

Technical Note

How precise do precision tints have to be and how many are necessary?

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Abstract

Among those individuals who habitually wear precision tints, reading speed can vary as a function of the chromaticity of the illuminating light. The reading speed decreases as the chromaticity departs from optimum, whether in saturation or in hue. When the distance in the CIE 1976 UCS diagram between the chromaticity of the illuminating light and that optimal for reading exceeds about 0.08, the colour has little residual benefit. We attempt to answer two questions numerically: (1) how is reading speed affected by the variation in the colour provided by the tint under different lighting conditions? (2) how many different tints does an ophthalmic tinting system need to be able to provide? Analysis of 1000 recent prescriptions suggests that, for most, the variation in colour with illumination is sufficient to reduce, but not eliminate, the beneficial effects of the tints. The number of trial tints required by an ophthalmic tinting system is a power function of the degree of efficacy desired, and for an average efficacy >95% of optimum, the number of trial tints needs to exceed 1000. In practice this requirement can readily be achieved by combining trial lenses and by appropriate dyeing techniques.

Keywords: dyslexia, migraine, ophthalmic tinting, precision tints, reading speed, tinting systems

Techniques for precision ophthalmic tinting are now in widespread use in the UK. Over 25 000 tints have been prescribed in general optometric practice using the Intuitive Colorimeter (Wilkins *et al.*, 1992a,b; Wilkins and Sihra, 2000), a coloriser that illuminates text with coloured light. In many individuals it is possible to find a hue and saturation that reduces perceptual distortion of the text and increases visual clarity and comfort. The appropriate colour differs from one individual to another, and has to be selected with precision for optimal effect (Wilkins *et al.*, 2005).

The disorders for which coloured overlays and precision tints have recently been shown to offer benefit are generally associated with an increased risk of seizures, consistent with a cortical hyperexcitability in the individuals affected. The disorders include photo-

sensitive epilepsy (Wilkins *et al.*, 1999), autism (Ludlow *et al.*, 2005) and migraine (Wilkins *et al.*, 2002). In migraine the benefit has been demonstrated in double-masked trials, although to date these are small-scale. There are also benefits in individuals with dyslexia and these are often associated with a family history of migraine (Maclachlan *et al.*, 1993). There are now several disparate but convergent lines of evidence indicating a cortical hyperexcitability in migraine (Huang *et al.*, 2003, 2004; Welch, 2003).

According to a hypothesis proposed by Wilkins (1995, 2003), the perceptual distortions of text occur because a spread of excitation causes visual neurones to fire inappropriately. The degree of susceptibility to distortions increases with, and therefore reflects, the degree of cortical hyperexcitability. The cortical hyperexcitability is hypothesised to be non-uniform, as is manifestly the case in epilepsy (Wilkins, 1995), and the tints are held to redistribute the cortical excitation that occurs in response to a visual stimulus. The redistribution is presumed to occur because of differences in the spectral sensitivity of cortical neurones (Zeki, 1990) and the topographic representation of colour in some cortical areas (Xiao *et al.*, 2003). According to the hypothesis,

Received: 11 March 2004

Revised form: 22 November 2004

Accepted: 27 November 2004

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comfortable colours redistribute the excitation in such a way as to reduce the excitation in hyperexcitable regions. This hypothesis explains the reduction in perceptual distortions with tints, if these distortions are indeed due to a spread of excitation.

A recent study involved individuals who had been assessed with the MRC system for Precision Ophthalmic tinting (Intuitive Colorimeter System; Wilkins, 2003) and now habitually wore coloured glasses when reading. The participants selected a chromaticity that provided the greatest clarity, using established techniques allowing for systematic colour sampling and colour adaptation. They were then asked to read text under a light having a wide variety of different colours, and reading speed was measured (Wilkins *et al.*, 2005).

