Technical Note

Colorimeter for the intuitive manipulation of hue and saturation and its role in the study of perceptual distortion

Arnold J. Wilkins, Ian Nimmo-Smith and Judy E. Jansons*

*Medical Research Council Applied Psychology Unit, 15 Chaucer Road, Cambridge CB2 2EF and *25 Keats Way, Hitchin SG4 0DP, UK*

(Received 21 January 1991, in revised form 18 November 1991)

A simple optical method for mixing coloured light is described. The observer has intuitive and approximately independent control over hue and saturation at constant brightness. The method facilitates colour matching by unpracticed observers. It allows children with reading difficulties to select a colour that reduces perceptual distortion of text. The chromaticity coordinates of this colour vary from one observer to another but can be very specific. Complementary colours can exacerbate the distortions and induce pain. For the majority of children reporting beneficial perceptual effects, the u' coordinate is less than 0.25.

Three coloured lights (primaries) can be mixed in varying proportions to produce a wide range (gamut) of different colours. The way in which the lights interact to produce a given colour is not intuitively obvious, so it can be difficult and time consuming to mix a particular shade. Burnham[1] overcame some of these difficulties with a device that enabled colour to be explored without a change in brightness, and Boynton and Nagy[2] developed his device in an apparatus that produced chromatic differences along the deutan and tritan axes in colour space. Neither of these devices provides an observer with the opportunity of mixing colours in an intuitive manner, that is, by varying colour and depth of colour (saturation) independently.

When text is illuminated by light of a particular chromaticity some children with reading difficulties report a reduction in the perceptual distortion of text, a distortion to which they are subject under white light[3,4]. The chromaticity coordinates that appear to have this beneficial effect vary from one observer to another. The following device was developed to enable children with learning difficulties to explore colour space.

Description of the apparatus

A transparent disc shown in *Figure 1a* is divided into three sectors. Filters are attached to the disc to colour one sector red, one green and one blue. The disc is free to rotate about a central axis and the axis is free to translate (move laterally). A beam of collimated white light, circular in outline, and with a diameter less than half that of the disc is directed through the disc. After passing through the disc the coloured light is mixed by multiple reflection. The filters on the disc are chosen so that they transmit similar photopic energy. The luminance can be changed without affecting colour by interposing various grades of metal mesh in the beam.

The proportion of red, green and blue light transmitted depends on the position of the beam with respect to the disc. When the beam and the disc are concentric (*Figure 1a*) the transmission of the filters and the sector angles can be adjusted so that the three primary colours are mixed in a proportion appropriate to produce a suitable white. Rotation of the disc is without effect, provided the beam is diffuse. The disc is free to move laterally, so that the beam of light can pass through the disc eccentrically. The proportion of the primary colours changes, increasing saturation (*Figure 1b*). The colour can then be varied by rotating the disc (*Figure 1c*).

The geometry of the exposed region of the disc is complex. *Figure 2a* shows an example of the configuration in which the disc is divided into three radial sectors each 120° at the apex. The areas of the sectors are given in the legend for this figure, expressed as a function of x, the distance between the centre of the beam of light and the centre of the disc. The graph in *Figure 2b* shows a triangular surface which describes in baricentric coordinates the proportion of the areas of the smaller circle taken by the sectors PXY, PXZ and PYZ. The concentric closed curves show the way in which the proportion varies as the disc is rotated (changing θ), and the radial curves show the variation with the eccentricity (x). The triangle can therefore be thought of as representing an arbitrary chromaticity diagram, the coordinates of the three primaries at the apices. For example, the apices of the triangle might represent the coordinates of three filters in the CIE 1976 uniform chromaticity scale diagram and the chromaticity coordinate of the centre could be that of some reference

Patent applied for.

