Preliminary observations concerning treatment of visual discomfort and associated perceptual distortion

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A system for therapeutic precision tinting is described. Some individuals who are subject to perceptual distortion of text no longer perceive the distortion when the text has a particular colour. A simple colorimeter enables an observer to illuminate text with light of a particular chromaticity, varying first CIE 1976 hue angle (h_{uv}), then saturation (s_{uv}), and then luminance, to obtain a setting that maximizes visual comfort and reduces any perceptual distortion. The colorimeter setting is then matched by a combination of tinted trial lenses. The combination uses only two dyes at a time from a selection of seven, unless a dark lens is required, when a third neutral (grey) dye is added. The subject observes both text and a normal scene when wearing tinted trial lenses. A variety of trial lenses are compared including those that match the colorimeter setting and others with similar hue angle. Spectacle lenses are then tinted so as to have a spectral transmission identical to that of the chosen combination of trial lenses. Certain patients with reading disorders, eye-strain, headaches or photosensitivy epilepsy report benefit when wearing spectacles tinted according to the above techniques. The physiological basis for the therapeutic effects is uncertain, but may involve a selective impairment of luminance or colour-difference channels.

Ophthalmic tints have a long history, although their use in treating reading disorders is a recent and controversial[1] innovation due to Irlen[2]. Irlen has described how many children with specific reading difficulty report perceptual distortions of text that impair fluency and are associated with visual discomfort. She reports that the distortions can be reduced by a specific tint, different for each individual, and she has developed proprietary techniques for the provision of such a tint. The following paper describes a rapid system for therapeutic precision tinting which was developed initially to investigate Irlen's findings, but which has subsequently appeared to be of use in certain cases of migraine and photosensitive epilepsy, as well as those of reading difficulty. The system uses a colorimeter to enable an observer to choose a therapeutic colour. That colour is matched using combinations of trial lenses. The trial lenses enable the observer to assess the tint under normal viewing conditions and they provide a simple formula to guide the dyeing of spectacle lenses.

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An intuitive colorimeter

A wide variety of colours can be produced by mixing three coloured lights in varying amounts but it can be difficult to mix the lights to match a particular colour. Colours exist in three intuitive dimensions (hue, saturation and brightness) all of which change when one of the lights is varied. We have therefore developed a simple variant of the Burnham colorimeter[3] that enables an observer to change just one dimension at a time. For example, hue can be varied, keeping saturation and brightness more or less constant[4]. A wheel is divided into three sectors, each sector transmitting light of a different colour. A collimated cylindrical beam of white light passes through the wheel, and is coloured as a result. The coloured light is then mixed by multiple reflection. When the wheel is concentric with the beam, the three sectors are mixed in equal proportion and, given the appropriate filters, the mixed light is white. The wheel is free to translate so that the beam can pass eccentrically through it. The filters then no longer have similar area. The mixture becomes progressively more saturated as eccentricity increases. The wheel is also free to rotate.

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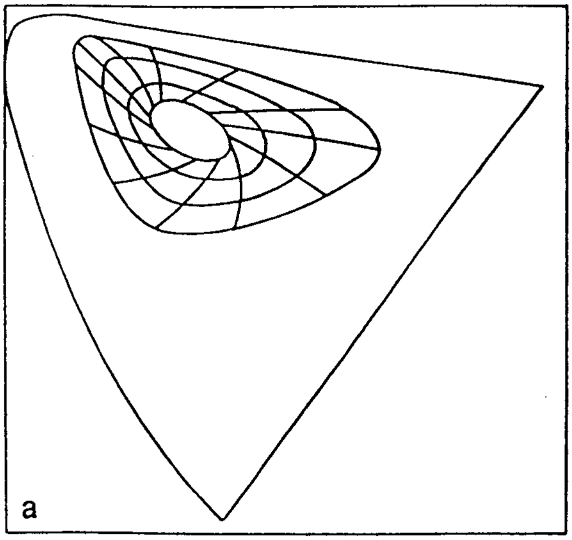