The participants included two females and three males aged 11–17 years (mean 13) who had been prescribed coloured glasses for the reduction of symptoms of visual stress when reading. All had received an ophthalmic, optometric and orthoptic assessment. One (OR) had a slight esophoria and myopia (R $-1.50/-0.50 \times 85VA = 6/9$; L $-0.25/-0.25 \times 175VA = 6/5$) and one (ZG) had a right convergent squint for near – operated at age, 4 and 7 years. She wore bifocals with a +2.00 DS reading addition, in both eyes. The remaining patients were emetropic and orthophoric and had normal visual acuity. Three patients (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 their coloured glasses for a minimum of 5 months prior to testing (average 18 months).

The participants were asked to read text aloud under light of different colours (using their refractive correction, but without their customary tints). The text consisted of randomly ordered common words arranged as a paragraph. Different passages were read, each for 45 s. Because of the random order, the words had to be seen to be read and could not be guessed from context. Variability in reading speed due to comprehension was thereby avoided. The speed of reading randomly ordered common words has been shown to have a high test–retest reliability. Although it is an unnatural task it has been shown to predict the reading speed in more everyday tasks, such as silent reading for comprehension (Wilkins, 2002).

Participants viewed text illuminated with coloured light in the Intuitive Colorimeter (Wilkins and Sihra, 2000). This 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*.

The chromaticity of the light was selected at random, and reading speed measured under the coloured light. The data were collected on two

sessions separated by at least 2 weeks. 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 diameter of the points in *Figure 1* is proportional to the reading speed at the chromaticity indicated by the position of the point, and the contours have been fitted by computer triangulation. The contours are similar in the first session (column 1) and the second session (column 2) despite the time interval between the sessions. The data from both sessions have been recast in the third column so as to show reading speed as a function of the difference in the colour between the chromaticity at which the reading speed was measured and that subjectively optimal for the individual concerned. The formula for CIELUV colour difference is based on the expressions $L^* = 116(Y/Y_n)^{1/3} - 16$, $u^* = 13L^*(u' - u_n')$, and $v^* = 13L^*(v' - v_n')$, and the colour difference ($\Delta E_{uv}^* = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{1/2}$) is designed for use where the differences 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, i.e. $[(u_2' - u_1')^2 + (v_2' - v_1')^2]^{1/2}$, 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, i.e. $1300[(u_2' - u_1')^2 + (v_2' - v_1')^2]^{1/2}$. 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 x -axis in *Figure 1* shows the 'colour difference' calculated in this way. The y -axis shows reading speed in terms of the number of words read in the time allowed (45 s). Although the optima for each individual are all very different (being shades of red, green or blue), the way in which reading speed decreases with the difference in colour from optimum is similar from one session to the next, and indeed is broadly similar for all individuals. The data have been fit by Gaussian functions, and for all individuals, a 'colour difference' of about 100 (corresponding to a distance of 0.077 in the CIEUCS diagram) is sufficient to reduce reading speed consider-