0275-5408/92/030381-05

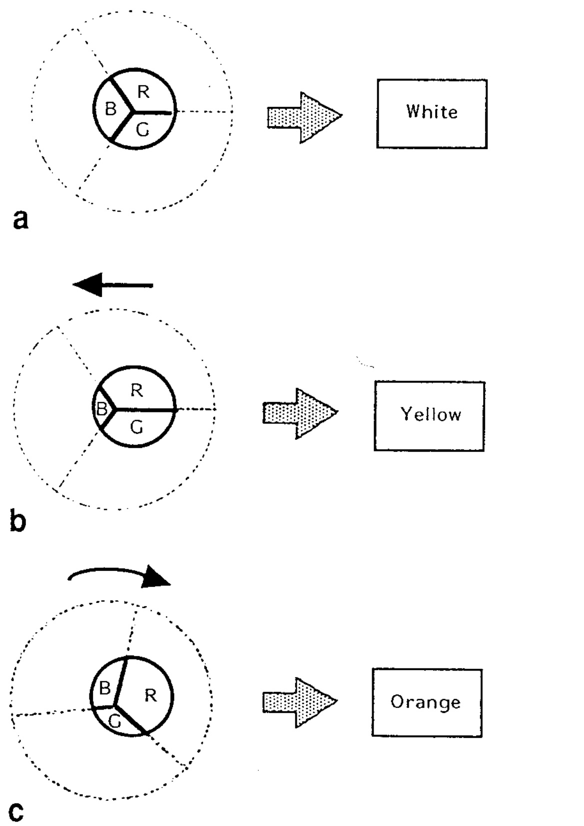

Figure 1 Illustration of the principle of the intuitive colorimeter. A transparent disc is divided into three sectors bearing filters coloured red (R), green (G) or blue (B). The disc is free to rotate about a central axis, and the axis can move horizontally varying its position with respect to a stationary circular beam of white light, the centre of which has the same vertical position as the centre of the disc. After passing through the disc, light from the beam is mixed by multiple reflection. (*a*) When the beam and disc are concentric, rotation of the disc is without effect. The transmission of the filters and their relative angular size can be adjusted so that the mixture has the coordinates of a suitable reference white. (*b*) As the disc is moved horizontally within the beam the relative proportions of the three primary colours change. (*c*) Rotation of the disc changes colour, and the saturation of the colour varies monotonically with the eccentricity of the disc

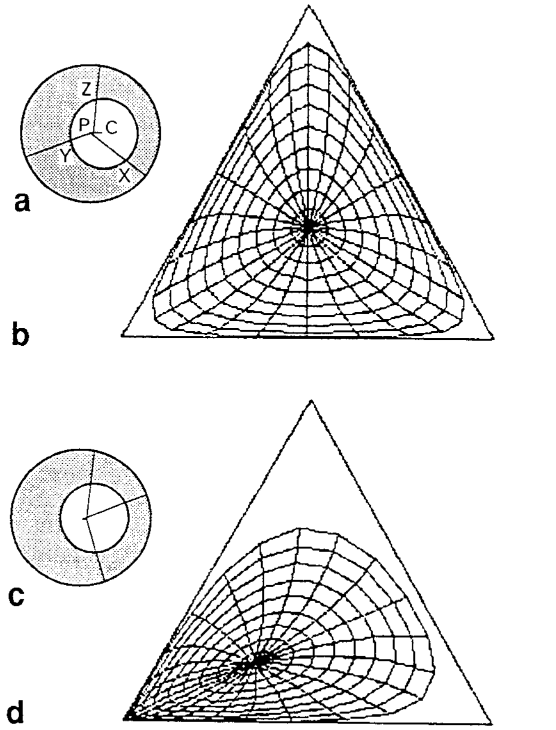

Figure 2 (*a*) The geometry of the colorimeter when the sectors subte equal angles at P of $2\pi/3$ (120°). The circular light beam, has cent C and radius CX, and the disc has centre P and radius greater th the diameter of the beam. If we let CX = 1 and CP = x then area eccentric sector PXY is given by the following expression:

$$1/2\{2\pi/3 + \arcsin(x\sin\alpha) - \arcsin(x\sin\theta) + x\sin[\alpha + \arcsin(x\sin\alpha)] - x\sin[\theta + \arcsin(x\sin\theta)]\}$$

where

$\alpha = 2\pi/3 + \theta$ and θ is the angle CPX

Similar expressions describe areas PXZ and PYZ. (*b*) a baricentric pl showing the manner in which the proportion of the three eccentr sectors (PXY, PXZ, and PYZ) is affected by rotating the disc (varyin θ) and by translating the disc (varying the distance CP). The close concentric curves are contours of constant x with $x = 0$ at the centr The outermost curve shows the contour obtained when P lies on th circumference of the beam, i.e. when x = radius CX. The curve radiating from the centre are lines of constant θ at intervals of $\pi/1$ (15°). When the sectors have the unequal angles shown in (*c*) th baricentric plot in (*d*) results

white. The closed concentric curves illustrate the way in which CIE 1976 u,v hue-angle (h_{uv}) would vary as the disc rotated. The distance from the centre would vary monotonically with the CIE 1976 u,v, saturation (s_{uv}). The concentric contours could be made to resemble the loci of the coordinates of Munsell chips with similar chromaticity (see reference 5, Figure 4.7, p. 82).

