear, typically with a UCS chromaticity difference of at least 0.06 (Wilkins et al., 1994). Such an approach was used in the double-masked study described above (Wilkins et al., 1994). The study showed a difference between optimal and suboptimal filters, but did not necessarily provide a comparison with an inactive placebo. The requirement for the suboptimal comparison filter to be similar in colour to the optimal filter in order to control for the placebo effect means that the real-world benefit from the optimal filter may be underestimated. An extreme example of this bias is a recent study (Suttle & Conway, 2024) in which the suboptimal filters selected were very similar to the optimal filters in colour (in fact within the limits of the repeatability of measurement (Aldrich et al., 2018; Wilkins et al., 2005). Both filters were likely to generate a similar treatment effect, and there was therefore no appropriate control or reasonable expectation of demonstrating a treatment effect (Suttle and Conway, , 2024; Wilkins, 2024). Any demonstration of the efficacy of coloured filters requires further convergent evidence from a variety of approaches. One possibility is to seek a physiological mechanism, and the remainder of this review presents such a mechanism.

2. Differences between comfortable and uncomfortable images

Images from nature, despite their heterogeneity, have in common certain statistical features that enable them to be encoded efficiently by cortical neurons. The relative contrast energy of a natural image remains approximately the same at all spatial scales (Field, 1987; Pentland, 1984). This feature can be characterized in terms of the Fourier amplitude spectrum. Natural images tend to have characteristic frequency spectra in which amplitude falls with increasing spatial frequency, f, and on average varies roughly as 1/f (Field, 1987). Because the bandwidth of spatial frequency channels remains constant when expressed on an octave scale, a similar amount of information is carried by each channel. Field (Field, 1987) argued that this is optimum for the 1/f amplitude spectrum of images from nature. The contrast sensitivity is low (the channel has low gain) for low spatial frequencies that have a high amplitude, and this conserves metabolic energy. The sensitivity increases as the amplitude decreases to a point where the signal to-noise ratio is low, and then falls at high spatial frequencies when the signal can no longer be discriminated from noise reliably. Atick and Redlich (Atick & Redlich, 1992) argued that this enables images with a 1/f amplitude spectrum to be coded efficiently. The coding of other images is expected to be less efficient, evoking non-sparse responses.

The receptive fields of neurons in the primary visual cortex are such that images with 1/f amplitude spectrum would produce a sparse cortical response (Atick and Redlich, 1992; Olshausen and Field, 1996; Simoncelli and Olshausen, 2001). The defining characteristic of this sparse response is that few neurons are active and many are quiescent, thereby reducing metabolic demand (Attwell & Laughlin, 2001). It is of obvious importance to minimise energy metabolism given that the brain uses about one fifth of the body's energy, even though few of its neurons are firing at any one time (Lennie, 2000).

There is a relationship between image structure and visual discomfort. Fernandez and Wilkins (Fernandez & Wilkins, 2008) asked observers to rate discomfort from a range of images including works of art and photographs. Comfortable images showed the 1/f amplitude spectrum common in natural scenes, whereas uncomfortable images showed a regression with disproportionately greater amplitude at spatial frequencies near 3 cycles deg^{-1}, a spatial frequency at which gratings induce perceptual distortion (Wilkins et al., 1984). Juricevic et al. (Juricevic, Land, Wilkins, & Webster, 2010) generated images from filtered visual noise and again demonstrated that discomfort increases with deviations from the spatial properties of natural scenes. Penacchio and Wilkins (Penacchio & Wilkins, 2015) used two-dimensional Fourier analysis thereby including the orientational properties of the images. From a wide variety of images, they were able to explain an average of 27 % of the variance in judgements of discomfort simply from the image luminance structure and the degree of its adherence to 1/f.

The above findings are consistent with the behaviour of a computational model of the visual cortex (Penacchio, Haigh, Ross, Ferguson, & Wilkins, 2021). Visual stimuli that have been rated as uncomfortable to look at give rise to a less sparse activation, and overall activation increases. The visual discomfort can therefore be seen as part of a homeostatic mechanism to reduce hypermetabolism (Wilkins & Hibbard, 2014).