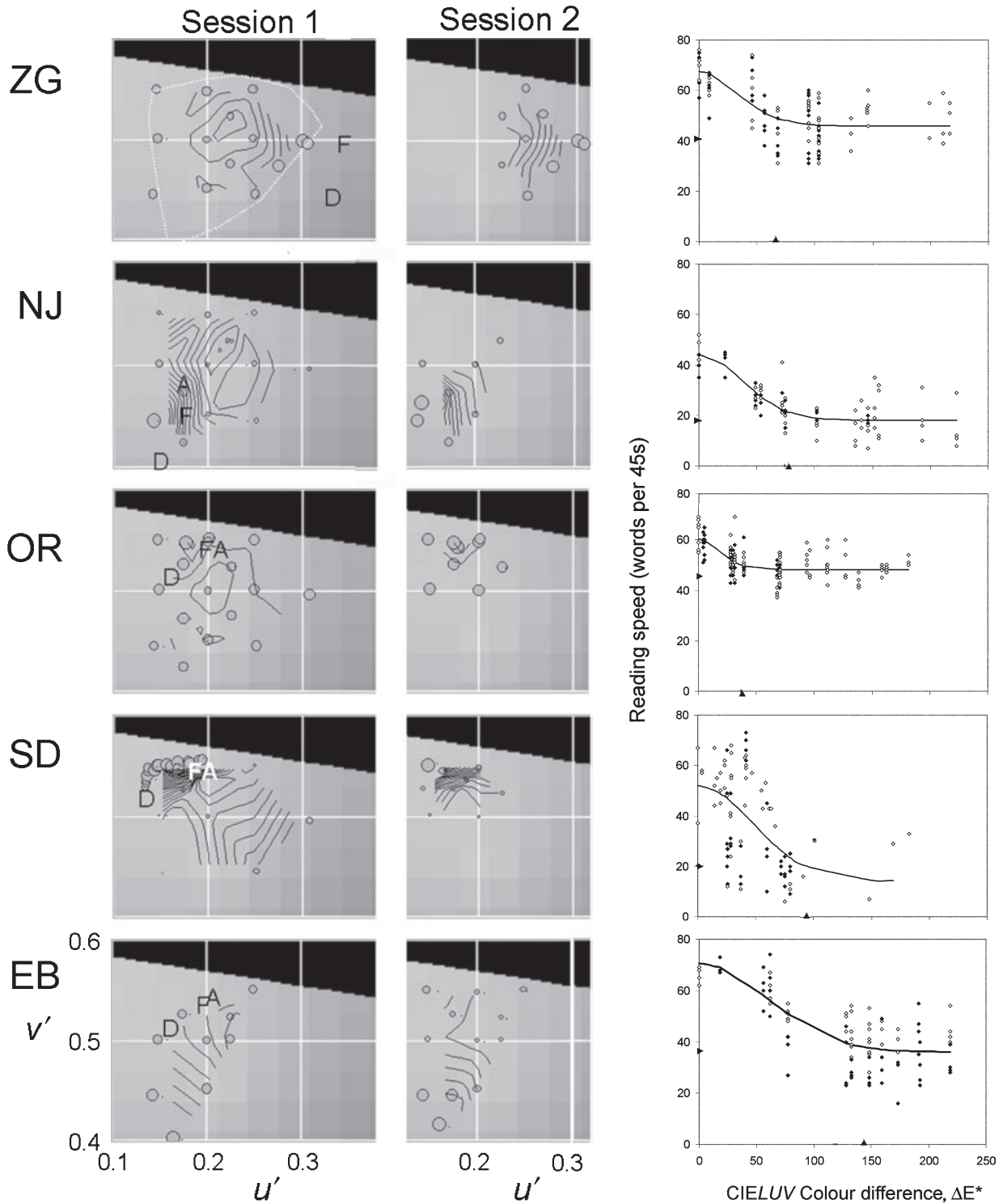


Figure 1. The first two columns show the reading speed of five individuals (rows) under light of different colours. The position of each point shows the chromaticity of the light, and the diameter of the point is directly proportional to the reading speed. Contours representing similar reading speed have been fitted by interpolation using a computer algorithm (triangulation). The contours are similar in Session 2 despite less data. The data have been re-plotted in the third column in terms of the difference in colour between the subjectively optimal colour and the colour under which the reading speed was measured. The colour difference was calculated as 1300 times the distance between chromaticities on the CIE UCS diagram (see text for rationale). The data have been fit by Gaussian functions. The graphs show that a colour difference of 100 (equivalent to about eight just-noticeable differences) is sufficient to eliminate most if not all advantage conveyed by colour. The chromaticity of a spectrally uniform surface viewed through the lenses and illuminated by incandescent light (CIE Type A), fluorescent light (CIE Type F3) or daylight (CIE Type D65), are shown in the first column by the letters A, F and D, respectively. After Wilkins *et al.* (2005).

ably, and in most cases to the reading speed under white light (Wilkins *et al.*, 2005).

The data in *Figure 1* were obtained from individuals who had experienced the use of coloured glasses. The colour that these glasses provided under incandescent (CIE Type A), fluorescent (Type F3) and daylighting (D65) (i.e. the chromaticities of these illuminants when filtered by the prescribed glasses) is shown by the position of the letters A, F and D, respectively, in the first column of *Figure 1*. For four patients, the positioning of these letters is close to the chromaticity optimal for reading. The fifth individual, however, was wearing green glasses but at the time of examination read most quickly under blue light. The way in which reading speed varied with colour is broadly the same for this individual as for the others, suggesting that experience with lenses of the appropriate colour does not contribute much to the nature or consistency of the data shown (for further details of the participants and the procedure, see Wilkins *et al.*, 2005).