When the eccentricity (x) is large the concentric curves do not appoximate a circle and the radial curves do not approximate straight lines, reflecting the fact that the separate variation of h_{uv} and s_{uv} can be achieved only approximately, and only over a limited gamut size. The largest locus shown is that obtained when PC is equal to the radius of the beam of light, indicating that the full gamut represented by the triangle is not obtained until PC exceeds the radius of the light beam.

Figure 3a illustrates a simple practical apparatus. *Figures 3b* and *c* show the gamut of colours realized in two versions of the apparatus, as measured using a Minolta TV colour analyser model TV2130. The closed curves represent the loci of chromaticity coordinates obtained when the disc is rotated, and the radiating curves the loci obtained as the eccentricity of the disc with respect to the light source is varied. In *Figure 3* equal sectors were used so as to provide loci symmetri about a reference white, maximizing the independence o hue angle and saturation. In *Figure 3c* unequal sector were used for the following reason.

Some colours can be strongly saturated, others cannot There are saturated reds, for example, for which there i no yellow with equivalent s_{uv}. There is therefore a limi to the size of gamut obtainable if hue and saturation ar to be separately varied using this method. It is sometime necessary to relax the requirements for the separat manipulation of hue and saturation in order to increas gamut size. In the version of the apparatus shown i *Figure 3c* the gamut size has been increased and the centr of the gamut adjusted by varying the angular size of th coloured sectors, giving green the largest sector. As result, the loci of coordinates obtained at high saturatio show a steep curve near green. *Figures 2c* and *d* show the corresponding geometry.

