Br Ir Orthopt J 2012; **9:** 3–8

Why do words jump? An exploration of visually symptomatic readers

NADIA NORTHWAY PhD BA DBO

Department of Life Sciences, Glasgow Caledonian University, Glasgow

Abstract

Aim: **To provide an insight into the current issues in assessing visually symptomatic readers and the role of the orthoptist in the management of these patients.**
Methods: **A literature-based review was undertaken to investigate the assessment of patients presenting with visual symptoms associated with reading. Areas related to binocular vision and visual stress, visual discomfort and illusions are covered. The importance of differentiating between the correction of visual discomfort and the correction of dyslexia is also highlighted.**
Results: **Visual symptoms associated with reading are common, particularly in struggling readers, and the incidence of binocular vision anomalies in these patients is high. An evidence base spanning more than 40 years has demonstrated that binocular vision anomalies are common in those who complain of symptoms when reading and that correction of these anomalies is associated with improvement in reading function. The production of visual distortions and discomfort and links with reading have been noted in the literature. The use of colour has also been advocated to reduce visual discomfort associated with reading, and theories of pattern glare, noise exclusion and hyperexcitability are still being pursued to try to improve our understanding of how colour affects visual processing and can reduce symptoms of headache and visual discomfort. In addition binocular vision anomalies and distortion of text known as visual stress can coexist, and differential diagnosis is required when trying to improve visual comfort when reading, thus providing a role for the orthoptist in such cases.**
Conclusions: **Orthoptists can play a vital role in the assessment of visually symptomatic readers and should modify their assessment, as well as considering a range of treatments when assessing visually symptomatic readers. They should, however, be clear that treating visual symptoms is not treatment for dyslexia *per se* but that alleviation of visual symptoms associated with reading can be beneficial to those with reading discomfort and can help those with dyslexia and those without known reading difficulties.**

Key words: Asthenopia, Binocular vision, Coloured lenses, Dyslexia, Symptoms, Visual stress

Correspondence and offprint requests to: Nadia Northway, Department of Life Sciences, Glasgow Caledonian University, Cowcaddens Road, Glasgow G4 0BA. e-mail: n.northway@gcu.ac.uk

Introduction

The cause of reading difficulty is complex and most would agree principally phonological[1] in nature; however, correcting visual functions used for near work may be critical in those with other neurophysiological barriers to reading such as dyslexia, and making the reading process physically more comfortable can be a considerable step towards more successful and comfortable reading. Orthoptists commonly assess asthenopic and visually symptomatic patients. The traditional focus of clinical investigation is on the quality of binocular vision, in particular near point of convergence, accommodation and fusional reserves when symptoms are precipitated by reading. Determining whether the symptoms described by the patients are attributable to poor binocular vision relies on history taking and comparing the results of clinical tests with known normative values. For those with poor binocular vision, such as convergence insufficiency, treatment with orthoptic exercises can be beneficial and successful in alleviating symptoms.[2,3] However, in recent times the use of a range of interventions has been suggested to alleviate headaches and visual symptoms associated with reading. Symptoms typically consist of text moving, blur and distortion, and headaches are typically frontal. The term 'visual stress' has been used to describe these symptoms.[4] Along with traditional optical and orthoptic interventions the use of colour has also been advocated to alleviate symptoms associated with reading. The clinician must be able to differentiate how these symptoms may be arising and advise treatment according to the current evidence base. This review will look at the assessment of visually symptomatic readers and the evidence available to clinicians when determining the aetiology of symptoms associated with reading.

Binocular vision

Evidence supporting the presence of poor binocular vision as a cause of symptoms related to reading is widespread. It has been documented by Stein,[5,6] Stein *et al*.,[6–16] Evans *et al*.[17] and Scott *et al*.[18] that binocular vision anomalies, in particular poor convergence, poor fusional vergence and poorly controlled accommodation, may contribute to some of the difficulties dyslexic readers experience and that these problems can affect the ability to read. If there are problems with binocular vision then the reader may experience blurring of the text, diplopia, movement of the text and ocular fatigue and discomfort, and it is important to treat these aspects of visual difficulty in order to alleviate visual discom-

fort. Northway and Dutton[19] have shown that binocular vision anomalies were present in approximately 50% of adults receiving literacy tuition (this study involved assessment of 108 adult learners of which 65 were treated and followed up for 1 year). In particular, the adult literacy study by Northway and Dutton[19] found 21% of the participants had decompensating heterophoria, 50% had convergence insufficiency and 62% had reduced fusional reserves. These findings are similar to those of Scott *et al*.[18] who studied schoolchildren in Scotland and England in a multicentre trial. In addition many studies have shown that improving binocular vision control does enhance reading ability.[6–16,20–30]