Although the effects of colour on reading speed may seem difficult to explain using conventional notions of colour-opponent processing, recent physiological studies have shown that in at least one visual area of the cortex (V2) cells are arranged not in an opponent manner, but in a topographic representation resembling the CIE uniform chromaticity diagram (Xiao *et al.*, 2003). Evidently stimuli of different colours are processed in different parts of the cortex without obvious colour opponency, at least as regards their spatial distribution within the cortex.

The above data raise two questions of clinical importance. First, 'Is the change in colour with different types of lighting sufficient to reduce or even eliminate the benefit from coloured lenses, given the evident dependence on a precise chromaticity?' and second, 'How many different trial tints does an ophthalmic tinting system need to provide in order to supply lenses that will have a given level of efficacy?' The following technical note attempts to address these questions numerically.

The first point to emphasise is that reading speed decreases with departures from optimal chromaticity, whether these are changes in saturation or in hue. It is the distance from optimum that is important regardless of its direction in the CIE 1976 UCS diagram, at least to a first approximation. The data in the third column in *Figure 1* have been fit by Gaussian functions, but for the sake of simplicity in the present context, the function shown graphically in *Figure 2* will be used. Reading speed will be considered to show a linear decrease with increasing 'colour difference' up to a 'colour difference' of about 100, and no further decrease thereafter. Given this approximation, the range (gamut) of chromaticities at which a tint is effective in increasing reading speed

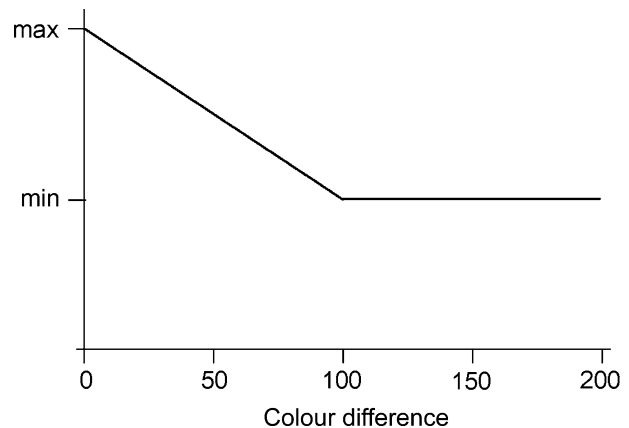


Figure 2. Simplified model of the data shown in *Figure 1*, indicating a linear decrease in reading speed with increasing difference between the colour under which the measurements are made and the colour optimal for reading. The reading speed reaches a minimum at a colour difference of 100, with no change thereafter. Colour difference is here calculated as 1300 times the separation of the chromaticities in the CIE UCS diagram, see text for rationale.

can be described as a circle with its centre at the optimum chromaticity, and a radius equivalent to a 'colour difference' of 100. Chromaticities that have no beneficial effect on reading speed might be expected to lie outside the circle, and those with good efficacy to lie close to the centre of the circle.

Figure 3 shows a selection of tints having the spectral transmission shown in the inset and chromaticities shown by the points in the associated CIE UCS diagram. The tints are those provided by the MRC system for Precision Ophthalmic tinting (Intuitive Colorimeter System), and are designed to have a chromaticity optimal under fluorescent lighting (CIE Illuminant F3). This chromaticity appears at the centre of the circle. The radius of the circles is equivalent to a 'colour difference' of 100, assuming constant luminance. The square points and triangular points show the chromaticities of the tint under a tungsten filament lamp (CIE Illuminant A) and under daylight (CIE Illuminant D65), respectively. As can be seen, all the points lie within the circle, indicating that all the tints are likely to have some benefit. The separation of the points differs markedly with the spectral transmission, however, and for the purple tint in *Figure 3d* the chromaticity under daylight lies close to the perimeter of the circle, indicating little residual benefit. Purple tints transmit at both ends of the visible spectrum, and exaggerate the differences between incandescent light (which has most power at long wavelengths) and daylight (which has considerable energy at short wavelengths). As a result, the change in chromaticity of a purple tint with different types of lighting may be such as to reduce its efficacy considerably. Fortunately, purple tints are rarely prescribed. *Figure 4* shows the

