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Increasing reading speed by using colours: Issues concerning reliability and specificity, and their theoretical and practical implications

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Abstract. By using techniques for precision ophthalmic tinting, individuals who report perceptual distortion of text can often find a colour of illumination that eliminates the distortions and increases reading speed. Most individuals choose green or blue hues, but there is considerable variability. We investigated how specific the colour has to be to obtain optimal reading speed.

Individuals who habitually wear coloured filters for reading were asked to read text illuminated by coloured light (without using their filters). Reading speed was measured repeatedly with light of different colours. The colour (chromaticity) at which reading was fastest was consistent from one test session to the next. It was different from one individual to another, but highly specific for each individual: departures of colour from optimum by about 6 JNDs eliminated most of the speed advantage conferred by the optimal colour. It was difficult to attribute the consistency and specificity simply to familiarity with the tint or immediate memory for the colour of illumination.

A consecutive sample of 1000 tint prescriptions was analysed numerically. For most prescriptions the variation in chromaticity with different types of lighting was not such as to remove all the potential benefit of the tint, as judged from a model of the effect of chromaticity on reading speed. The exceptions were the few tints that were weakly saturated or purple in colour.

Across participants, reading speed was not consistently related to the scotopic energy, to the energy captured by any cone class, or to opponent colour processes. The reading was generally slowest with white light, and not with the colour complementary to the optimum. Explanations in terms of magnocellular deficits and cortical hyperexcitability are briefly discussed.

1 Introduction

The MRC system for precision ophthalmic tinting (Wilkins et al 1992a) was introduced in the UK in 1993 and since then more than 25 000 people have been prescribed coloured glasses to help with reading. Placebo-controlled studies have demonstrated that the effects of colour on reading fluency are specific and different for each individual (Wilkins et al 1994, 2002) but precisely how specific the tint has to be is not yet known. The following studies were performed to explore the specificity of the effect of colour on reading fluency. They suggest that central mechanisms underlie the effect.

The individuals who benefit from coloured filters usually complain of perceptual distortions of the text such as apparent movement of the letters, blurring, or coloured halos; distortions that abate when the text is illuminated by coloured light (Wilkins et al 1992b). These individuals have abnormally large microfluctuations during steady-state accommodation (Simmers et al 2001b). The fluctuations are reduced when the coloured glasses are worn, but also when neutral filters of similar photopic transmission are worn, suggesting that, although the microfluctuations of accommodation are a physiological sign of an underlying abnormality, they are not a cause of the perceptual distortions, nor their reduction with colour. Instead, the mechanisms for the benefit of colour appear to be central in origin. This is because the colour optimal for use in overlays, which cover the page and provide a surface colour, is different from the colour optimal for use in lenses, which colour the entire visual scene (Lightstone et al 1999).

The following study involved individuals who had been assessed with the MRC system and then habitually wore coloured glasses when reading. They were asked to read text aloud under light of different colours so as to assess the way in which reading speed was affected by the chromaticity of the illumination. The text consisted of randomly ordered common words arranged as a paragraph. Because of the random order, the words had to be seen to be read and could not be guessed from context. Variance in reading speed due to comprehension was thereby avoided. The speed of reading randomly ordered common words, as in the 'Rate of Reading Test' (Wilkins et al 1996) has been shown to have a high test–retest reliability. With immediate retest, the correlation between test and retest is greater than 0.8 (Wilkins et al 2001, study 1), and it remains so, even with an interval between tests of 8 weeks (Wilkins et al 1996).

The increase in reading speed with coloured overlays has been shown to predict the subsequent use of the overlays (Jeanes et al 1997) and to be associated with perceptual changes (Wilkins and Lewis 1999), suggesting that the test is a valid measure of visual aspects of reading.

The increase in reading speed with the use of coloured overlays is correlated with the increase with overlays in the speed of performance on a task requiring silent reading for comprehension (Wilkins et al 2001). This suggests that variance due to visual aspects of reading, as assessed by the speed of reading randomly ordered common words, is a component of the variance in more typical reading tasks.

2 Study 1

Five individuals who had been prescribed coloured glasses to reduce symptoms of visual stress when reading were asked to read without their tinted glasses. We measured the speed of reading when the text was illuminated with light of various colours and studied precisely how reading speed changed with colour.