The association of visual symptoms with reading began several decades ago. Dunlop[7,31] reported the concept of the unstable 'reference eye' as a source of jumping text when reading, and the Dunlop reference eye test was developed on the synoptophore. In theory those with an unstable reference eye would report movement of text as they rapidly switched fixation from one eye to the other; however, more recent work has shown that the Dunlop test may not be reliable and there is debate about its efficacy, with Goulandris *et al*.[32] reporting that it is unreliable but Stein *et al*.[7] stating that correct use of the test could identify children who will be less able readers. The treatment of choice if an unstable reference eye is suspected is monocular occlusion. The work of Stein and colleagues[6–16] has demonstrated improved reading in response to the use of monocular occlusion both in isolation and with yellow filters. This research concluded that monocular occlusion stabilises fixation, improves magnocellular function and reduces perceptual distortion when reading. This work dominated the UK orthoptic input to reading difficulty in the1980s; however, these methods are less popular today and the results have not been repeated by other investigators.

For a number of patients, though, treatment of poor binocular vision, poor vergence and unstable fixation may show improved clinical measures but the patient continues to be symptomatic. One such reason may be the presence of accommodative lag.

Accommodative lag and visual discomfort

Because visual discomfort is often associated with near work, new research has examined the role of accommodation dysfunction in discomfort symptoms.[33] Accommodative insufficiency is known to lead to fatigue when reading; however, Chase *et al*.[34] have shown that the common push-up measure of accommodation overestimates accommodative performance. A strong and positive correlation between accommodative lag and visual discomfort symptoms was found under near-work conditions by Chase *et al*.[34] and they concluded that the prevalence of accommodative insufficiency was much higher than estimated by clinical measures when an open field autorefractor was used to assess accommodative lag. Others[35] have aso shown that accommodative lag increases more quickly in visually symptomatic readers, making blur more likely. This, however, has been linked to another visual disorder known as 'visual stress' by Allen *et al*.,[36] who have shown that coloured backgrounds can reduce accommodative lag in visually symptomatic readers and that visual stress may cause accommodative fatigue and inaccuracy. Conversely, it is also possible that accommodative inaccuracy may make the perception of distortion more obvious since blur can enhance the appearance of spatial distortion.[37] These facts suggest that clinical examination should include assessment of accommodative lag, and this can easily be done using dynamic retinoscopy. A variety of techniques are possible but a Modified Nott method has been shown to be reliable and this technique, once mastered, has a range of clinical applications including assessing children with learning difficulties and determining whether patients are reporting genuine blur in suspected malingering. It consists of a retinoscope being placed alongside and as close as possible to a fixation target. The retinoscope reflex is observed while the subject is fixating the target. All the measurements are taken under binocular viewing conditions from the least hypermetropic meridian of the subject's eyes. A 'with' movement indicates a lag of accommodation, and the practitioner moves farther away from the subject to reach a neutral point. An 'against' movement indicates a lead of accommodation, and the practitioner moves closer to the patient to achieve neutrality. The target remains in its original position.[38] More than 1 dioptre of lag is considered to be outwith normal limits and indicates accommodative inaccuracy. Thorough assessment of accommodation should form an essential part of investigating binocular function, and its possible link with visual stress should also be considered in the symptomatic patient. There are, in the author's experience, patients who show increased lag and who do not respond to conventional orthoptic treatment or indeed to a near add, while they still show evidence of lag and visual symptoms persist. In such cases visual stress or pattern glare should be considered as a possible underlying reason for visual symptoms.[36]