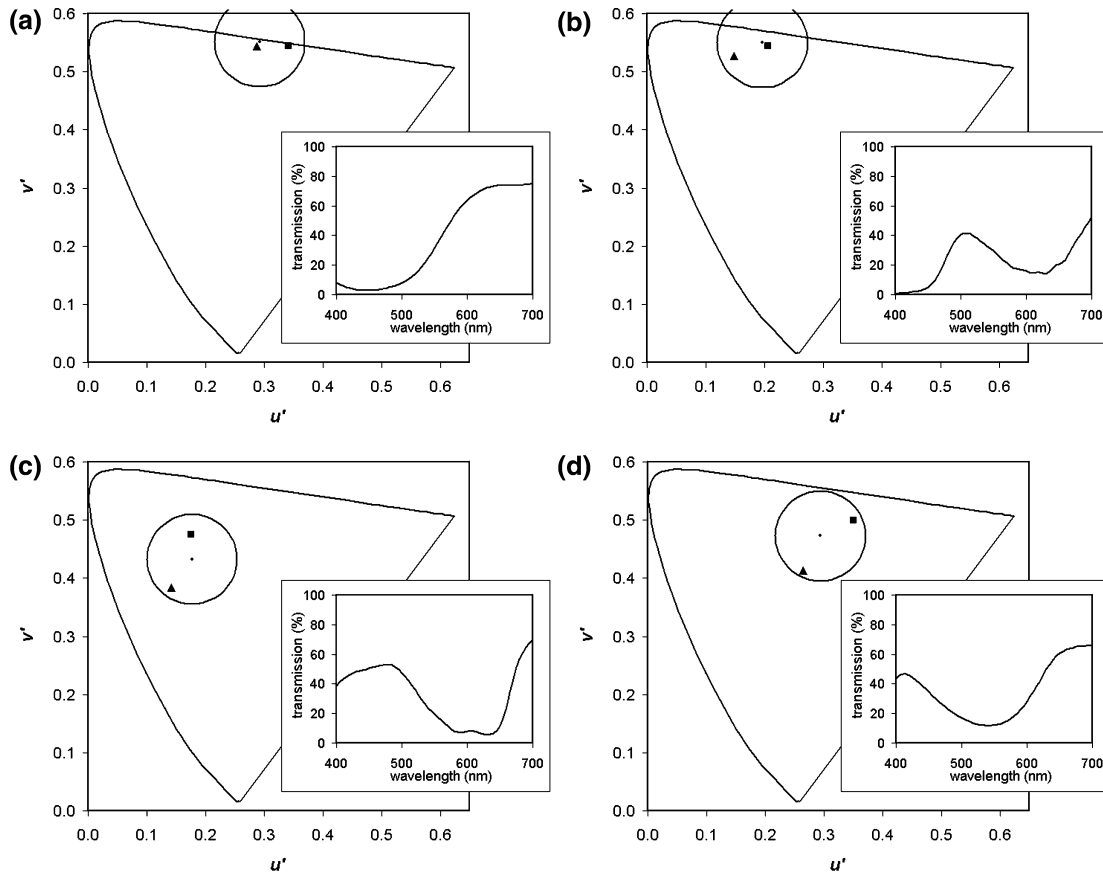


Figure 3. The spectral transmission (inset) of four sample tints: (a) orange; (b) lime green; (c) turquoise and (d) purple, together with their associated chromaticities. The chromaticity of the each under fluorescent lighting (CIE Illuminant F3) is shown by the centre of the circle. Square and triangular points show the chromaticity of the tint under incandescent lighting (CIE Illuminant A) and under daylight (CIE Illuminant D65), respectively.

chromaticities of 1000 recent prescriptions for Precision Tints.