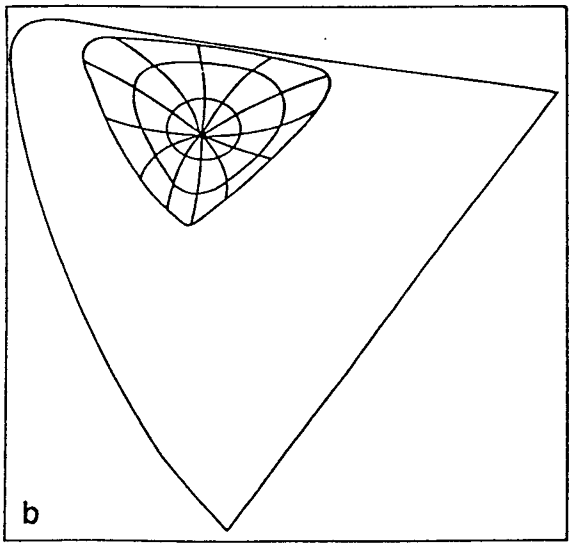

Figure 1 CIE 1976 UCS diagrams showing the loci of chromaticity coordinates obtained by rotating the wheel of the colorimeter (closed curves) and by moving the lever (radiating curves). Version used in preliminary studies (*a*); version used with tinting system (*b*). All coordinates within the outer curves were obtainable apart from those within the innermost curves in (*a*)

This changes the hue. In terms of the CIE 1976 UCS diagram (*Figure 1*), rotating the wheel moves the coordinates of the mixed light in a near-circular locus centred on white. Changing its eccentricity moves the coordinates along radii from white.

In the following studies two versions of the above colorimeter have been used. In the initial studies the colorimeter had the gamut shown in *Figure 1a*, and in later studies involving the precision tinting, the gamut in *Figure 1b*. Light from a theatre lantern passed through a Perspex disc in which theatrical colour filters were sandwiched. After passing through the disc the light struck a matt white surface, and was scattered within a box with matt white inner surfaces. Text was mounted on one of these surfaces and viewed through an aperture in the box. The observer could rotate the disc, using a wheel, and could move the disc eccentrically in the beam using a lever. Luminance was varied by placing a series of plates with different metal mesh in the beam of light. This inexpensive alternative to neutral density filters left the colour temperature of the light quite unaltered.

The colorimeter had several advantages for research: hue, saturation and brightness could be varied intuitively and more-or-less independently; the variation was continuous rather than discrete so that an infinite choice of colour could be made within the gamut available; no coloured surfaces were visible within the colorimeter, so it was unnecessary to consider the particular spectral power distribution of the illuminant, and related colour constancy mechanisms.

We examined 22 children with reading difficulties whilst the apparatus underwent development. The children were selected as reporting perceptual distortion of text, for example, instability of words or letters (the letters 'wobbled', 'fizzed', 'moved about'). Some of the children were referred by local educational psychologists and teachers, others were brought by their parents in response to an article in *Living* magazine. The children were asked to vary the colour of the light to see if they could obtain a setting that reduced their perceptual distortions. Settings were obtained at a variety of levels of saturation whilst they observed a page. The page resembled text and consisted of random letters arranged in strings 1–7 letters in length. The space-averaged luminance was initially about 15 cd m^{-2} but was varied to determine whether the observer reported a decrease in perceptual distortion when the luminance was reduced.