Visual stress, pattern glare and using colour

For some people, viewing text can result in the appreciation of a range of visual distortions. There are several hypotheses about why this should occur. Visual stress, pattern glare or visual distortion is a phenomenon that all can experience. Many of us recognise them as visual illusions. Visual illusions such as those seen in the Hermann grid (Fig. 1) can be seen by most people. The explanation suggested is based on neurophysiological findings demonstrating that retinal ganglion cells have an antagonistic centre/surround organisation.[39,40] Consequently, when the grid consists of black squares and white bars, an ON-centre retinal ganglion cell responds much more vigorously to a small bright spot placed in its receptive field centre than to a large bright spot that activates both the centre and the surround of the receptive field. This theory, however, does not account for the fact that the illusion remains regardless of the size of the grid or indeed explains how colour smudges are seen if coloured grids are used. Nor does it explain why some people may be more aware of such effects when viewing text.

Alternative theories linked to cognitive processing in

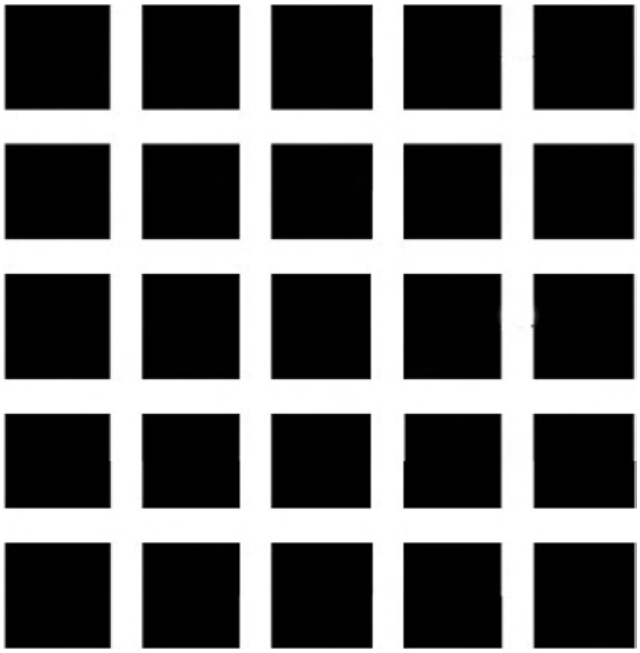

Fig. 1. Hermann grid. When scanning across the squares, grey circles can be seen at the intersection of the black squares and white lines.

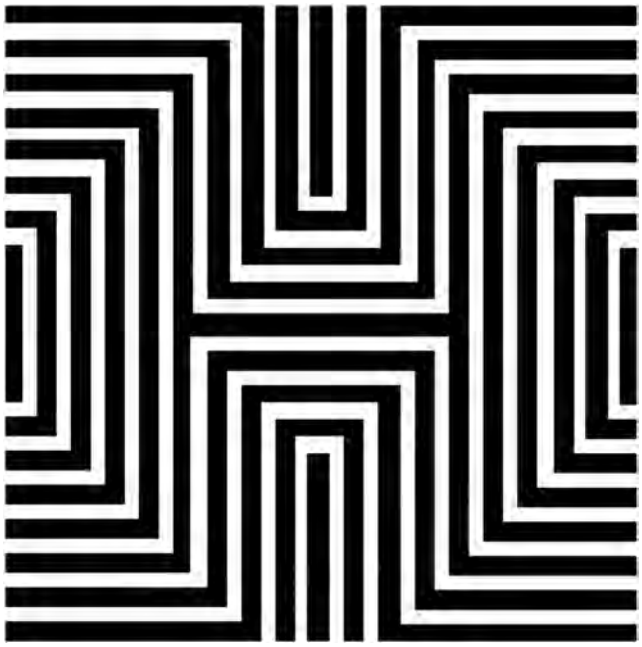

Fig. 2. Patterns in this image give rise to the illusion of movement, and the background and foreground can jump when viewed at the correct viewing distance.