2.1 *Participants*

Two females and three males aged 11–17 years (mean 13 years) had been prescribed coloured glasses for the reduction of symptoms of visual stress when reading, by established techniques (Wilkins 1995). All had received an ophthalmic, optometric, and orthoptic assessment. One (OR) had a slight esophoria and myopia ($R\ -1.5/-0.5 \times 85 = 6/9$; $L\ -0.25/-0.25 \times 175 = 6/5$) and one (ZG) had a right convergent squint for near—operated at age 4 and 7 years. She wore bifocals with a +2.0 DS reading addition, in both eyes. The remaining participants were emetropic and orthophoric and had normal visual acuity. Three participants (OR, ZG, and EB) had a family history of migraine, and one (SD) had special educational needs. None had anomalous colour vision on clinical testing (Ishihara and City University tests). All had continued using the coloured glasses for a minimum of 5 months prior to testing (average 18 months).

2.2 *Procedure*

Participants viewed text illuminated with coloured light in the *Intuitive Colorimeter*, a coloriser that permitted continuous and separate variation of hue and saturation within a gamut bounded by the outer curve in the top left panel of figure 1 (Wilkins and Sihra 2000). The viewing distance was 0.4 m. The luminance of the page was 25 cd m^{-2}—a level similar to that obtained when the coloured glasses were worn under conventional office lighting levels. The participants selected a chromaticity that provided the greatest clarity, using established techniques allowing for systematic colour sampling and colour adaptation (Wilkins 2003). The participants then read different passages of text, each under light of a different colour. The passages consisted of 20 lines spaced 4.1 mm apart, each line with the same 15 high-frequency words