Preliminary findings

The following is a summary of the preliminary findings, which have been described elsewhere[4]. For most children, but not all, there was a region of colour space within which they reported that their perceptual distortions abated. The region showed consistency within the UCS diagram, and at retest, but varied from one observer to another. A few children reported a reduction in perceptual distortion but showed no consistency as to the associated chromaticity coordinates. For most observers, adults included, there was a region of colour

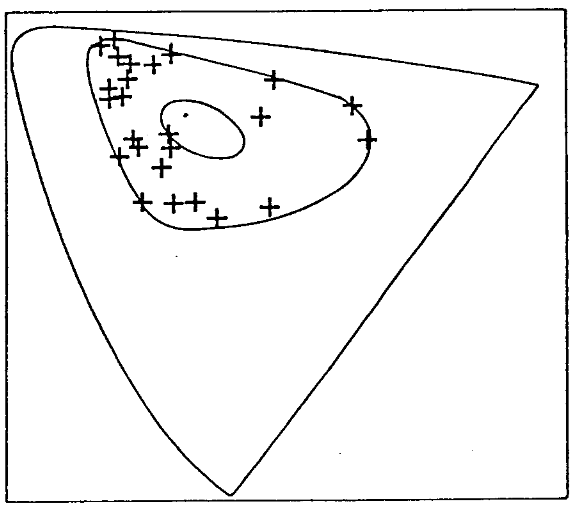

Figure 2 CIE 1976 UCS diagram showing colorimeter settings, +, at which optimal reduction of distortion was reported by 22 children who were subject to perceptual distortion of text under normal viewing conditions

space in which the distortions were exacerbated, and the text could become painful. Sometimes signs of discomfort were obvious: there was wincing and aversion of gaze. This region in which discomfort occurred was usually complementary to the region in which distortions abated. In general, there was a tendency for the symptom-free area of colour space to be within the left-hand half of the UCS diagram ($u' < 0.25$); see *Figure 2*.

In agreement with previous work[5]*, most of the children had migraine or had a family history of migraine. Their tendency to choose colours complementary to red is therefore consistent with the finding that adults with migraine report maximal discomfort from reddish illuminants when reading[6]. For some observers the specificity and consistency in the choice of colour was remarkable. Preliminary work indicates that the consistency is close to that obtained in normal observers when they are repeatedly shown a particular shade of colour and asked to reproduce it immediately from memory.

A priori considerations would suggest that a colorimeter setting is not likely to be of use in the selection of an ophthalmic tint. The brain constructs a 'model' of the spectral power distribution of a light source from the light reflected by a large number of surfaces with different spectral reflectances. It uses this 'model' to discount the effects of the illuminating light, and compute the colour of the surfaces on the basis of the light they reflect. A pair of tinted lenses have an effect similar (but not equivalent) to that of changing the colour of the illuminating light. Within limits, coloured surfaces viewed through a tinted lens look more or less normal, and the colour of the illuminating light is perceived to have changed. The reflections that occur between surfaces mean that a coloured lens can never have exactly the same effect as a change in the colour of the light source. As a result of the above colour constancy mechanisms, a colour that reduces symptoms in the colorimeter, which has no coloured surfaces, should not necessarily do so when the colour is provided by tinted glasses, and a variety of surfaces with difference spectral reflectance play a role. The following study suggested that despite the above considerations, the colorimeter setting did in fact provide a good indication of a potentially therapeutic colour for tinted lenses.

Comparison of techniques

Nine children (aged 12–16 years) who reported perceptual distortion of text and who had severe reading difficulties were assessed using the colorimeter and also by alternative proprietary techniques developed by Irlen[2]. These latter techniques involved the repeated application of coloured trial lenses, initially singly and then in combination. The proprietary examination took place in a room lit by a mixture of daylight and the light from a fluorescent lamp. The order of the examinations was counterbalanced, and they were performed within 2–24 h of each other.

It was surprising that, in eight of the nine children, the colour appearance of the combination of trial lenses agreed very closely with the colour appearance of the colorimeter (h_{uv} within ± 20 degrees). The ninth did not give a consistent setting in the colorimeter. This suggested that in severe cases, at least, the colour setting was robust and that it was relatively unaffected by the presence of coloured surfaces in the field of view. (Coloured surfaces were visible when trial tints were used, but the colorimeter had no coloured surfaces.) Perhaps the mechanisms responsible for the distortions involve visual areas previous to those in which colour constancy is computed and depend instead simply on the relative activation of the photoreceptors.