the visual cortex V1 are believed to provide alternative theories of how such phenomena occur.[40] Early psychophysically based data have linked illusions of spatial frequency, orientation and motion to a release of inhibition of specific cell groups,[41–43] suggesting hyperexcitability or overstimulation of the visual cortex. Evidence of the effect of intermediate spatial frequencies was presented by Chronicle and Wilkins,[44] who found that using a square wave with a fundamental spatial frequency of 3–4 cycles/deg as a background resulted in maximum distortion or illusion. An example of a pattern that gives rise to distortion can be seen in Fig. 2. There is also evidence that these distortions are problematic in certain patient groups, particularly those who suffer from photosensitive epilepsy, in whom strong patterns or flicker may result in seizures.[45] In addition, patterns and flicker may induce migraine.[46–48] For some people viewing text can result in the appreciation of a range of visual distortions. It has been shown that the spatial properties of printed text resemble a grating, which may elicit pattern glare in susceptible individuals, and that judgement of clarity is affected by the spatial properties of the text.[47] Wilkins and Nimmo-Smith[49,50] demonstrated that text may appear as patterns of stripes and that these effects were worst when the lines of text were closely spaced; also that certain font types were more unpleasant to look at than others. When text creates visual distortion this is labelled 'scotopic sensitivity' by Irlen,[51] and as Meares-Irlen syndrome (MIS)/visual stress by British eye care professionals paying tribute to Meares[52] who recognised the high prevalence of visual symptoms in poor readers and Helen Irlen's observation that colour could help. The term 'MIS' is used in the field of reading difficulty; however, the terms 'pattern glare' and 'visual stress' tend to be used when discussing headache or other neurological conditions.

In other words the distortions that some people seem aware of when reading text may be a variation of other perceptual phenomena. Using coloured overlays and lenses has been suggested to reduce the visual distortion and symptoms associated with reading[47] and headache.[53] The efficacy of coloured lens therapy in treating the symptoms of MIS was demonstrated in a double-masked placebo trial using Wilkins' Intuitive Colorimeter.[54] With this apparatus the subject views text illuminated by light whose hue, saturation and luminance can be varied independently throughout a large region of colour and optimal tint to reduce visual symptoms. In addition it has been shown that the overlay colour may differ from that chosen for lenses.[55] This is due largely to colour adaptation. On using the Intuitive Colorimeter the subjects rapidly adapt to the colour, and become unaware of exactly what colour they are viewing. The double-masked placebo-controlled trial showed that the benefit from coloured filter therapy in MIS is not solely attributed to a placebo effect. In addition there is a substantial body of research that has shown colour can have positive effects on reading performance and reduce visual discomfort.[56,57] There are, however, critics of this method of treatment who have refuted the need for individual colours or that colour can influence reading.[58–60] However, the methodologies of these studies vary, with some excluding the presence of binocular vision anomalies, hence making comparisons of the studies impossible. More importantly there is confusion regarding the terminology used, some considering the research to be an assessment of the use of colour in dyslexia whilst others consider it to be investigation of the alleviation of visual symptoms associated with uncomfortable reading. It would also seem difficult to determine the efficacy of a coloured overlay if associated visual problems have not been ruled out as a

potential source of symptoms and inefficient reading performance, and many studies fail to do this. Due to the controversy associated with this approach, protocols and standards are advocated by both The British and Irish Orthoptic Society and The College of Optometrists regarding the assessment of visually symptomatic readers, and various sources[19,61] give guidance on the clinical assessment and treatment of visually symptomatic readers.

More recent research has added to our understanding of how colour may influence neurophysiological processing in terms of reading improvements and in migraine. Northway *et al*.[62] have shown that dyslexics with visual stress have poorer visual detection skills when dynamic noise is present. They measured contrast thresholds for discriminating symbols in the absence and presence of visual noise. The results showed that visually symptomatic dyslexics, who otherwise had elevated contrast thresholds for discriminating symbols in visual noise, had thresholds similar to non-dyslexics when wearing coloured filters. These findings provide evidence that in visually symptomatic dyslexics coloured filters can improve noise exclusion to normal levels. They found that coloured lenses reduced the effects of visual noise and that when they were wearing their prescribed coloured tints dyslexic readers could detect letters as well as control subjects could. Neutral density filters matching the luminance of the coloured lenses failed to reduce the effects of noise and enhance visual detection performance in psychophysical tests.