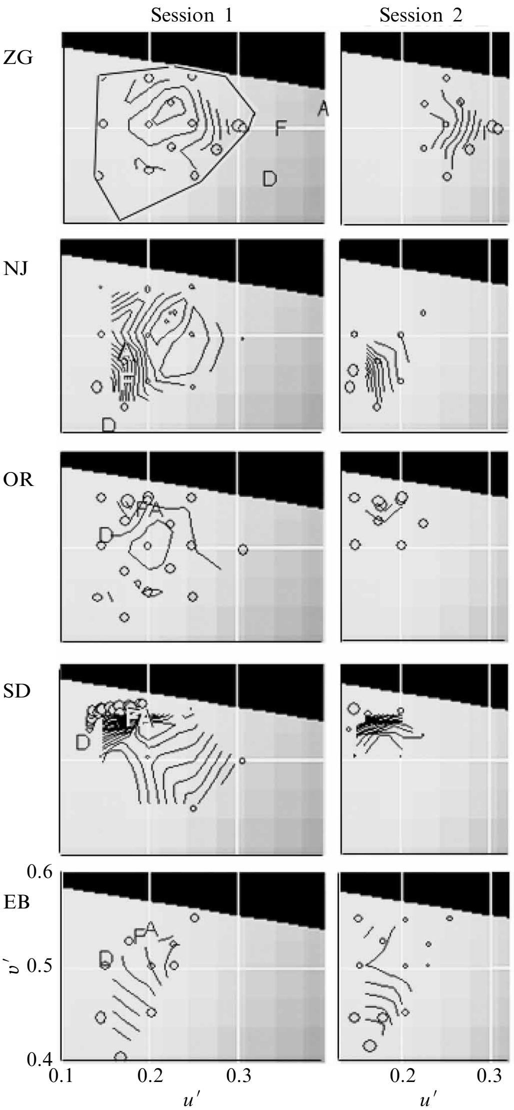


Figure 1. Reading speed and colour. CIE 1976 Uniform Chromaticity Scale diagrams (abscissa u', range 0.1 – 0.4; ordinate v', range 0.4 – 0.6) showing variation in reading speed with colour. Although expressed in Cartesian coordinates, the diagrams can be thought of as polar plots with origin at 'white' ($u' = 0.22$, $v' = 0.52$), the radius representing saturation and the angle representing hue. The width of the points is directly proportional to the number of words correctly read in 45 s, similarly so for session 1 and session 2, shown in the left and right diagrams of each pair respectively. Interpolated contours show reading speed and were obtained by triangulation (Delaunay method) by using a surface plotting program 3Dfield written by Vladimir Galouchko. Each contour differs from its neighbour by 10% of the speed under white light. The letters D, F, and A in the left diagram of each pair are positioned so as to give the chromaticities of a spectrally uniform surface viewed through the participant's tinted glasses and illuminated by daylight (CIE Standard illuminant D65), fluorescent light (CIE Type F3), and incandescent light (CIE Standard illuminant A), respectively. The limits of the gamut of colours available in the coloriser are shown by the outer curve in the top left-hand panel.

(and, cat, come, dog, for, is, look, my, not, play, see, the, to, up, you) in a different random order, printed in black ink, reflectance 4.7%, on white paper in 10-point Arial font with *x* height of 2.9 mm. Each passage was read aloud for 45 s and the number of words correctly read was noted, ignoring the few words that were not read in the correct order relative to their neighbours. The colour of the light was then changed and a different passage was read. The procedure continued with frequent breaks until a wide variety of different chromaticities had been sampled in random order (avoiding those at which discomfort was extreme), with a minimum of four measurements of reading speed at each (except in the case of one individual, SD, where fewer measurements were made with a larger number of colours). The chromaticities were chosen so as to sample chromaticity throughout the gamut with a particular emphasis on chromaticities close to that at which perception was reported to be optimal. Data were collected in two sessions spaced at least two weeks apart, with a different random order of presentation.

2.3 *Results*

The reading speeds for the five participants in two sessions (spaced at least two weeks apart) are shown as a function of the chromaticity of the illuminating light in figure 1. The left column of panels shows data for the first session, and the right column for the second session. The chromaticities sampled are shown by the position of the points of various sizes, the radius of each point being directly proportional to mean reading speed at the chromaticity specified by the position of the point (largest points, the quickest). The contours were obtained by triangulation (Delaunay method) with the use of a surface plotting program 3Dfield written by Vladimir Galouchko. The contours are spaced in intervals of 10% of the reading speed under 'white' light (chromaticity 0.22, 0.52).

The change in reading speed with colour is shown by the position and spacing of the contours in the panels in the first two columns of figure 1. The contours are similar in the two columns and show a consistency from one test session to the next, within the constraints of the restricted samples of session 2.

The optima differed from one person to another, as can be seen from the different positions of the contours in each individual case.

The data in figure 1 have been replotted as graphs in figure 2. The ordinates show the number of words read in the 45 s interval. The abscissae show the differences in colour between the colour at which the measurements were made and the colour selected by each participant as optimal for perception (expressed as CIELUV colour difference—see Appendix). For NJ, OR, and ZG the chromaticity optimal for perception was the same as that at which the reading speed was maximal. The data show a decline in reading speed with difference in colour from subjective optima. Notice that, for every participant, the data from the first session (open points) are similar to those from the second session (filled points).

The data from each session were modelled with a Gaussian function having a maximum at the chromaticity at which the subjective clarity of the text was greatest (not necessarily that at which reading was fastest—see above paragraph). The function was constrained to have the same overall mean as the data, and the gain (height) and spread (standard deviation) were fit to the data by least squares. Table 1 shows the values of height and standard deviation for functions fit to data from the first session and to data from the second session. The values are generally similar, although for one set of data the function did not converge on a least-squares solution. The similarity between the two sessions effectively rules out practice as an explanation for speed improvement, however unlikely that might be, given the random order of sampling chromaticities.

Table 1. Parameters of the Gaussian functions used to fit data from sessions 1 and 2 and both sessions combined. The height of the function (difference in reading speed at the peak of the function versus that at the tail) is expressed in words per 45 s, and the standard deviation is expressed in units of colour difference calculated as described in the Appendix [the value of 2 standard deviations (SDs) is tabulated]. The variance explained by the Gaussian function is shown as a percentage. The data for SD in session 2 did not converge on a least-squares solution.