The findings further suggested that the colorimeter could provide a rapid indication of a potentially therapeutic tint. To assess whether this was the case it was necessary to develop a tinting system. This was because many of the settings in the colorimeter could not easily be reproduced with the cosmetic tints available on the market and because the Irlen tints were proprietary.

Therapeutic precision tinting

Lenses and dyes

Organic dyes suitable for tinting allyl-diglycol-carbonate resin (CR39) lenses were selected on the basis of six principles.

1. Where the primary dyes were available, they were used in preference to the composites (mixtures of chemicals) commonly used for cosmetic dyes. Primary dyes were available for all except green and turquoise, which were provided by mixing yellow and blue primary dyes.
2. The dyes were chosen for their stability in the tint bath.
3. The spectral transmission curves of lenses tinted with the dyes were as smooth as possible. With cosmetic tints the spectral transmissions are sometimes very uneven. When trial tints are superimposed, one transmission curve is multiplied by another, which can increase the unevenness. An uneven spectral power distribution can increase metamerism, making colours more confusable.
4. The dyes were suitable for rapid tinting. For blue, the dye with the smoothest spectral transmissions was far too slow to be practical.
5. The hue angles of the dye colours were equally spaced, so as to sample colour space evenly.
6. A relatively large number of dyes (seven) was selected so there would always be one colour from the selection that would have a colour appearance close to that of the colorimeter setting.

The dyes chosen had the following colours: rose, orange, yellow, green, turquoise, blue and purple. The chromaticity coordinates of the trial lenses are shown by the large diameter points in the central panel of *Figure 3*. A neutral grey dye was added so that the transmission could be varied independently of colour.

Trial lenses were prepared using these dyes with different degrees of deposition of dye so as to vary the saturation of colour. The trial lenses were arranged in pairs (one for each eye) and five pairs were provided for each of the seven dyes (six for rose). The deposition increased geometrically from one pair to the next (see *Figure 3*, peripheral panels) so that 31 (i.e. $2^5 - 1$) levels

*In reference 5 there are the following printers' errors. The 4th paragraph should refer to *absorptance*, not *absorption*; the 10th Column of Table 2 should read *Suppression*, not *Supplement*, and the column entries beneath should read *intermittent*, not *internal*.