Wilkins[47] has proposed that patterns may give rise to cortical hyperexcitability and that this leads to unpleasant visual distortions. There is some evidence that hyperexcitability in the visual cortex is a feature of migraine.[63] These responses may occur in the V1, V2 or V3 areas of the brain.[53,60] Interestingly, researchers[53,64] have shown that V2 in the visual cortex may have separate colour-selective cells in the macaque monkey. It is therefore possible that coloured lenses may affect processing in some parts of the visual cortex and that this may ultimately influence processing in further cortical areas such as V3, where it has been shown that there is hyperexcitability in migraine sufferers with visual distortions.[65,66] By altering or favouring processing in certain areas of V2, it may be possible to alter processing in other visual areas. This is, however, speculative and further research is required to determine how altering processing in V2 would affect other visual areas. Recent functional magnetic resonance imaging (fMRI) studies[53,66] have also shown that coloured lenses normalise cortical activation and spatial frequency tuning in migraineurs, which suggests a neurological basis for the therapeutic effect of these lenses in reducing visual cortical hyperactivation in migraine and possibly reducing overstimulation or noise effects. It is thus possible that visual distortion that hinders reading by creating visual discomfort, or gives rise to headaches or seizures, is a neurophysiological response that fMRI studies may allow us to understand better in the future. However, it should be made clear that there is no direct evidence to suggest that the benefits derived by migraine sufferers and visually symptomatic readers are indeed the same thing or linked, and further work is required to determine exactly how coloured filters may benefit a range of conditions.

Conclusions

Separating out the possible causal factors of visual symptoms is key to any clinician assessing visually symptomatic readers or indeed those who suffer from frequent headaches. Correction of a range of visual anomalies has resulted in improved reading and visual comfort in the multicentre trial conducted by Scott *et al*.[18] and in the adult literacy study.[19] In particular the adult literacy study[19] noted that those who received treatment showed an improvement in visual function, reading speed, visual comfort and reading level when compared with a delayed treatment group, although results should be viewed with some caution due to difficulties in executing the study and the many factors that may have affected those involved. Improvements in reading speed and level were noted in the first 3 months of treatment, and continued improvement in reading ability was seen 12 months after treatment even though no further reading instruction was being received.

These results should be interpreted carefully. Treating visual symptoms does not cure reading disability such as dyslexia, but it does facilitate reading practice. Improvement in reading is undoubtedly a result of increased reading practice in response to improved visual performance, and the additional practice results in better reading skills as opposed to direct correction of dyslexic-type difficulties. Visual discomfort and headache were often cited by the adults in the adult literacy study[19] as a source of frustration when reading, a limiting factor on the amount of time spent reading, and a primary reason to categorise themselves as poor readers and thus avoid reading. Many had never experienced reading without blur or headache prior to treatment. It is also possible that by carrying out more near work, visual functions for near also benefit from more use and improve.

The presence of binocular vision anomalies undoubtedly would explain many of the symptoms of discomfort and headache experienced during reading and would explain why those with symptoms can find reading physically arduous. A thorough assessment of refraction, and binocular vision including accommodative lag, should always be carried out when assessing visually symptomatic readers. However, visual symptoms associated with visual stress cannot be ruled out. Visual stress results in symptoms of fatigue and headache when reading and as such requires differential diagnosis from binocular vision problems. To this end, despite the controversy about the role of colour in reading difficulty and its effect on dyslexia, the orthoptist should consider using coloured overlays or lenses when asthenopic symptoms persist and other clinical measures seem within normal limits. The clinician should also bear in mind that visual stress may in itself underlie increased accommodative lag[36] and persistent binocular vision weakness despite treatment. It remains the case, however, that many of those who have difficulty reading may have a range of conditions creating unpleasant symptoms

when reading. This forms a significant barrier to reading, since pain or discomfort is a signal in the human body to stop an activity. It is thus likely that removal of these visual barriers encourages learners to read for longer and it may be that reading becomes more pleasurable, leading to more practice, which in turn culminates in better reading. The impact of any visual anomaly may also be greater in poor or less able readers since they read in a different way, with more fixations, greater time spent reading and longer duration of fixations, with longer latency[67–69] (visual behaviours that may make the spatial aspects of text more obvious). Able readers make fewer fixations, take less time to read and skim read,[67–69] making the demands on the visual system less arduous and possibly the pattern effects less obvious or distracting.[47]