Subject	Session 1			Session 2			Both sessions		
	height	2 SDs	variance explained/%	height	2 SDs	variance explained/%	height	2 SDs	variance explained/%
ZG	19	66	46	26	78	53	21	67	46
NJ	28	77	49	22	52	78	26	74	66
OR	14	39	36	10	33	43	12	37	36
SD	39	102	34	–	–	–	38	95	26
EB	26	125	60	43	106	69	35	118	58
Average	25	82	45	25	67	61	26	78	47

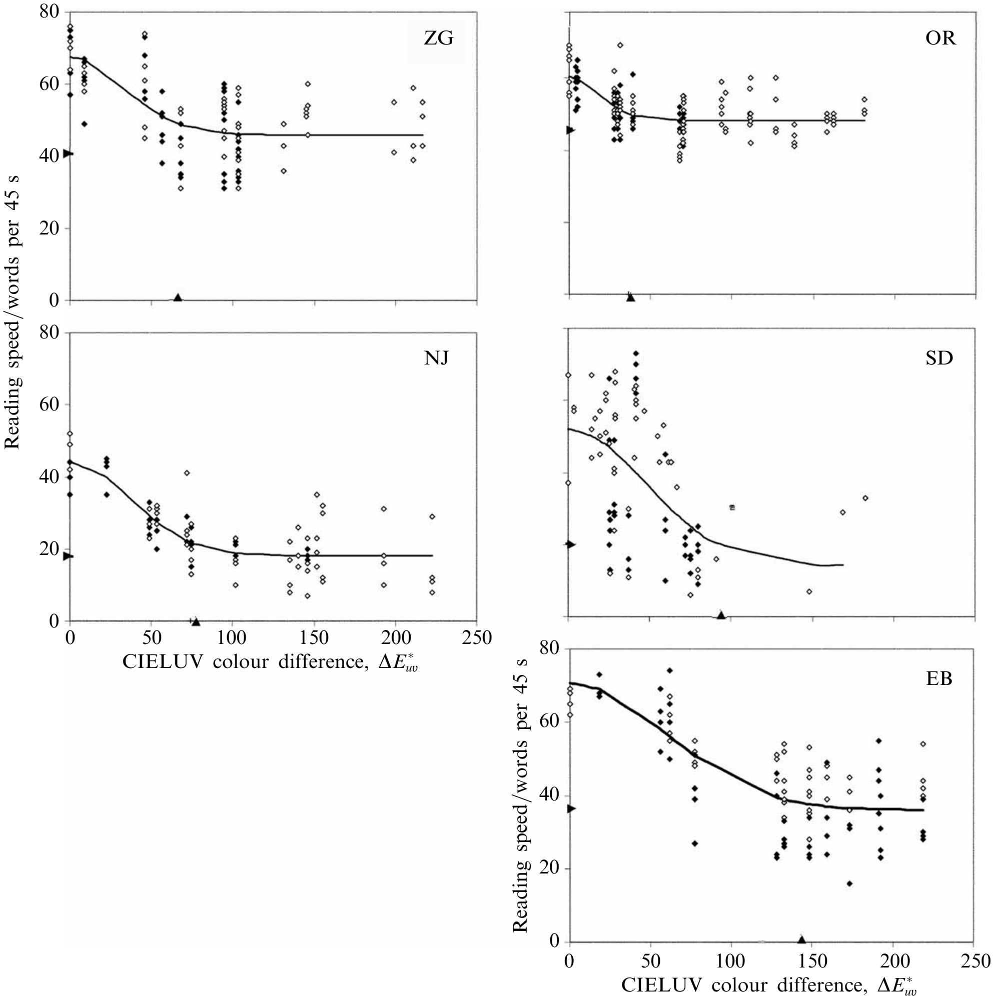


Figure 2. Reading speed as a function of the difference between the colour chosen as optimal for perception and the colour under which reading speed was measured. The mean reading speed at each colour is given on the ordinate as words correctly read per 45 s (range 0 – 80 in every case). The reading speed under 'white' light ($u' = 0.22$, $v' = 0.52$) is shown by the arrow on the ordinate. The abscissa gives the difference between the colour at which the measurements were made and the colour chosen as optimal for perception, expressed as colour difference calculated as described in the Appendix. The continuous curves show a Gaussian function fit to the scatter of points by least squares. The arrow on the abscissa shows the colour difference at which the Gaussian was 2 SDs from maximum. The percentage of variance explained by each curve is shown in the last column of table 1.