To seek an answer to the first question concerning the effects of different lighting, the spectral transmissions of the 1000 prescriptions whose chromaticities are shown in *Figure 4* were examined, and the chromaticity of the lens was calculated under the standard illuminants, CIE Type A, F3 and D65. In all patients the tints were prescribed using the MRC system. Each tint was selected on the basis of its chromaticity under white halophosphate fluorescent lighting, close to the F3 illuminant. The tints may therefore be assumed to be optimal under light with the CIE F3 spectral power distribution. The 'colour differences' between the chromaticity under the F3 illuminant and that under the other two illuminants, Types A and D65, were calculated. Note that it was not possible to take the luminous transmittance into account in these calculations because lighting level varies under natural viewing conditions, and varies by an amount considerably greater than any variation due to the tints. Incandescent sources are generally associated with lower levels of illuminance

than fluorescent lighting or daylight, and this might be expected to influence the effects of changes in chromaticity. Unfortunately, there are currently no data to indicate how reading speed is affected by luminance in patients who wear tints.

The average 'colour difference' between the chromaticity under Type F3 and Type A was 43 (S.D. 29) and that between Type F3 and Type D65 was, 72 (S.D. 17). Note that the 'colour difference' is lower for incandescent light than daylight, and that this might tend to offset any differences due to lighting level, differences that we have been unable to consider here. The above averages are less than 100 and would therefore suggest that despite the specificity of the effects of colour on reading, some residual benefit of the tints is available under incandescent light and daylight, provided the differences in level are not such as to greatly increase the effects of 'colour difference'. There were, however, a few tints (2.7%) for which the 'colour difference' between the optimal chromaticity (the chromaticity under CIE illuminant F3) and that under either Standard Illuminant A or D65, exceeded 100. These are represented by crosses

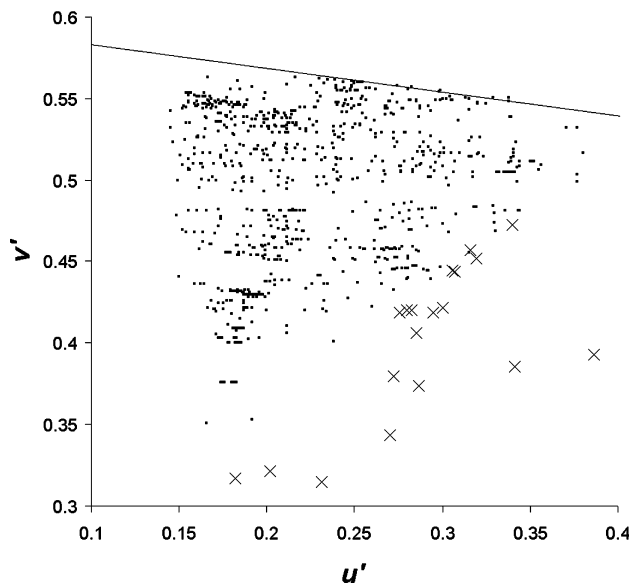


Figure 4. 1000 consecutive prescriptions for precision tints. Chromaticities are shown by points in the CIE UCS diagram. The crosses mark points for which the chromaticity of the tint under the CIE F3 illuminant and that under either illuminant A or D65 exceeded a colour difference of 100. Colour difference is here calculated as 1300 times the separation of the points in the CIE 1976 UCS diagram, see text for rationale. To reduce superposition, points have been randomly jittered on the u' coordinate.

in *Figure 4*. The position of the points indicates that the majority were strongly saturated and a shade of purple in colour. This finding suggests that it is advisable to check the efficacy of a tint under a variety of different light sources, particularly if the tint is purple. A similar conclusion was reached when the Gaussian functions were used to estimate the reading speed of each of the 1000 lenses under the three illuminants (Wilkins *et al.*, 2005). Note that this conclusion stands even if it is unrealistic to ignore lighting level, as in the above calculations.