In conclusion, assessing the visually symptomatic reader requires thorough history-taking, modified clinical examination and a methodological approach to assessment and differential diagnosis. This can lead to highly effective care that has great impact on the lives of patients and is core to the work of an orthoptist. As stated earlier the cause of reading difficulty is complex and most would agree principally phonological.[1] However, until studies are clearer about what they are claiming to improve, inconsistency and lack of clarity in the literature is likely to continue. It remains the case, though, that correcting visual functions used for near work may be critical to the facilitation of comfortable reading, particularly in those with other neurophysiological barriers to reading such as dyslexia, and making the reading process physically more comfortable can be a considerable step towards more successful and comfortable reading for all.

References

1. Snowling MJ. Developmental reading disorders. *J Child Psychol Psychiatry* 1991; **32:** 49–77.
2. Lavrich JB. Convergence insufficiency and its current treatment. *Curr Opin Ophthalmol* 2010; **21:** 356–360.
3. Scheiman M, Copper J, Mitchell GL, *et al*. A survey of treatment modalities for convergence insufficiency. *Optom Vision Sci* 2002; **79:** 151–157.
4. Wilkins AJ, Smith J, Willison CK, *et al*. Stripes within words affect reading. *Perception* 2007; **36:** 1788–1803.
5. Stein J. The magnocellular theory of developmental dyslexia. *Dyslexia* 2001; **7:** 12–36.
6. Stein JF, Riddell P, Fowler S. Dyslexia and monocular occlusion. *The Lancet* 1985; **ii**(8460): 883–884.
7. Stein JF, Riddell PM, Fowler MS. The Dunlop test and reading in primary-school children. *Br J Ophthalmol* 1986; **70:** 317–320.
8. Stein J, Fowler S. Effect of monocular occlusion on visuomotor perception and reading in dyslexic-children. *The Lancet* 1985; **ii**(8446): 69–73.
9. Stein JF, Richardson AJ, Fowler MS. Monocular occlusion can improve binocular control and reading in dyslexics. *Brain* 2000; **123:** 164–170.
10. Stein JF, Fowler S. A physiologic theory of visual dyslexia. *Adv Neurol* 1984; **42:** 233–246.
11. Stein JF, Fowler S. Diagnosis of dyslexia by means of a new indicator of eye dominance. *Br J Ophthalmol* 1982; **66:** 332–336.
12. Stein JF, Fowler S. Unstable reference hemisphere in visual dyslexia. *Neurosci Lett* 1979; **Suppl**(3): S214.
13. Stein JF, Richardson AR, Winter J, Hanson P. Delayed steady state visual evoked potentials in developmental dyslexics. *Electroencephalogr Clin Neurophysiol* 1997; **102:** 36P.
14. Stein JF, Riddell PM,Fowler MS. Fine binocular control in dyslexic children. *Eye Trans Ophthalmol* 1987; **1:** 433–438.
15. Stein JF, Riddell PM, Fowler S. Disordered vergence control in dyslexic-children. *Br J Ophthalmol* 1988; **72:** 162–166.
16. Stein MT, Zentall S, Shaywitz S, Shaywitz B. A school-aged child with delayed reading skills. *J Dev Behav Pediatr* 1999; **20:** 381–385.
17. Evans BJ, Patel R, Wilkins AJ, *et al*. A review of the management of 323 consecutive patients seen in a specific learning difficulties clinic. *Ophthalmic Physiol Opt* 1999; **19:** 454–466.
18. Scott L, McWhinnie H, Taylor L, *et al*. Coloured overlays in schools: orthoptic and optometric findings. *Ophthalmic Physiol Opt* 2002; **22:** 156–165.
19. Northway N, Dutton, GN. Undetected visual defects in adult literacy. In: *Learning Connections*. Glasgow: Scottish Government, 2010.
20. Stein J. Dyslexia: impaired temporal information-processing. *Ann N Y Acad Sci* 1993; **682:** 83–86.
21. Stein J. Visuospatial perception and reading problems. *Ir J Psychol* 1989; **10:** 521–533.
22. Stein J. Dyslexia. *Br Med J* 1988; **297:** 854–854.