The data for the first and second sessions were combined, and a Gaussian function fitted to the combined data. The height and standard deviation are also shown for the combined data in table 1. The Gaussian fits to the data accounted for a statistically very highly significant proportion of the variance in every case. The minimum value of the F ratio was 9.0 with degrees of freedom for the numerator of 3 and for the denominator of more than 80. In every case the associated probability level was less than 0.00001.

In figure 2, the arrowheads on the ordinates show the average reading speed under 'white' light (chromaticity: $u' = 0.22$, $v' = 0.52$) for each individual. The colour difference at which the fitted function is 2 standard deviations (SDs) from optimal is shown on the abscissa by an arrowhead.

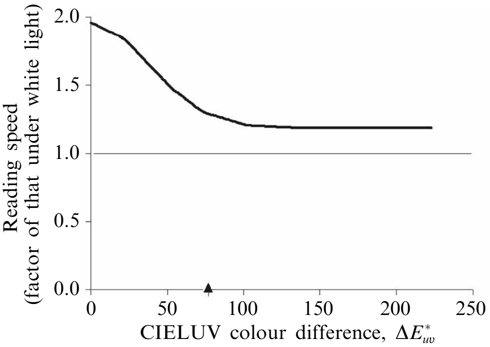


Figure 3. Gaussian function based on the average parameters of height and standard deviation for the Gaussian functions shown in figure 2. The reading speed is expressed on the ordinate as a factor of the reading speed under 'white' light ($u' = 0.22$, $v' = 0.52$), shown by the horizontal line. The function is 2 SDs from maximum at a colour difference of 78, shown by the arrow on the abscissa.

Figure 3 shows the function with the values of height and standard deviation for the data from both sessions averaged across participants. The ordinate is expressed as a factor of the reading speed under 'white' light. On average, the reading speed was 2.0 times that under 'white' light when the colour was subjectively optimal. A colour difference of 78 corresponds to a distance of 2 SDs, indicating that at a colour difference of 78 the advantage conveyed by colour had been reduced to less than 5% of its maximum. A colour difference of 78 corresponds to about 6 just noticeable differences (JNDs) (Hunt 1991, page 69).

Note that although the curve in figure 3 is based on data that include measurements made under 'white' light, the curve asymptotes above the value of 1.0. This is because reading speed was measured at many colours, some with a difference in colour from optimal similar to that for 'white' light, but associated with slightly higher reading speeds—see figure 2. The reading speed under 'white' light was therefore compared with that under 'non-optimal coloured' light, that is light with a saturation, s_{uv}, greater than 1.0, having a difference in colour from optimal similar to that of 'white' light (to within a colour difference of 20). The reading speed was on average 21% slower under the 'white' light than under the 'non-optimal coloured' light ($t_4 = 2.6$, $p = 0.06$, two-tailed). This suggests that a wide range of colours can improve reading marginally relative to white light, but that for optimal improvement the selection of a precise chromaticity is important.

2.4 *Discussion*

The colour optimal for reading speed differed for each individual, and consistently so. Reading speed decreased substantially as the colour departed from optimum, so that for all participants reading was no longer much advantaged by colour when the colour had departed from optimal by about 6 JNDs.

Study 2 was undertaken to establish whether colour memory might provide an explanation for the test–retest consistency.

3 Study 2

3.1 *Procedure*

Six males and sixteen females aged 18–29 years, with normal scores on the Ishihara and City University tests of colour vision, memorised the colour of a given standard light illuminating a diffuse surface of uniform spectral reflectance in the coloriser (luminance 25 cd m^{-2}). The saturation was then reset to zero and the hue angle changed by 90°, and participants *immediately* reproduced the memorised shade by separate adjustment of hue and saturation. Two standards were presented for reproduction, with chromaticity chosen at random with replacement from the optima shown by the five participants in figure 1.

3.2 *Results*

The median colour difference between standard and adjustment was 39 (interquartile range 24 – 58), and therefore large in relation to the colour difference responsible for most of the change in reading speed with colour noted in figure 2.