Turning to the second question, that concerning the number of tints necessary for optimal treatment, we need to consider the range of colours (gamut) needed, and how a tinting system is going to distribute the available tints across the required gamut. We begin with the issue as to what the required gamut actually is. The CIE 1976 UCS diagram provides a reasonable description of the effects of colour upon reading speed, as can be seen from *Figure 1*. Were there any suggestion of colour-opponency in the data shown in *Figure 1* (reading being faster under red light if it is slower under green, etc.) then a different representation of colour might have been appropriate. However the data in *Figure 1* would seem to suggest that an optimal tinting system would distribute the available tints evenly over the CIE 1976 UCS diagram so as to provide a tint close to the individual requirements of different patients. This

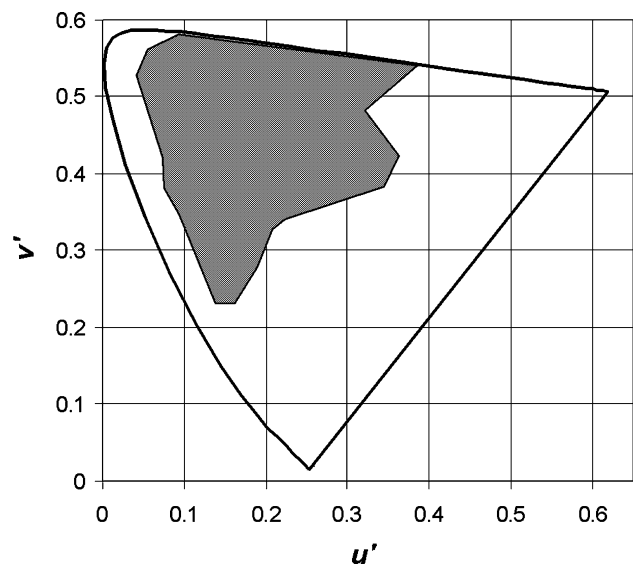


Figure 5. Gamut of tints available using conventional CR39 dyeing techniques, including only those having photopic transmission >5%.

is not to say that the tints should cover the entire diagram: there are regions of the diagram that represent colours that are too strongly saturated to be made available in lenses, simply because the lenses would be too dark. The gamut of tints that offer sufficient transmission can be estimated from the spectral transmission functions of conventional dyes used in combination. A representative gamut is shown in *Figure 5*. Ophthalmic tints outside the gamut shown in this figure might be expected to have transmissions of <5% and therefore to be of little clinical use. The gamut shown by the shaded area in *Figure 5* can be taken to specify the range of colours that any ophthalmic tinting system should be able to provide. The gamut has an area of 0.08, i.e. about 40% of the area enclosed by the entire CIE 1976 UCS diagram.

As argued above, each tint has a region over which it is effective that can, crudely, be described as a circle in CIE 1976 UCS diagram. The circles corresponding to the available tints can be arranged as in *Figure 6* to provide the most efficient coverage of the gamut, in this case a gamut with area of 0.08.

In *Figure 6* the chromaticities of the available tints are represented by the centres of hexagons implied by the intersections of the circles. (The figure includes only one hexagon, for clarity.) The clinically required tint is represented by a point somewhere on the surface. The closer to the centre of a hexagon the point lies, the smaller the 'colour difference' between the clinically required tint and the tint available, in other words, the greater the efficacy of the tinting system. The surface in *Figure 6* can be tiled by a few large hexagons or by many small ones. The greater the number of hexagons and the smaller they are, the closer to the centre of one of the

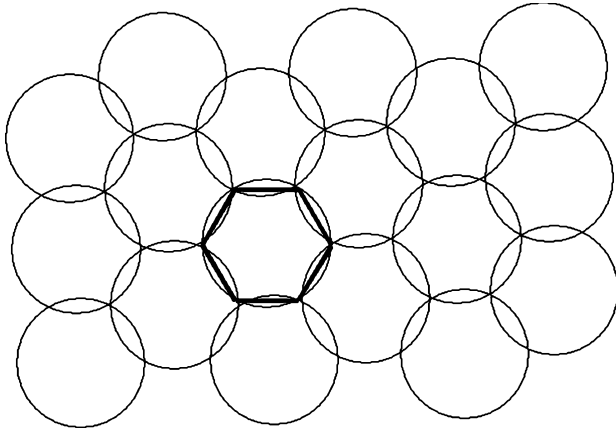


Figure 6. Tessellation of a plane with circles. The entire surface is covered with minimal overlap when the intersections form regular hexagons as per the example shown centre.