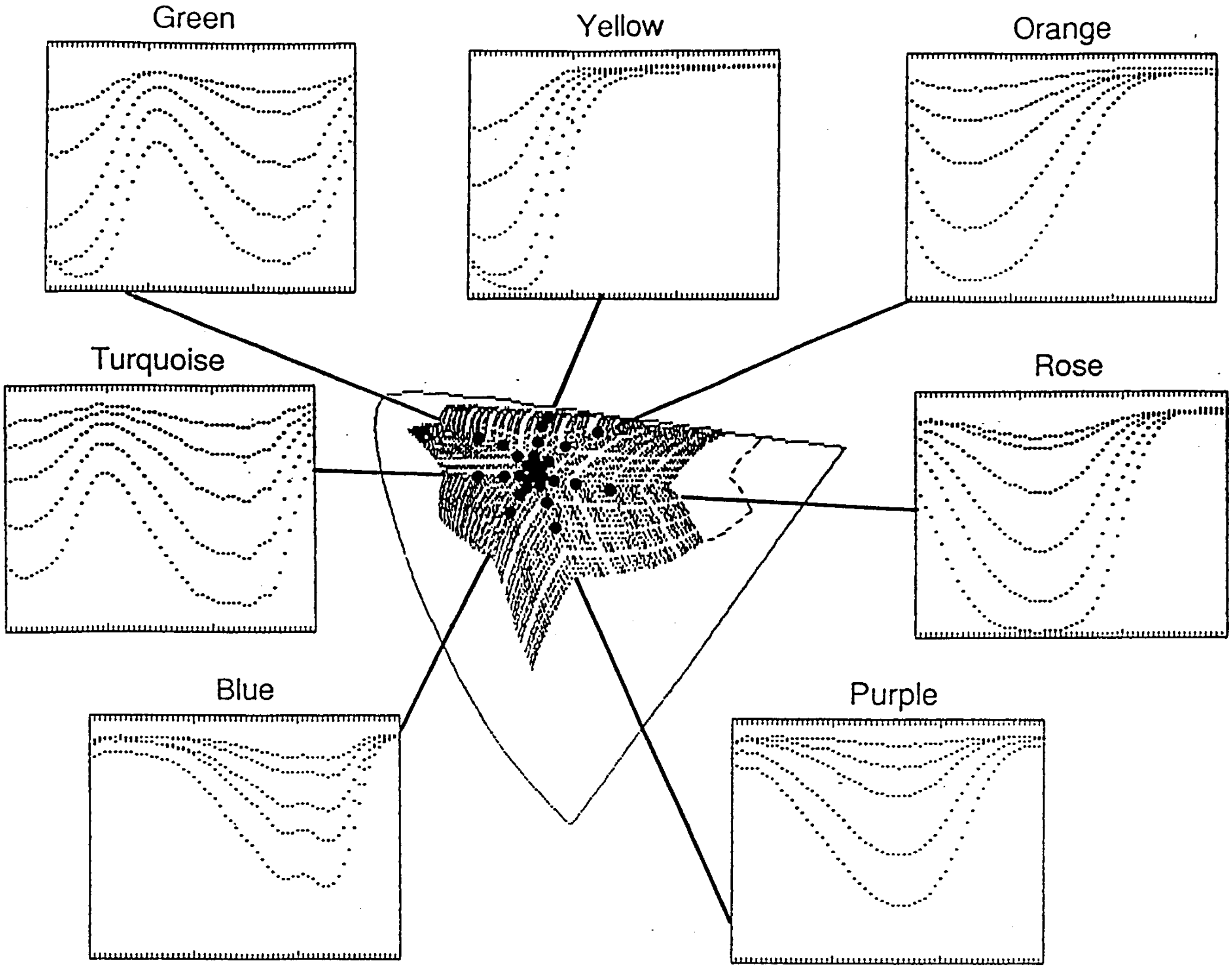

Figure 3 Centre: CIE 1976 UCS diagram showing chromaticity coordinates of the trial lenses, ●, and combinations of these lenses, •, when the dyes were combined two at a time. Periphery: transmissions of the trial lenses (0–100%) as a function of wavelength (400–700 nm). The perimeter of the obtainable combinations using a sixth rose lens is shown, ---

of dye deposition could be obtained by superimposing the trial lenses, adding them in all possible combinations.

The trial lenses for two dyes could be combined so that $31 \times 31 = 961$ tints with colours in between those of the two dyes were obtainable. *Figure 3* shows the $u'v'$ coordinates of the 961 combinations of orange and rose, the 961 combinations of rose and purple, purple and blue, blue and turquoise, etc. As can be seen, a large area of the UCS diagram has been evenly and densely sampled using only two dyes at a time, both with similar hue angle. The area is extended as shown by the broken line when a sixth trial lens is added for the rose dye. The photopic transmission of the tints could be separately adjusted by adding neutral density filters.