3.3 *Discussion*

The change in reading speed with colour in study 1 showed a consistency that was difficult to attribute to immediate colour memory, as assessed on the basis of the intermediate reproduction of colour by normal observers.

The range of chromaticities that the filters would provide in the case of a spectrally uniform surface viewed under incandescent lighting (CIE Standard illuminant A), fluorescent lighting (CIE Type F3), and daylight (CIE Standard illuminant D65) are shown on the left-hand diagram of each pair in figure 1 by the letters A, F, and D, respectively. Although for participants OR, NJ, and SD the lens tint under fluorescent lighting had a colour similar to that chosen as optimal, this was not the case for all participants, notably EB, who was wearing green glasses but read more quickly under blue light, and did so consistently in sessions 1 and 2. His optimal tint had changed in the year since it was first prescribed, and he was issued with a revised tint after session 2. In the case of EB, at least, the consistency between sessions 1 and 2 cannot be attributed to familiarity with lenses of similar colour.

Although the specificity of the effects of colour on reading cannot in all participants simply be attributed to experience with the lenses, it is nevertheless possible that use of coloured lenses prior to the study had in some way enhanced the specificity of the effects of colour, and that individuals without this experience would show a less specific effect.

4 General discussion

The results of the above studies have theoretical and practical consequences that will now be explored.

4.1 *Theoretical consequences*

Figure 4 shows the ratio of scotopic energy to the (constant) photopic energy of the light in the *Intuitive Colorimeter* (Wilkins and Sihra 2000), as a function of chromaticity. As might be anticipated, the blue light has greater scotopic energy than the red. Were the rods preferentially or selectively involved in the mechanisms responsible for increasing reading speed, one might have anticipated some similarity between the

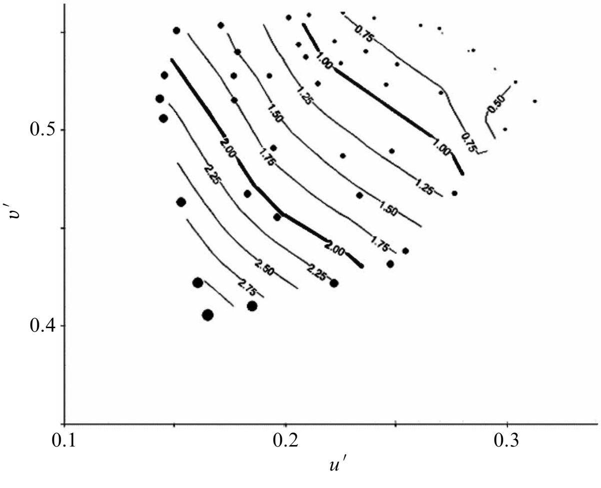


Figure 4. CIE 1976 UCS diagram. Scotopic energy in the *Intuitive Colorimeter*. The size of the points is directly proportional to the scotopic energy. The contours show equal scotopic energy under the experimental conditions used. The photopic energy was held constant at 25 cd m^{-2}. The contours show the ratio of scotopic energy to photopic energy, and the contours for 2.00 (left) and 1.00 (right) are shown bold.

contours of constant scotopic energy and those in figure 1, which show reading speed as a function of chromaticity.

The participants did not show evidence of colour-vision abnormalities. The iso-reading-speed contours shown in figure 1 do not show any obvious relation to the axes of colour confusion in protan, deutan, or tritan observers (see Hunt 1991, figure 3.7). If a cone abnormality was responsible in some way for the benefits of colour in improving reading speed, one might have anticipated some colour-vision abnormality or a similarity between colour confusion axes and iso-reading-speed contours.

The colour associated with slowest reading was usually white (see figure 1), and not the colour complementary to that at which reading was fastest. This finding is not easily explained in terms of opponent colour channels or indeed in terms of accommodation, if accommodation requires a broad spectral content (Atchison et al 1993).