By increasing the number of primaries (and the numbe

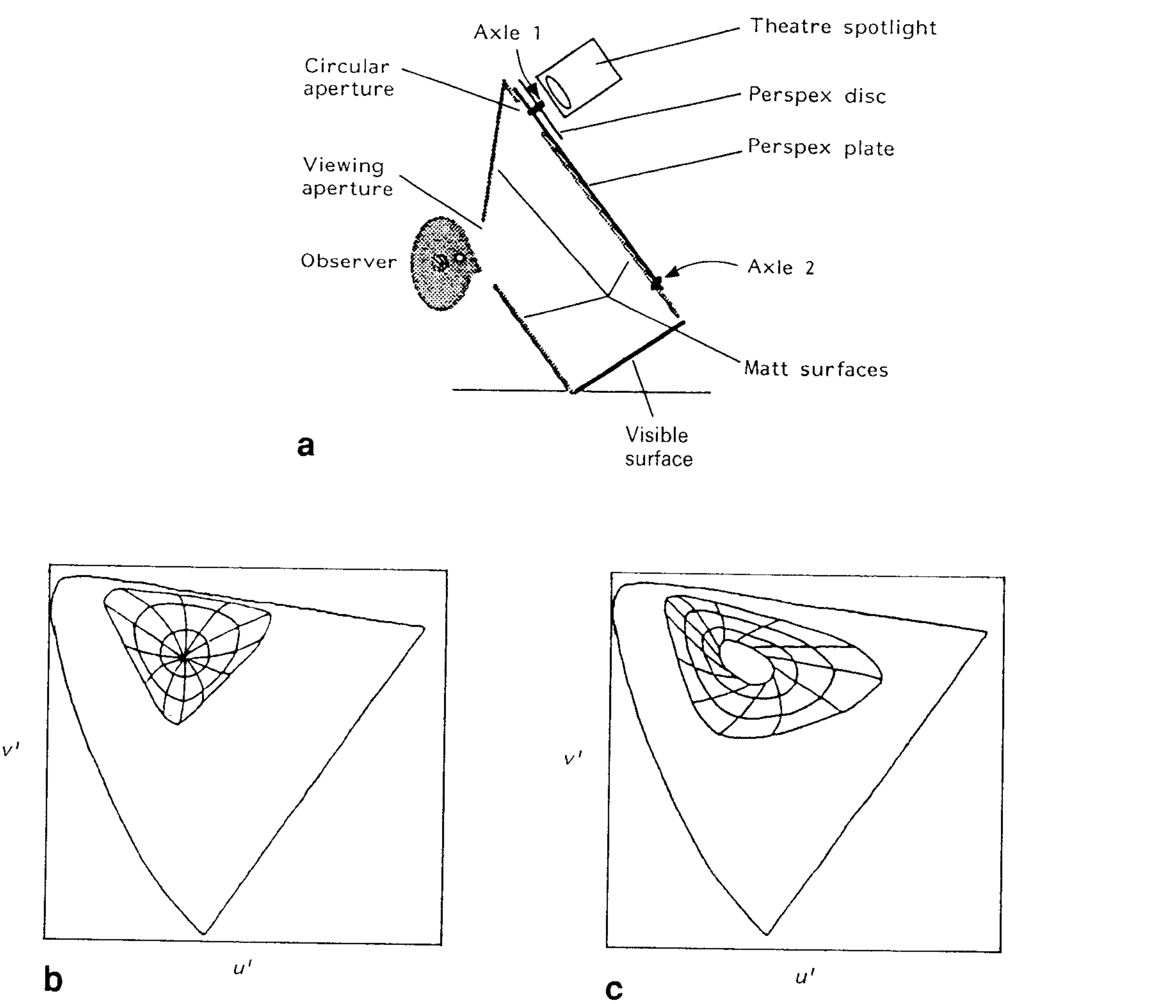

Figure 3 (*a*) Cross section of the apparatus. Light from a theatre spotlight is directed at a perspex disc which is attached to a perspex plate by axle 1 about which it is free to rotate. The plate rotates about axle 2, which, given the distance between axles 1 and 2, provides for a close approximation to a linear translation of the position of 1 within the beam from the spotlight by means of a lever (not shown). The perspex disc can be rotated by means of a belt passing around its circumference and also around a pulley wheel (not shown) on axle 2. The beam passes through theatre filters attached to the disc then through a circular aperture and into a box with matt surfaces of high and spectrally even reflectance. A viewing aperture in the box enables an observer to see a surface illuminated with coloured light. A small aperture in the box (not shown) enables the colour mixture to be compared with that of standard sources, filtered as appropriate. (*b*) and (*c*) CIE 1976 UCS diagram showing the loci of chromaticity coordinates obtained when the sectors are equal (*Figure 2a*), or unequal (*Figure 2c*). The closed curves show loci obtained by rotating the pulley wheel, and the radiating curves loci obtained by moving the lever

of sectors) it is possible to increase the independence of hue and saturation. Whether the additional complexity is justified depends on the gamut required and the use to which the colorimeter is put.

Provided the light source remains stable and the coloured filters do not deteriorate, the apparatus can be calibrated and used to provide light of any chromaticity coordinates within the available gamut. It is necessary only to convert the appropriate disc angle and eccentricity to the corresponding u' and v' values via a calibration graph similar to that shown in *Figures 3b* and *c*.

Perceptual distortion of text

Wilkins and Neary[4] examined a series of children who had been supplied tinted glasses by the Irlen Institute[3]. These individuals claimed that coloured spectacles reduced the distortions of text to which they were usually subject. The apparatus with gamut shown in *Figure 3c* or similar has been used to assess the degree to which coloured light reduces distortions in a further group of young people. All had difficulty reading and reported perceptual distortion of text.

An 18-year-old woman provided the data shown in *Figure 4a*. She was asked to rotate the wheel of the colorimeter, varying colour, to see if she could find a setting in which the distortions on a page of text disappeared. The text was an array of random letters arranged in strings to resemble words in a single paragraph. The settings are shown with the symbol '+'. The subject was then asked to turn the wheel slowly until the distortions reappeared and the settings are shown with the symbol '−'. She did this repeatedly at different eccentricities of the disc. There as a very small area of the chromaticity diagram in which the distortions consistently disappeared. It was so small that it might have been missed by a limited range of tinted glasses or coloured overlays.

Data from a 15-year-old boy are shown in *Figure 4b*.