The images that are capable of inducing seizures in patients with photosensitive epilepsy are those with Fourier amplitude spectra that maximally depart from 1/f, suggesting that the seizures arise as the result of a large neural response. (A role for the synchronisation of this response can be inferred from the effects of moving patterns (Binnie, Findlay, & Wilkins, 1985) but this need not concern us here).

The relationship between image structure, metabolism, discomfort and seizures applies not only to luminance variation but also to variation in colour. Images with large and un-natural colour contrasts are generally uncomfortable. Haigh et al. (Haigh et al., 2013) presented gratings with various colour contrasts and showed that ratings of discomfort increased with the difference in the component UCS chromaticities. Penacchio et al. (Penacchio et al., 2021) showed that for more complex images (works of art) discomfort increased with the average difference in UCS chromaticity between neighbouring pixels. The difference in chromaticity was large in uncomfortable stimuli compared to that typical in natural scenes, consistent with the earlier findings of Juricevic et al. (Juricevic et al., 2010) and, incidentally, also consistent with the effects of coloured flicker on seizure risk (Haigh, Cooper, & Wilkins, 2018).

As might be anticipated from the above, uncomfortable images are associated with greater energy metabolism. Images with repetitive structure such as certain building frontages are judged uncomfortable and give a large cortical haemodynamic response (Le et al., 2017); as do simpler uncomfortable patterns of stripes (unidimensional gratings) (Haigh et al., 2013). When the stripes are coloured the size of the cortical haemodynamic response depends upon the difference in UCS chromaticity: the larger the difference in chromaticity, the greater the response (Haigh et al., 2013).

In summary, certain stimuli that have an un-natural spatial and chromatic structure are uncomfortable, consistent with suggestions from computational neurology that they are processed inefficiently. They give rise to a large neural response, which can on occasions trigger seizures.

3. Differences between individuals

When healthy individuals are asked to observe epileptogenic grating patterns, some report discomfort and perceptual illusions referred to as *pattern glare* (Wilkins & Evans, 2010). Other individuals find the patterns quite innocuous (Wilkins et al., 1984). In the Pattern Glare Test an observer is simply asked to list the distortions seen in the pattern. The number listed and the discomfort evoked provide a measure of the individual observer's susceptibility (Monger, Wilkins, & Allen, 2015). Such uncomfortable patterns have little effect on accommodation (Haigh, Jaschinski, Allen, & Wilkins, 2013) even though individuals with visual stress generally have slightly weak accommodation (Allen, Hussain, Usherwood, & Wilkins, 2010). Despite this, the illusions and distortions depend simply on the spatial frequency and are independent of viewing distance (Monger, Shah, Wilkins, & Allen, 2016).

The individuals who are particularly susceptible to the illusions and discomfort report relatively frequent headaches, and many of the headaches would be classified as migraine (Wilkins et al., 1984). The behaviour of the computational model of the visual cortex referred to above shows that the greater susceptibility of some observers can be modelled by a reduced cortical inhibition (Penacchio et al., 2021). The illusions may result from an inappropriate firing of cortical neurons due to a spread of cortical activation, reflecting a failure of cortical inhibition and a resultant cortical hyperexcitability (Wilkins et al., 1984).

There is other convergent evidence that the cortex is hyperexcitable in migraine (Aurora and Wilkinson, 2007; Coppola et al., 2021; Chen et al., 2011). Individuals with migraine are particularly susceptible to sensory illusions, not only visual but auditory (Brighina et al., 2015). They show an aversion to epileptogenic patterns at a lower contrast than occurs in healthy observers (Haigh, Chamanzar, Grover, & Behrmann, 2019) and an atypically large BOLD fMRI response to such patterns (Huang, Cooper, Satana, Kaufman, & Cao, 2003).

In summary, there are large differences in the susceptibility of individuals to discomfort from images, and these differences are often associated with headache and migraine and may reflect a cortical excitability.