hexagons the point will lie. (The more tinted lenses a system has, the closer to the required tint one of the lenses is likely to be.) The maximum distance of a point to the centre of the nearest hexagon is given by the radii of the intersecting circles in *Figure 6*. The number of circles required to cover the surface is given by the area of the surface (0.08) divided by the area of a hexagon. It is on this basis that the broken curve in *Figure 7* has been calculated. It has been assumed that the efficacy of a tint falls off as shown in *Figure 2*.

If a point is randomly positioned within a hexagon, the distance from that point to the centre of the hexagon averages 0.61 ($1/3 + \ln(3)/4$) times the length from centre to apex. Given the function in *Figure 2*, it is possible to estimate the average efficacy of a tinting system. This is shown by the solid line in *Figure 7*.

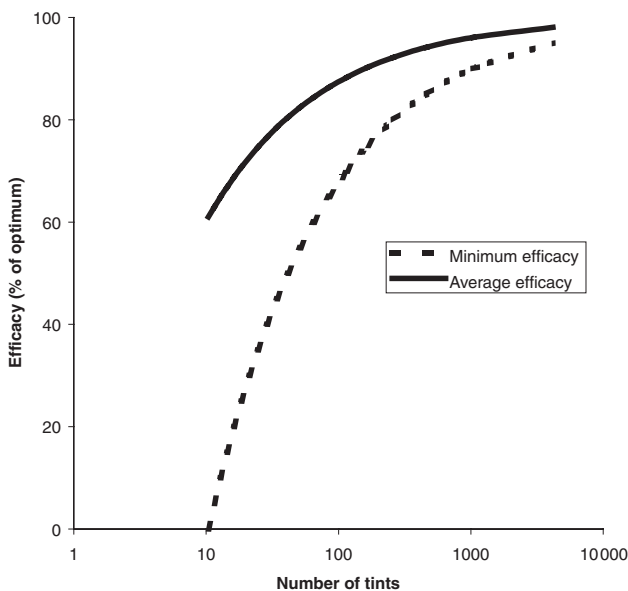


Figure 7. An estimate of the average and minimum efficacy of tints expressed as a function of the number available in a tinting system.

The functions shown in *Figure 7* have been generated on the assumption that for optimal efficacy, each individual needs a precise chromaticity and that the efficacy of the tint drops off linearly as the chromaticity departs from this optimum, reaching zero efficacy when the ‘colour difference’ exceeds 100. The functions will change if different colour spaces are used, and if the proportion of the space that is capable of being sampled by ophthalmic tints is changed. The function will nevertheless remain a power law, that is, the number of tints required to achieve optimal efficacy will increase as a power of the degree of precision required.

Implications

The function in *Figure 7* shows that the average level of efficacy for systems with eight colours is likely to be <50% of optimum, and for systems with 30 colours, <75% of optimum. The above calculations suggest that for an average efficacy >95% of optimum, at least 1000 trial tints are required. This is a minimum estimate that assumes that the trial tints are distributed evenly across the gamut. If this assumption is not met, the number of required tints will be larger still. Although the number of tints required may appear very large, this large number is easily achieved: trial lenses having dyes with two different but neighbouring chromaticities can be superimposed in systematic combinations and used to guide the dyeing of spectacle lenses (Wilkins *et al.*, 1992b; Wilkins, 2003).

Conclusion

The numerical analyses would seem to indicate the following answers to the questions posed above: (1) for most individuals, the variation in colour with illumination is sufficient to reduce, but not eliminate, the beneficial effects of the tints; (2) for an average efficacy >95% of optimum the number of trial tints needs to exceed 1000.

Acknowledgements

The authors thank Tim Noakes of Cerium Visual Technologies for the use of the data on prescriptions with the MRC system for precision ophthalmic tinting (Intuitive Colorimeter System). They also thank the anonymous referees whose comments helped to improve this paper.

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