The fact that only two dyes were needed to obtain any shade (and a third to vary transmission) means that it was very simple to dye spectacle lenses to the appropriate shade. The chosen trial lenses were separated into two stacks, each stack consisting of lenses tinted with the same dye. The spectacle lenses were dipped into one dye until the colour appearance matched that of one of the stacks of trial lenses. The trial lenses from the second dye were then added to the stack so that all the relevant trial lenses were now superimposed. The spectacle lenses were then dipped into the second dye until the colour appearance matched that of all the superimposed trial lenses. The colour appearance was judged when the spectacle lenses and the stack of trial lenses were placed side by side on white paper and viewed through two apertures in a sheet of white card, thus eliminating the perceptual effects of the edges of the lenses. The comparison was made under three different illuminants ('full-spectrum' fluorescent light, tungsten–halogen light and daylight). When matched in this way the spectral transmission of the spectacle lenses was virtually identical to that of the stack of trial lenses, differing only slightly in overall transmission.

The tinting system has been used in conjunction with the colorimeter in the studies now to be described.

Assessment procedure

The colorimeter contained a large (A4) page of random letters, unless the subject's signs or symptoms suggested that this was too uncomfortable to view, in which case the text was partially covered with white paper.

Beginning with a low saturation, the subject slowly rotated the wheel of the colorimeter, varying hue angle, noting the colours that made the text least comfortable. These hue angles were subsequently avoided, particularly at higher saturations. The subject then set the wheel to a colour that was the most comfortable. If the subject found this difficult, a colour complementary to the least comfortable colour was chosen by the examiner. Next, the subject operated the lever, varying saturation until the best setting was achieved. The hue angle was then fine-tuned, by instructing the subject to operate the wheel 'in much the same way as the dial on a radio set'. If the subject again appeared uncertain, alternative settings of hue and saturation were provided by the examiner for successive pairwise comparison. If consistent settings of hue and saturation were not obtained, the procedure was terminated. If consistent settings of hue and saturation were obtained, luminance was varied by interposing different grades of metal mesh in the beam of light so as to assess whether a neutral tint was necessary.

The viewing aperture was then closed, revealing two comparison ports: the first port showing a white surface within the box, lit with the appropriate mixture of coloured light, and the second, a white surface lit with 'cool white' (F2) fluorescent light, luminance 35 cd m^{-2}.

The examiner selected a trial lens that was nearest in appearance to the colour of the first port and held this in front of the second so as to compare the colour appearance of the two ports. The examiner then superimposed a trial lens from only one of the neighbouring colours to refine the colour appearance, selecting trial lenses from only two dyes until the colour appearance of the two ports matched. A duplicate combination of lenses was then prepared and the two sets of lenses given to the subject to try as a pair (one lens combination for each eye). The subject then compared this combination of lenses with combinations of a range of similarly coloured lenses in order to select the one most comfortable for viewing text and natural scenes. In particular, the subject was given the option of reducing the saturation of the colour, and the lowest saturation sufficient to reduce symptoms of discomfort and perceptual distortions was selected.

Preliminary results

During the last year, whilst the above techniques have been under development, 108 subjects have been examined. (The assessments were undertaken binocularly except in one child where there was evidence of uniocular pathology.) Tinted lenses suitable for fitting into frames were supplied free of charge. A detailed assessment of the results is not yet possible, but the following points can be made.

When they held to their eyes the trial lenses that best matched their colorimeter setting, most subjects reported a reduction in discomfort and distortion. This was usually the case not only when they looked at text, but also when they viewed a natural scene lit with daylight. If the colorimeter had a high saturation, however, some subjects preferred a similar but less saturated colour, presumably because this interfered less with the colour appearance of objects and left white surfaces white in appearance. This observation is not at variance with the earlier suggestion that colour constancy mechanisms play a minimal role in the selection of a therapeutic tint.

One subject with a history of amblyopia was examined monocularly as well as binocularly. He gave different settings with the two eyes monocularly but ultimately elected to use a single tint binocularly, the colour having chromaticity coordinates on a line joining the coordinates of the two monocular settings.

In the case of children with reading disorders, parents' comments show considerable consistency. The children are reported to enjoy wearing their coloured glasses, and their attitude to reading is said to have changed. They usually read for longer without eye-strain and have fewer headaches. They sometimes, but not always, show improved reading.