4. Effect of colour on discomfort and hypermetabolism

There are many studies that have investigated the use of coloured filters to reduce discomfort when reading. There have been several extensive reviews usually of individuals diagnosed with dyslexia rather than simply with visual stress. Visual stress and perceptual distortion are not a common cause of reading difficulty and filters are not an effective treatment for dyslexia in general (Griffiths, Taylor, Henderson, & Barrett, 2016). However, the increase in reading rate with a filter has been confirmed in studies of visual stress (Evans & Allen, 2016). For example, in a study by Monger et al. (Monger et al., 2015) a substantial proportion of university undergraduates with full refractive correction reported that an individually chosen coloured filter overlaid on the text made it easier and more comfortable to read. The chromaticity chosen was reliable at re-test by a different examiner. A third examiner presented gratings that increased progressively in contrast. The threshold contrast at which discomfort (pattern glare) was first reported was lower in the students who reported greater comfort with an overlay. A fourth examiner measured the speed with which randomly ordered common words could be read aloud with and without the chosen overlay. The speed was greater with the overlay in those who reported increased comfort.

Any coloured filter will necessarily increase the contrast between some coloured surfaces and reduce the contrast between others. If a coloured lens is strongly saturated the contrast is likely to be reduced more often than it will be increased because of restrictions on the gamut. This might be expected to reduce discomfort, given the effect of colour difference on both discomfort and cortical metabolism reviewed above. If the scene is text, however, the ratio of brightness between white and black surfaces (the physical contrast) is not obviously affected by a coloured lens. Brightness contrast is transduced by a neural signal resulting from the energy captured by long- and middle-wavelength cones. It is possible that this signal is affected when one or both cone classes are adapted in an atypical way, as when the illumination has a chromaticity that departs from the daylight locus. Near infrared spectroscopy provides a convenient measure of the haemodynamic response of the visual cortex, and can evidently provide an objective correlate of visual discomfort (Haigh et al., 2013; Le et al., 2017). It would be interesting to use this technique to study the response to contrast variation under illumination with atypical chromaticities, given that pattern glare can sometimes be reduced when the gratings are appropriately

Fig. 1. Powerful patterns in architecture. The grating has the spatial properties sufficient to induce distortions, headaches and even seizures.

coloured (Monger et al., 2015).

Tinted lenses with a colour selected individually to reduce discomfort have been reported beneficial in a wide range of neurological disorders, including photosensitive epilepsy, autism spectrum disorder, head injury and migraine with aura (Wilkins, Arnold, Evans, & Plant, 2022). Many of these disorders are co-morbid with epilepsy and the cortex may be hyperexcitable. After head injury, individually chosen tints have been reported to increase reading speed (Wilkins et al., 2022). In autism spectrum disorder they have been reported to improve not only reading speed but the recognition of the facial expression of emotion (Ludlow et al., 2020). In migraine with aura they increase the speed of visual search (Vieira, van der Linde, Bright, & Wilkins, 2020) and normalise the otherwise abnormally large fMRI-BOLD response to visual patterns that occurs in anterior visual areas of the brain (Huang et al., 2003). Photophobia is common in all these conditions and the detriment to visual performance is consistent with a non-optimised representation in the visual cortex.

Given the above, it seems that the most parsimonious interpretation of the effects of colour on visual discomfort should be sought in cortical rather than retinal mechanisms. In patients with photosensitive epilepsy there are often differences in the excitability of the two cerebral hemispheres (Wilkins, Binnie, & Darby, 1981); even when the epilepsy is *primary generalised.* Some patients are sensitive only to grating patterns in a particular orientation (Wilkins, Darby, & Binnie, 1979). This suggests that any cortical excitability can be patchy rather than diffuse and uniform. In visual area V2, neurons coding for colour are disposed on the cortical surface so that the representation of colour is much like that in the CIE Uniform chromaticity diagram (Xiao, Wang, & Felleman, 2003). It is therefore possible that coloured filters change the distribution of cortical excitation, thus avoiding locally hyperexcitable areas. Colour and orientation are jointly coded and spatially organized in primate primary visual cortex (Garg, Li, Rashid, & Callaway, 2019); so the effects of tints on spatial vision are to be expected.

The mechanisms may not be exclusively cortical. There are large differences between people in the proportions of photoreceptors: the L:M ratio varies among normal trichromats from 1:1 to 1:16.5 (Hofer, Carroll, Neitz, Neitz, & Williams, 2005). It is possible that these differences are responsible for the differences between people in the colour they find therapeutic. However, the prevalence of visual stress among individuals with anomalous colour vision seems no different from that in the general population, and their choice of colour is not obviously different. No formal surveys have been undertaken, but might be instructive.