23. Stein J, Fowler S. Visual dyslexia. *Trends Neurosci* 1981; **4:** 77–80.
24. Stein J, Talcott J, Walsh VV. Controversy about the visual magnocellular deficit in developmental dyslexics. *Trends Cogn Sci* 2000; **4:** 209–211.
25. Stein J, Walsh V. To see but not to read: the magnocellular theory of dyslexia. *Trends Neurosci* 1997; **20:** 147–152.
26. Stein JF. Developmental dyslexia, neural timing and hemispheric lateralization. *Int J Psychophysiol* 1994; **18:** 241–249.
27. Stein JF. Dyslexia, temporal processing and cerebral lateralization. *Int J Psychophysiol* 1994; **18:** 150–150.
28. Stein JF. Hemispheric-specialization and dyslexia. *Reading Writing* 1991; **3:** 435–440.
29. Stein JF. Unfixed reference, monocular occlusion, and developmental dyslexia: a critique. *Br J Ophthalmol* 1989; **73:** 319–320.
30. Stein JF, Fowler S. A physiologic theory of visual dyslexia. *Adv Neurol* 1984; **42:** 233–246.
31. Dunlop D, Dunlop P, Fenelon B. Vision-laterality analysis in children with reading disability: the results of new techniques of examination. *Cortex* 1973; **9:** 227–236.
32. Goulandris NK, Snowling MJ, Walker I. Is dyslexia a form of specific language impairment? A comparison of dyslexic and language impaired children as adolescents. *Ann Dyslexia* 2000; **50:** 103–120.
33. Borsting E, Chase CH, Ridder WH 3rd. Measuring visual discomfort in college students. *Optom Vision Sci* 2007; **84:** 745–751.
34. Chase C, Tosha C, Borsting E, Ridder WH 3rd. Visual discomfort and objective measures of static accommodation. *Optom Vision Sci* 2009. **86:** 883–889.
35. Tosha C, Borsting E, Ridder WH 3rd. Accommodation response and visual discomfort. *Ophthalmic Physiol Optics* 2009; **29:** 625–633.
36. Allen PM, Hussain A, Usherwood C, Wilkins AJ. Pattern-related visual stress, chromaticity, and accommodation. *Invest Ophthalmol Vis Sci* 2010; **51:** 6843–6849.
37. Okada Y, Ukai K, Wolffsohn JS, Gilmartin B, Iijima A, Bando T. Target spatial frequency determines the response to conflicting defocus- and convergence-driven accommodative stimuli. *Vision Res* 2006; **46:** 475–484.
38. McClelland JF, Saunders KJ. The repeatability and validity of dynamic retinoscopy in assessing the accommodative response. *Ophthalmic Physiol Opt* 2003; **23:** 243–250.
39. Kuffler SW. Discharge patterns and functional organization of mammalian retina. *J Neurophysiol* 1953; **16:** 37–68.
40. Schiller PH, Carvey CE. The Hermann grid illusion revisited. *Perception* 2005; **34:** 1375–1397.
41. Georgeson MA. Apparent spatial frequency and contrast of gratings: separate effects of contrast and duration. *Vision Res* 1985; **25:** 1721–1727.
42. Georgeson MA. The effect of spatial adaptation on perceived contrast. *Spatial Vision* 1985; **1:** 103–112.
43. Conlon E, Lovegrove W, Barker S, Chekaluk E. Visual discomfort: the influence of spatial frequency. *Perception* 2001; **30:** 571–581.
44. Chronicle EP, Wilkins AJ. Colour and visual discomfort in migraineurs. *The Lancet* 1991; **338:** 890.
45. Millett CJ, Fish DR, Thompson PJ. Photosensitivity: better informing patients with epilepsy of their individual risk. *Seizure* 1998; **7:** 97–99.
46. Marcus DA, Soso MJ. Migraine and stripe-induced visual discomfort. *Arch Neurol* 1989; **46;** 1129–1132.
47. Wilkins A. Reading and visual discomfort. In: *Visual Processes in Reading and Reading Disabilities*. NJ: Lawrence Erlbaum, 1993.
48. Harle DE, Shepherd AJ, Evans BJW. Visual stimuli are common triggers of migraine and are associated with pattern glare. *Headache* 2006; **46:** 1431–1440.
49. Wilkins A, Nimmo-Smith I, Tait A, *et al*. A neurological basis for visual discomfort. *Brain* 1984; **107:** 989–1017.