The following cases have proved particularly instructive.

A 14-year-old girl complained of daily headaches behind the right eye, which was amblyopic. Letters appeared unstable: she would read *was* for *saw* and *vice versa*. She was given yellow glasses after an assessment similar to that described above. She kept a diary from which the following are quotations: 'All stress went from my eyes that I did not know was there ... Can read faster ... Don't need to think hardly ... MUCH easier ... When reading, words spread out. Have realised that is why I used to write with very large spaces between words. Now I don't – that means I don't get told off any more.' She goes on to describe a reduction of her headaches.

A 20-year-old woman had a similar problem, although her reading difficulties were more severe. Two of us (T.M. and S.Y.) had noted that she was unable to read words correctly because she was uncertain as to the relative position of letters. She would read *saw* as *was*, *on* as *no*, etc. When she read using a yellow colour, either in the colorimeter or using tinted lenses, the errors of reversal

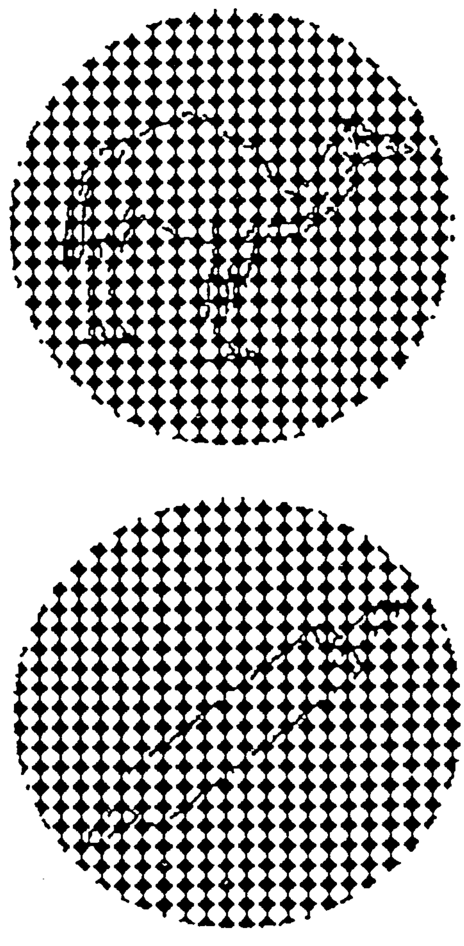

Figure 4 Masked line drawings. Improvement in perception sometimes results from wearing tinted lenses

no longer occurred. She reported that the letters did not then move around. She had an early history of strabismus, treated with eye exercises that were not completed. Her acuity in the left eye was poor. Covering one eye improved reading but did not prevent the reversals.

An improved perception of the masked drawings in *Figure 4* is occasionally observed in children with reading difficulties who find the glasses helpful. The drawings can, however, be too stressful in some cases, and many show no improvement in perception. (The test is available from the first author on request.)

Tinted glasses appear also to have been helpful in four cases of photosensitive epilepsy. The following is one of the clearer cases. A 32-year-old woman suffered photosensitive epilepsy. She was intolerant of sodium valproate. She selected a rose tint. 'I find now that bright electric light, whether fluorescent or incandescent, no longer causes discomfort. I can only describe the relief as comparable to a cool breeze in an over-heated environment ... I can now read for quite long periods or watch televison without developing the tiredness/headache that was previously so common. I have had no recurrence of epilepsy since using the spectacles ...'.

Two cases of severe migraine also appear to have benefitted. A 45-year-old woman had a 10-year history of classical migraine with several attacks per week. She was admitted to hospital in 1989 with a suspected subarachnoid haemorrhage. The CT scan was negative and the final diagnosis was probable vascular headache. She selected a yellow tint and has suffered only two attacks in the last 6 months, both minor.