Another possible retinal mechanism for the individual differences concerns exposure to fluorescent lighting. Until recently all fluorescent lighting varied in both illuminance and chromaticity twice with each cycle of the electricity supply (Wilkins & Clark, 1990); a variation known to cause headaches and eye-strain (Wilkins, Nimmo-Smith, Slater, & Bedocs, 1989). The electroretinogram has an upper frequency limit of about 200 Hz (Berman, Greenhouse, Bailey, Clear, & Raasch, 1991) which suggests that retinal neurons will necessarily follow the variation in chromaticity of the lighting, and fatigue or adaptation may be a consequence, even resulting in discomfort from certain colours.

Higher frequency temporal variation may also be problematic. Some individuals can see flicker as a pattern during a saccade at flicker frequencies in excess of 11 kHz (Brown, Foulsham, Lee, & Wilkins, 2020); particularly individuals with high velocity saccades (Kang, Lee, Kim, & Pak, 2023). These individuals are more likely to report eyestrain in everyday life (Brown et al., 2020). The repetitive pattern generated during a saccade may interact with the spatial aspects of text, in particular the repetitive patterns of letter strokes that interfere with the correction of vergence following a saccade (Jainta, Jaschinski, & Wilkins, 2010). This may explain why square-wave modulation of light at 600 Hz reduces reading speed, and particularly so in individuals with pattern glare who experience discomfort and distortions from repetitive patterns (Laycox, Thompson, Haggerty, Wilkins, & Haigh, 2024).

The findings listed above are diverse but convergent and suggest a specific underlying pathophysiology: in susceptible individuals (those with a hyperexcitable visual cortex) a strong un-natural excitation of the visual cortex (and the visual system more generally) leads to perceptual distortion, discomfort and ultimately pain and even seizures. Tinted lenses of the appropriate (individually selected) hue and saturation reduce the discomfort, possibly because of a change in the cortical distribution of activation.

5. Future work

Spatially periodic patterns are prevalent in the modern urban environment (see Fig. 1), particularly in architecture and text. The distortions and discomfort they evoke are clearly related one to the other, but their role in the provocation and prevention of headache and photophobia has yet to be clinically elucidated. A full explanation of the mechanisms whereby discomfort is reduced by coloured filters may only be possible when the individual differences in choice of comfortable colour can be predicted from other independent measures of visual function.

CRediT authorship contribution statement

Arnold J. Wilkins: Writing – review & editing, Writing – original draft, Conceptualization.

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Data availability

No data was used for the research described in the article.

References

Aldrich, A., Lovell-Patel, R., Allen, P., & Wilkins, A. (2018). The Repeatability of Colorimetry is Precise(ly) as Expected. *Neuro-Ophthalmology & Visual Neuroscience, 3* (1), 1–6. https://doi.org/10.12691/novn-3-1-1

Allen, P. M., Hussain, A., Usherwood, C., & Wilkins, A. J. (2010). Pattern-related visual stress, chromaticity, and accommodation. *Investigative Ophthalmology & Visual Science, 51*(12), 6843–6849. https://doi.org/10.1167/iovs.09-5086. Epub 2010 Jul 7 PMID: 20610842.

Atick, J. J., & Redlich, A. N. (1992). What does the retina know about natural scenes? *Neural Computation, 4*, 196–210.

Attwell, D., & Laughlin, S. B. (2001). An energy budget for signaling in the grey matter of the brain. *Journal of Cerebral Blood Flow and Metabolism, 21*(10), 1133–1145. https://doi.org/10.1097/00004647-200110000-00001. PMID: 11598490.

Aurora, S. K., & Wilkinson, F. (2007). The brain is hyperexcitable in migraine. *Cephalalgia, 27*(12), 1442–1453. https://doi.org/10.1111/j.1468-2982.2007.01502.x. PMID: 18034688.

Berman, S. M., Greenhouse, D. S., Bailey, I. L., Clear, R. D., & Raasch, T. W. (1991). Human electroretinogram responses to video displays, fluorescent lighting, and other high frequency sources. *Optometry and Vision Science, 68*(8), 645–662. https://doi.org/10.1097/00006324-199108000-00012. PMID: 1923343.

Binnie, C. D., Findlay, J., & Wilkins, A. J. (1985). Mechanisms of epileptogenesis in photosensitive epilepsy implied by the effects of moving patterns. *Electroencephalography and Clinical Neurophysiology, 61*(1), 1–6. https://doi.org/10.1016/0013-4694(85)91065-x. PMID: 2408857.