50. Wilkins AJ, Nimmo-Smith MI. The clarity and comfort of printed text. *Ergonomics* 1987; **30:** 1705–1720.
51. Irlen H. *Reading by the Colors: Overcoming Dyslexia and Other Reading Disabilities through the Irlen Method*. Penguin/Putnam, 1991.
52. Meares O. *Figure-Ground, Brightness Contrast and Reading Disabilities: A Request from a Teacher to Researchers*. The author, 1979.
53. Huang J, Zong X, Wilkins A, Jenkins B, Bozoki A, Cao Y. fMRI evidence that precision ophthalmic tints reduce cortical hyperactivation in migraine. *Cephalalgia* 2011; **31:** 925–936.
54. Wilkins AJ, Evans BJ, Brown JA, *et al*. Double-masked placebo-controlled trial of precision spectral filters in children who use coloured overlays. *Ophthalmic Physiol Opt* 1994; **14:** 365–370.
55. Lightstone A, Lightstone T, Wilkins A. Both coloured overlays and coloured lenses can improve reading fluency, but their optimal chromaticities differ. *Ophthalmic Physiol Opt* 1999; **19:** 279–285.
56. Evans BJ, Joseph F. The effect of coloured filters on the rate of reading in an adult student population. *Ophthalmic Physiol Opt* 2002; **22:** 535–545.
57. Bouldoukian J, Wilkins AJ, Evans BJ. Randomised controlled trial of the effect of coloured overlays on the rate of reading of people with specific learning difficulties. *Ophthalmic Physiol Opt* 2002; **22:** 55–60.
58. Ritchie SJ, Della Sala S, McIntosh RD. Irlen colored overlays do not alleviate reading difficulties. *Pediatrics* 2011; **128:** e932–938.
59. Handler SM, Fierson WM, Ophthalmology TSO, Council on Children with Disabilities AAOO, American Association for Pediatric Ophthalmology, Strabismus, Orthoptists AAOC. Learning disabilities, dyslexia, and vision. *Pediatrics* 2011; **127:** e818–e856.
60. Menacker SJ, Breton ME, Breton ML, Radcliffe J, Gole GA. Do tinted lenses improve the reading performance of dyslexic children? A cohort study. *Arch Ophthalmol* 1993; **111:** 213–218.
61. Evans BJW. The need for optometric investigation in suspected Meares–Irlen syndrome or visual stress. *Ophthalmic Physiol Opt* 2005; **25:** 363–370.
62. Northway N, Manahilov V, Simpson W. Coloured filters improve exclusion of perceptual noise in visually symptomatic dyslexics. *J Res Reading* 2010; **33:** 223–230.
63. Hadjikhani N, Sanchez Del Rio M, Wu O, *et al*. Mechanisms of migraine aura revealed by functional MRI in human visual cortex. *Proc Natl Acad Sci USA* 2001; **98:** 4687–4692.
64. Xiao Y, Wang Y, Felleman DJ. A spatially organized representation of colour in macaque cortical area V2. *Nature, Lond* 2003; **421:** 535–539.
65. Moutoussis K, Zeki S. The relationship between cortical activation and perception investigated with invisible stimuli. *Proc Natl Acad Sci USA* 2002; **99:** 9527–9532.
66. Wilkins A, Huang J, Cao Y. Prevention of visual stress and migraine with precision spectral filters. *Drug Dev Res* 2007; **68:** 469–475.
67. Black JL, Collins DW, De Roach JN. Zubrick S. A detailed study of sequential saccadic eye movements for normal- and poor-reading children. *Percept Mot Skills* 1984; **59:** 423–434.
68. Black JL, Collins DW, De Roach JN, Zubrick SR. Dyslexia: saccadic eye movements. *Percept Mot Skills* 1984; **58:** 903–910.
69. Biscaldi M, Gezeck S, Stuhr V. Poor saccadic control correlates with dyslexia. *Neuropsychologia* 1998; **36:** 1189–1202.