Magnocellular deficits are seen in some individuals with dyslexia and it has been argued that these deficits are responsible for the beneficial effects of coloured filters (eg Chase et al 2003; Edwards et al 1996; Lehmkule 1993). Although such benefits have been associated with dyslexia both in the public mind and that of some researchers (eg Williams et al 1996), the prevalence of benefits in dyslexia is only slightly greater than in the population at large, non-significantly so in some studies (Evans and Joseph 2002; Wilkins 2003), and by no means all dyslexic individuals benefit. Moreover, individuals who benefit from coloured filters do not show deficits on tasks that are thought to be subserved by the magnocellular system (Simmers et al 2001a). Spectral filters have been shown to increase reading speed in individuals with autism (Ludlow et al, submitted), and to have other therapeutic benefits in head injury (Jackowski et al 1996), in migraine (Wilkins et al 2002), and in epilepsy (Wilkins et al 1999), all disorders that are associated with cortical hyperexcitability.

Wilkins (2003) has proposed a general explanation for the effects of filters in terms of cortical hyperexcitability. According to this explanation, when coloured filters are used the excitation that results from visual stimulation is redistributed in such a way as to reduce excitation in local areas of hyperexcitability. Given the possibility of topographic encoding of colour in the cortex (Xiao et al 2003) the contours shown in figure 1 might perhaps reflect just such an effect. Be that as it may, the theory of hyperexcitability in migraine and its reduction with coloured filters has found recent support in functional magnetic resonance imaging studies (Huang et al 2003, 2004) and may apply in dyslexia, given the co-morbidity between dyslexia and migraine and between migraine and epilepsy.

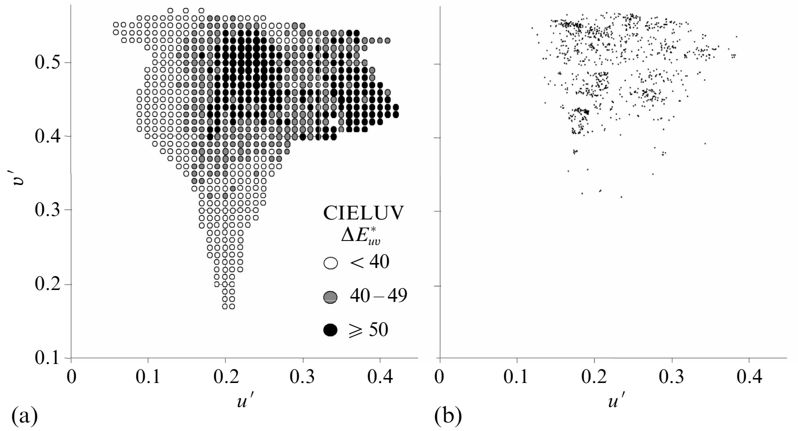
Explanations in terms of magnocellular deficits and cortical hyperexcitability may eventually converge, given that individuals with migraine have been shown to exhibit magnocellular deficits (McKendrick and Badcock 2003). The present findings do not discriminate between the two explanations: neither can give a good account of the variety of optimal colours, or their specificity, and there is as yet no way of adequately predicting which individual will benefit from which colour.

4.2 *Practical consequences*

The specificity shown in figure 1 raises the question as to the extent to which variation in lighting can reduce the beneficial effect of a tint. This was assessed by subsidiary analytical studies.

The tints used by the participants in study 1 had been prescribed with the use of the MRC system for Precision Ophthalmic tinting. The system aims to provide the optimal chromaticity under ‘white’ halophosphate fluorescent lighting (CIE Type F3). This lighting was chosen because it is the most ubiquitous, because it is relatively constant, and because it is easy to obtain. The system provides any desired chromaticity with a spectral transmission that is as smooth as possible, the purpose being to reduce metamerism under light sources with similar chromaticity but different and uneven spectral power distribution (Wilkins et al 1992b).

For tints of various colours we calculated the difference between the colour of the tint under the fluorescent light for which it was designed (CIE Type F3), and under two other ubiquitous types of light: daylight (represented by CIE Standard illuminant D65) and incandescent light (represented by CIE Standard illuminant A). In figure 5a the location of the points specifies the colour of the tint under CIE Type F3 lighting, and the shading of the points is proportional to the difference in colour obtained under incandescent lighting (CIE illuminant A) or daylight (CIE illuminant D65), whichever gave the larger difference. It will be seen that tints with low saturation, ie points closest to the centre of the diagram and those with purple hue (points on the lower right hand side of the diagram) show the largest effect of illumination. Points to the left of the diagram show the smallest effect of illumination.