Brighina, F., Bolognini, N., Cosentino, G., Maccora, S., Paladino, P., Baschi, R., … Fierro, B. (2015). Visual cortex hyperexcitability in migraine in response to sound-induced flash illusions. *Neurology, 84*(20), 2057–2061. https://doi.org/10.1212/WNL.0000000000001584. Epub 2015 Apr 17. Erratum in: Neurology. 2016;86(12):1172. doi: 10.1212/WNL.0000000000002557. PMID: 25888559.

Brown, E., Foulsham, T., Lee, C., & Wilkins, A. (2020). Research Note: Visibility of temporal light artefact from flicker at 11 kHz. *Lighting Research & Technology, 52*(3), 371–376. https://doi.org/10.1177/1477153519852391

Chen, W. T., Lin, Y. Y., Fuh, J. L., Hämäläinen, M. S., Ko, Y. C., & Wang, S. J. (2011). Sustained visual cortex hyperexcitability in migraine with persistent visual aura. *Brain, 134*(Pt 8), 2387–2395. https://doi.org/10.1093/brain/awr157. Epub 2011 Jul 4 PMID: 21729907.

Coppola, G., Pierelli, F., Schoenen, J., Wang, S.-J., & Chen, W.-T. (2021). Neurophysiological model of migraine pathophysiology: Bringing the past into the future. *Neurophysiology of the Migraine Brain, 223–236*. https://doi.org/10.1007/978-3-030-56538-1_17

Evans, B. J., & Allen, P. M. (2016). A systematic review of controlled trials on visual stress using Intuitive Overlays or the Intuitive Colorimeter. *Journal of Optometry, 9* (4), 205–218. https://doi.org/10.1016/j.optom.2016.04.002. Epub 2016 Jul 11. PMID: 27425262; PMCID: PMC5030324.

Evans, B. J. W., Allen, P. M., & Wilkins, A. J. (2017). A Delphi study to develop practical diagnostic guidelines for visual stress (pattern-related visual stress). *Journal of Optometry, 10*(3), 161–168. https://doi.org/10.1016/j.optom.2016.08.002. Epub 2016 Nov 24. PMID: 27890547; PMCID: PMC5484780.

Fernandez, D., & Wilkins, A. J. (2008). Uncomfortable images in art and nature. *Perception, 37*(7), 1098–1113. https://doi.org/10.1068/p5814. PMID: 18773732; PMCID: PMC2581924.

Field, D. J. (1987). Relations between the statistics of natural images and the response properties of cortical cells. *Journal of the Optical Society of America. A, 4*(12), 2379–2394. https://doi.org/10.1364/josaa.4.002379. PMID: 3430225.

Garg, A. K., Li, P., Rashid, M. S., & Callaway, E. M. (2019). Color and orientation are jointly coded and spatially organized in primate primary visual cortex. *Science, 364* (6447), 1275–1279. https://doi.org/10.1126/science.aaw5868. PMID: 31249057; PMCID: PMC6689325.

Gilchrist, J. M., Allen, P. M., Monger, L., Srinivasan, K., & Wilkins, A. (2021). Precision, reliability and application of the Wilkins Rate of Reading Test. *Ophthalmic & Physiological Optics, 41*(6), 1198–1208. https://doi.org/10.1111/opo.12894. Epub 2021 Sep 29 PMID: 34585769.

Griffiths, P. G., Taylor, R. H., Henderson, L. M., & Barrett, B. T. (2016). The effect of coloured overlays and lenses on reading: A systematic review of the literature. *Ophthalmic & Physiological Optics, 36*(5), 519–544. https://doi.org/10.1111/opo.12316. PMID: 27580753.

Haigh, S. M., Jaschinski, W., Allen, P. M., & Wilkins, A. J. (2013). Accommodation to uncomfortable patterns. *Perception, 42*(2), 208–222. https://doi.org/10.1068/p7397. PMID: 23700959.

Haigh, S. M., Barningham, L., Berntsen, M., Coutts, L. V., Hobbs, E. S., Irabor, J., … Wilkins, A. J. (2013). Discomfort and the cortical haemodynamic response to coloured gratings. *Vision Research, 30*(89), 47–53. https://doi.org/10.1016/j.visres.2013.07.003. Epub 2013 Jul 15 PMID: 23867567.