A 42-year-old woman reported two isolated episodes of loss of left-sided vision without associated pain. Nearly every day she suffered nausea 'like being car sick'. She selected a blue tint. She has had only two episodes in the last 6 months. The remission of symptoms has meant that it has proved possible to withdraw all propanolol.

One patient with reading difficulty was also subject to attacks of panic. A 43-year-old woman suffered panic in supermarkets. She selected a yellow tint. Now she no longer panics, and reports improved balance. She is an artist by profession and when drawing she finds she is no longer reversing shapes.

The history of a 25-year-old woman brings all these points together. She had suffered two seizures, and her EEG demonstrated photosensitivity. She suffered 1–3 bad headaches per month. She reported a barrel-like distortion of a page of text, with words jumping 'in much the same way as stripes do on a striped shirt when you are trying to iron it'. She had discovered for herself that these distortions disappeared when she looked through an orange–brown lens. In the colorimeter she could not find this brown colour but was surprised when the distortions disappeared under an orange–yellow light. Brown is not a spectral colour, and is not available in the colorimeter. It is perceived when a yellow or orange surface appears dark. When the coloured lens that matched the colorimeter setting was shown her she recognized the colour as the one that helped. Evidently, in her case, at least, the colorimeter adjustments were being made on the basis of symptoms rather than simply preference or prejudice. She compared a range of similarly coloured lenses and rejected all but one, the one that matched the colorimeter setting. Her headache frequency has since been reduced.

The above histories have the status of anecdotes. The tinting system is now undergoing placebo-controlled clinical trials.

Theoretical speculation

Many of the children with reading difficulties had migraine in the family. Adults with migraine tend to find red colours uncomfortable for reading[6]. Although yellow was a commonly chosen colour in the histories described above, the children tended to make colorimeter settings that were complementary to red. There are good grounds for believing that a disease such as migraine could have effects on the visual system that are quite specific. Ischaemic damage[3] might be expected to affect selectively cells that have a high metabolic turnover, for example, the relatively large cells of the magnocellular pathways and/or the cytochrome oxydase blobs and stripes. This damage might have consequences for the processing of colour.

One of the clinical features common in migraine and present in all the above cases is the complaint of a sensitivity to glare from bright light and high-contrast patterns. The following simple hypothesis enables the wide variety of choices of therapeutic colour to be interpreted as due to various degrees of impairment in the processing of luminance information or colour information, and in particular, it enables the choice of colours complementary to red to be attributed to an impairment of the luminance channel.

It has been argued by Buchsbaum and Gottschalk[8] that receptor signals are combined into a luminance channel conveying most of the information and two colour difference channels, one red–green and the other yellow–blue. They derived this familiar concept from first principles using the assumption that the transmission of information over visual pathways is made as efficient as possible. They argued that because the receptor spectral sensitivities overlap it would be inefficient to transmit signals from the receptors without preprocessing to reduce the redundancy. The transmission can be made efficient by decorrelating the receptor output and transmitting a luminance signal and two colour-difference signals. It is perhaps unsurprising that the brain may use optimally efficient signal processing, but it follows from the mathematics presented by Buchsbaum and Gottschalk that if one of the channels were selectively impaired by disease, the information transmission could be re-optimized by changing the output from the photoreceptors. Such a change could, for example, result from the wearing of a tinted lens, particularly a strongly coloured lens that overcame the effects of the receptor adaptation that would undoubtedly occur. We are currently exploring models of the changes in the distribution of information in luminance and colour-difference channels that would result from lenses with various colours. Given the assumptions made by Buchsbaum and Gottschalk, colours complementary to red would reduce the information processed by the luminance channel. In short, we follow Fergus Campbell in postulating visual deficits that originate in channels, in particular colour vision deficits that are due to deficient pathways rather than deficient photoreceptors*. The

*There is, as yet, no evidence that conventional colour vision deficits are particularly prevalent in these cases, at least as measured using simple clinical tests.

effects of such deficiencies can perhaps be ameliorated by tinted lenses.

Acknowledgements

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