(a) (b)

Figure 5. (a) CIE UCS diagram showing the effect of light source on the chromaticity of a spectrally uniform surface viewed through a selected tint. The chromaticity of the tint under fluorescent lighting (CIE Type F3) is given by the location of the point. The shading of the point is dependent upon the difference between the chromaticity under the fluorescent lighting and that under either CIE Standard illuminant A or CIE Standard illuminant D65, whichever is the larger difference. (b) Chromaticities under fluorescent lighting (CIE Type F3) of 1000 consecutive prescriptions issued with the use of the *Intuitive Colorimeter* (Wilkins and Sihra 2000)—data courtesy of Cerium Visual Technologies. To reduce the superposition of points and thereby represent their density, the u' and v' position of each point has been randomly jittered by up to 0.005 (less than 1%).

Figure 5b shows the chromaticities under CIE Type F3 lighting of a consecutive sample of 1000 tints. Note that the majority of tints are on the left of the diagram being either blue or green, and therefore likely to be least affected by illumination.

The model shown in figure 3 was used to calculate the average reading speed for the 1000 tints under incandescent lighting and daylight, and the respective figures averaged 1.6 (SD = 0.3) and 1.3 (SD = 0.1) times the reading speed under 'white' light ($u' = 0.22$, $v' = 0.52$). The calculations therefore suggest that the majority of tints are affected by the lighting under which they are worn, but not to such an extent as to eliminate all benefit. The calculations further suggest that the current practice of selecting the optimal chromaticity under a source of fluorescent lighting similar to CIE Type F3 is appropriate, given that some compromise between the tint required for daylight and incandescent light is necessary.

The calculations also support the experimental design used in two double-masked studies (Wilkins et al 1994, 2002). The studies compared the incidence of symptoms when a tint of the optimal colour under F3 lighting was worn with that when a control tint of different colour was worn. In both studies the tints were selected with the use of the *Intuitive Colorimeter*. In the first study, the control tint was of saturation, s_{uv}, similar to the optimal tint, but differed in hue angle, h_{uv}, just sufficiently for perceptual distortions to appear. The average difference in chromaticity corresponded to about 6 JNDs. In the second study, all tints were separated by a colour difference of 78. From figures 2 and 3 it can be seen that colour differences of this size are sufficient to have eliminated most of the benefit of the optimal tint, at least as regards reading speed.

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APPENDIX: CIELUV colour difference

The formula for CIELUV colour difference is based on the expressions

$$L^* = 116(Y/Y_n)^{1/3} - 16\,, \quad u^* = 13L^*(u' - u'_n)\,, \quad \text{and} \quad v^* = 13L^*(v' - v'_n)\,,$$

and the colour difference $\{\Delta E^*_{uv} = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{1/2}\}$ is designed for use where the diferences between colour patches are discerned in the context of an adapting reference illuminant (usually white), represented by values of Y_n, u'_n, and v'_n. Note that when the luminance is constant and the chromaticity of the adapting light remains unchanged, the expression for ΔE^*_{uv} reduces to $1300[(u'_2 - u'_1)^2 + (v'_2 - v'_1)^2]^{1/2}$, where (u'_1, v'_1) and (u'_2, v'_2) are the chromaticities of the patches. In the present context the field was of uniform chromaticity—that of the adapting illumination. The expression for colour difference if conventionally applied could have yielded a colour difference of zero. An expression for the difference in colour between the different illuminations was nevertheless required. In the event, it was decided to use the separation of the chromaticities in the CIE 1976 UCS diagram, ie $[(u'_2 - u'_1)^2 + (v'_2 - v'_1)^2]^{1/2}$, where (u'_1, v'_1) and (u'_2, v'_2) are the chromaticities. Rather than express this distance in $u'v'$ coordinates, necessitating four decimal places, the expression was multiplied by 1300, ie $1300[(u'_2 - u'_1)^2 + (v'_2 - v'_1)^2]^{1/2}$. It may be noted that, because the luminance was constant, this latter expression is identical to the CIELUV colour difference when the adapting reference illumination is constant. The values of colour difference in this paper are based on this calculation.

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