Haigh, S. M., Cooper, N. R., & Wilkins, A. J. (2018). Chromaticity separation and the alpha response. *Neuropsychologia, 8*(108), 1–5. https://doi.org/10.1016/j.neuropsychologia.2017.11.020. Epub 2017 Nov 20 PMID: 29157999.

Haigh, S. M., Chamanzar, A., Grover, P., & Behrmann, M. (2019). Cortical hyper-excitability in migraine in response to chromatic patterns. *Headache, 59*(10), 1773–1787. https://doi.org/10.1111/head.13620. Epub 2019 Aug 27 PMID: 31454074.

Harding, G. F. A., & Jeavons, P. M. (1994). *Photosensitive epilepsy*. Cambridge University Press.

Hofer, H., Carroll, J., Neitz, J., Neitz, M., & Williams, D. R. (2005). Organization of the human trichromatic cone mosaic. *The Journal of Neuroscience, 25*(42), 9669–9679. https://doi.org/10.1523/JNEUROSCI.2414-05.2005. Erratum. In: J Neurosci. 2006 Jan 11;26(2):722. PMID: 16237171; PMCID: PMC6725723.

Huang, J., Cooper, T. G., Satana, B., Kaufman, D. I., & Cao, Y. (2003). Visual distortion provoked by a stimulus in migraine associated with hyperneuronal activity. *Headache, 43*(6), 664–671. https://doi.org/10.1046/j.1526-4610.2003.03110.x. PMID: 12786927.

Hughes, L. E., Wilkins, & Arnold, J. (2000). Typography in children's reading schemes may be suboptimal: evidence from measures of reading rate. *Journal of Research in Reading, 23*, 314–324.

Irlen, H. (1983). Successful treatment of reading difficulties. In Annual Convention of the American Psychological Association.

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. https://doi.org/10.1167/10.13.2. PMID: 21149306.

Juricevic, I., Land, L., Wilkins, A., & Webster, M. A. (2010). Visual discomfort and natural image statistics. *Perception, 39*(7), 884–899. https://doi.org/10.1068/p6656. PMID: 20842966; PMCID: PMC2941908.

Kang, H., Lee, C. S., Kim, J. G., & Pak, H. (2023). Saccadic eye movement speed is related to variations in phantom array effect visibility. *Science Reports, 13*, 11576. https://doi.org/10.1038/s41598-023-38477-z

Laycox, C. A., Thompson, R., Haggerty, J. A., Wilkins, A. J., & Haigh, S. M. (2024). Flicker and reading speed: Effects on individuals with visual sensitivity. *Perception, 53*(8), 512–528. https://doi.org/10.1177/03010066241252066. Epub 2024 May 6 PMID: 38711325.

Le, A. T., Payne, J. R., Clarke, C. L., Kelly, M. A., Prudenziati, F., Armsby, E., … Wilkins, A. J. (2017). Discomfort from urban scenes: Metabolic consequences. *Landscape and Urban Planning, 160*, 61–68. https://doi.org/10.1016/j.landurbplan.2016.12.003

Lennie, P. (2000). Color vision: Putting it together. *Current Biology, 10*(16), R589–R591. https://doi.org/10.1016/s0960-9822(00)00632-1. PMID: 10985374.

Ludlow, A. K., Giannadou, A., Franklin, A., Allen, P. M., Simmons, D. R., & Wilkins, A. J. (2020). The possible use of precision tinted lenses to improve social cognition in children with autism spectrum disorders. *Vision Research, 170*, 53–59. https://doi.org/10.1016/j.visres.2020.03.007. Epub 2020 Apr 4 PMID: 32259647.

Meares, O. (1980). Figure/background, brightness/contrast and reading disabilities. *Visible Language, 14*, 13–29.

Miller, S., Razvi, S., & Russell, A. (2010). Reading epilepsy. *Practical Neurology, 10*(5), 278–281. https://doi.org/10.1136/jnnp.2010.217786. PMID: 20858629.

Monger, L. J., Wilkins, A. J., & Allen, P. M. (2015). Pattern glare: The effects of contrast and color. *Frontiers in Psychology, 27*(6), 1651. https://doi.org/10.3389/fpsyg.2015.01651. PMID: 26579034; PMCID: PMC4621622.

Monger, L. J., Shah, D., Wilkins, A. J., & Allen, P. M. (2016). The effect of viewing distance on responses to the pattern glare test. *Clinical & Experimental Optometry, 99*(1), 47–50. https://doi.org/10.1111/cxo.12364. PMID: 26875852.

Newmark, M. E., & Penry, J. K. (1979). *Photosensitivity and epilepsy: A review*. New York: Raven Press.

Olshausen, B., & Field, D. (1996). Natural image statistics and efficient coding. *Network: Computation in Neural Systems*. https://doi.org/10.1088/0954-898x/7/2/014

Penacchio, O., Haigh, S. M., Ross, X., Ferguson, R., & Wilkins, A. J. (2021). Visual discomfort and variations in chromaticity in art and nature. *Frontiers in Neuroscience, 20*(15), Article 711064. https://doi.org/10.3389/fnins.2021.711064. PMID: 34987354; PMCID: PMC8720932.

Penacchio, O., & Wilkins, A. J. (2015). Visual discomfort and the spatial distribution of Fourier energy. *Vision Research, 108*, 1–7.

Pentland, A. P. (1984). Fractal-based description of natural scenes. *IEEE Transactions on Pattern Analysis and Machine Intelligence, PAMI-6*, 661–674.

Ritchie, S. J., Della Sala, S., & McIntosh, R. D. (2011). Irlen colored overlays do not alleviate reading difficulties. *Pediatrics, 128*(4), e932–e938. https://doi.org/10.1542/peds.2011-0314. Epub 2011 Sep 19 PMID: 21930551.

Robinson, G. L., & Foreman, P. J. (1999). Scotopic sensitivity/Irlen syndrome and the use of coloured filters: A long-term placebo controlled and masked study of reading achievement and perception of ability. *Perceptual and Motor Skills, 89*(1), 83–113. https://doi.org/10.2466/pms.1999.89.1.83. PMID: 10544403.

Simoncelli, E. P., & Olshausen, B. A. (2001). Natural image statistics and neural representation. *Annual Review of Neuroscience Preprint at*. https://doi.org/10.1146/annurev.neuro.24.1.1193

Suttle, C. M., & Conway, M. L. (2024). Efficacy of coloured lenses for patients diagnosed with visual stress. *Clinical and Experimental Optometry*. https://doi.org/10.1080/08164622.2024.2302822

Vieira, A., van der Linde, I., Bright, P., & Wilkins, A. (2020). Preference for lighting chromaticity in migraine with aura. *Headache, 60*(6), 1124–1131. https://doi.org/10.1111/head.13801. Epub 2020 Apr 13 PMID: 32282067.

Weaver, D. F. (2014). Font specific reading-induced seizures. *Clinical Neurology and Neurosurgery, 125*, 210–211. https://doi.org/10.1016/j.clineuro.2014.07.035. Epub 2014 Aug 20 PMID: 25178914.

Wilkins, A. J. (1995). *Visual stress*. Oxford University Press.

Wilkins, A. J. (1996). A system for precision ophthalmic tinting and its role in the treatment of visual stress. In C. M. Dickinson, I. J. Murray, & D. Garden (Eds.), *John Dalton's Colour Vision Legacy* (pp. 695–708). London: Taylor and Francis.

Wilkins, A. J. (2024). Re: Efficacy of coloured lenses for patients diagnosed with visual stress. *Clinical and Experimental Optometry, 1–2*. https://doi.org/10.1080/08164622.2024.2372394

Wilkins, A. J., Allen, P. M., Monger, L., & Gilchrist, J. (2016). Visual stress and dyslexia for the practising optometrist. *Optometry Practice, 17*(2), 103–112.

Wilkins, Arnold, J., Evans, B. J., & Plant, G. T. (2022). Potential uses for precision tinted lenses in a neurology clinic. *touchREVIEWS Neurology, 18*(2), 93–102. https://doi.org/10.17925/USN.2022.18.2.93

Wilkins, A. J., & Clark, C. (1990). Modulation from fluorescent lamps. *Lighting Research and Technology, 22*(2), 103–109.

Wilkins, A. J., Binnie, C. D., & Darby, C. E. (1980). Visually-induced seizures. *Progress in Neurobiology, 15*(2), 85–117. https://doi.org/10.1016/0301-0082(80)90004-0. PMID: 6779350.

Wilkins, A. J., Binnie, C. D., & Darby, C. E. (1981). Interhemispheric differences in photosensitive epilepsy. I. Pattern sensitivity thresholds. *Electroencephalography and Clinical Neurophysiology, 52*(5), 461–468. https://doi.org/10.1016/0013-4694(81)90030-4. PMID: 6171412.

Wilkins, A., Nimmo-Smith, I., Tait, A., McManus, C., Della Sala, S., Tilley, A., … Scott, S. (1984). A neurological basis for visual discomfort. *Brain, 107*(Pt 4), 989–1017. https://doi.org/10.1093/brain/107.4.989. PMID: 6509314.

Wilkins, A., Milroy, R., Nimmo-Smith, I., Wright, A., Tyrrell, R., Holland, K., … Noakes, T. (1992). Preliminary observations concerning treatment of visual discomfort and associated perceptual distortion. *Ophthalmic & Physiological Optics, 12*(2), 257–263. https://doi.org/10.1111/j.1475-1313.1992.tb00302.x. PMID: 1408185.

Wilkins, A., Cleave, R., Grayson, N., & Wilson, L. (2009). Typography for children may be inappropriately designed. *Journal of Research in Reading, 32*.

Wilkins, A. J., Darby, C. E., & Binnie, C. D. (1979). Neurophysiological aspects of pattern-sensitive epilepsy. *Brain, 102*(1), 1–25. https://doi.org/10.1093/brain/102.1.1. PMID: 106922.

Wilkins, A. J., & Hibbard, P. B. (2014). Discomfort and hypermetabolism. *AISB 2014–50th Annual Convention of the AISB*.

Wilkins, A. J., & Nimmo-Smith, M. I. (1987). The clarity and comfort of printed text. *Ergonomics, 30*(12), 1705–1720. https://doi.org/10.1080/00140138708966059. PMID: 3443093.

Wilkins, A. J., Nimmo-Smith, I., & Jansons, J. E. (1992). Colorimeter for the intuitive manipulation of hue and saturation and its role in the study of perceptual distortion. *Ophthalmic & Physiological Optics, 12*(3), 381–385. PMID: 1454378.

Wilkins, A. J., Nimmo-Smith, I. M., Slater, A., & Bedocs, L. (1989). Fluorescent lighting, headaches and eye-strain. *Lighting Research and Technology, 21*(1), 11–18.

Wilkins, A. J., & Sihra, N. (2001). A colorizer for use in determining an optimal ophthalmic tint. *Color Research and Application, 26*, 246–253. https://doi.org/10.1002/col.1022

Wilkins, A. J., Evans, B. J., Brown, J. A., Busby, A. E., Wingfield, A. E., Jeanes, R. J., & Bald, J. (1994). Double-masked placebo-controlled trial of precision spectral filters in children who use coloured overlays. *Ophthalmic & Physiological Optics, 14*(4), 365–370. PMID: 7845693.

Wilkins, A. J., & Evans, B. J. W. (2010). *Pattern Glare Test. ioo sales*. Newington Causeway, London: Institute of Optometry.

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 & Physiological Optics, 16*, 491–497.

Wilkins, A. J., Sihra, N., & Myers, A. (2005). Increasing reading speed by using colours: Issues concerning reliability and specificity, and their theoretical and practical implications. *Perception, 34*(1), 109–120. https://doi.org/10.1068/p5045. PMID: 15773610.

Wilkins, A. J., Smith, J., Willison, C. K., Beare, T., Boyd, A., Hardy, G., … Harper, S. (2007). Stripes within words affect reading. *Perception, 36*(12), 1788–1803. https://doi.org/10.1068/p5651

Wilkins, A., Smith, K., & Penacchio, O. (2020). The influence of typography on algorithms that predict the speed and comfort of reading. *Vision (Basel), 4*(1), 18. https://doi.org/10.3390/vision4010018. PMID: 32178260; PMCID: PMC7175152.

Xiao, Y., Wang, Y., & Felleman, D. J. (2003). A spatially organized representation of colour in macaque cortical area V2. *Nature, 421*(6922), 535–539. https://doi.org/10.1038/nature01372