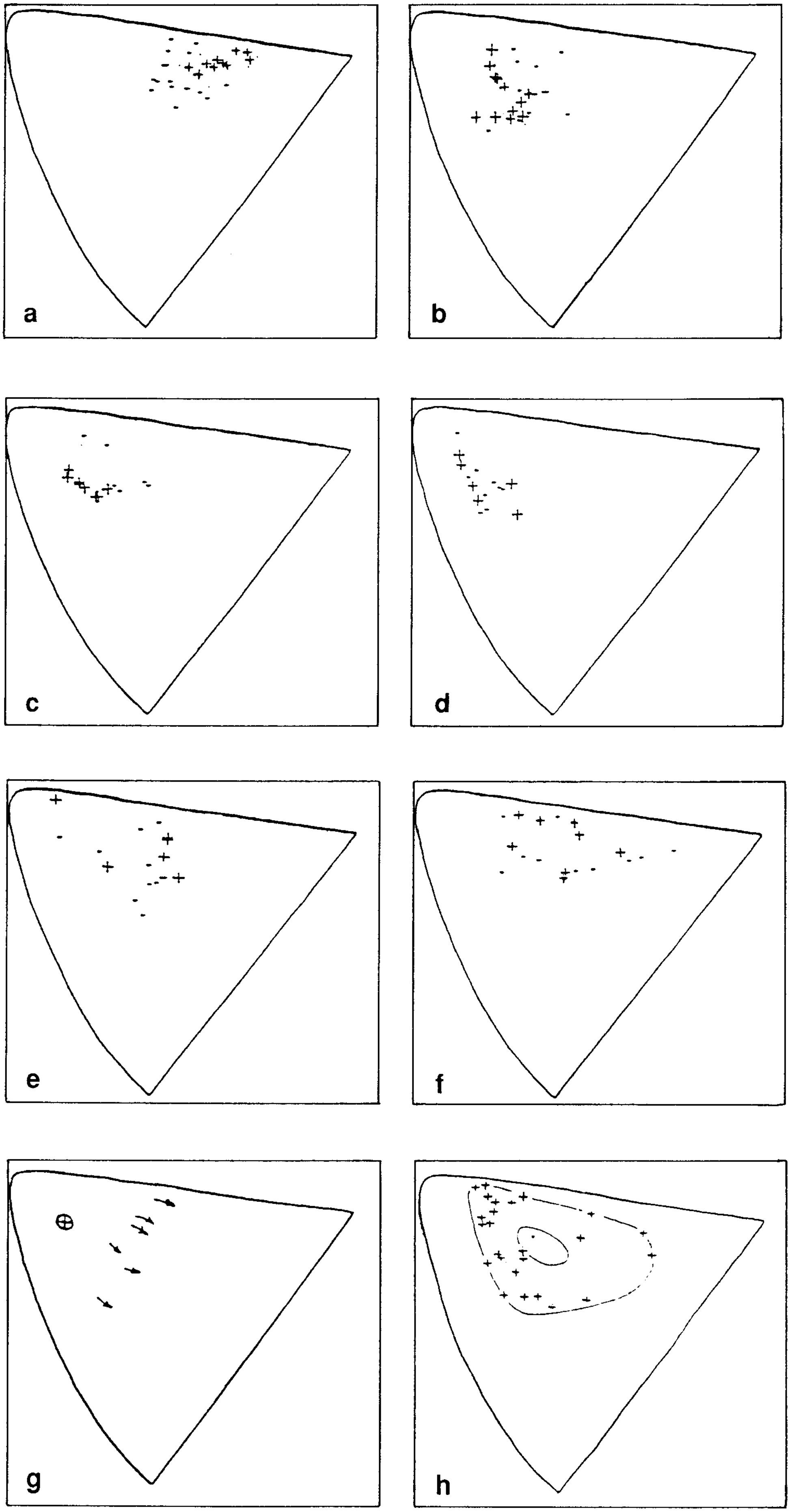

Figure 4 CIE 1976 UCS diagrams summarizing data from children reporting perceptual distortion of text: –, hue at which perceptual distortions occurred; +, hue at which distortions were absent. (*a*)–(*g*) show data from individuals and (*h*) data from a group

Note that the distortions disappeared when the light was an unsaturated blue or a saturated green. *Figures 4c* and *d* represent data from a 10-year-old girl obtained on two occasions one week apart.

The technique does not necessarily result in patches in colour space. It is quite possible for children to report distortions that are inconsistent and may relate to tiredness or other factors. Data for two boys, aged 9 and 10 years, are presented in *Figures 4e* and *f* and show an inconsistent scatter in the chromaticity diagram. The data were obtained using the same technique and instructions as those used to obtain the settings shown in the previous figures.

Figure 4g presents data for a 14-year-old girl who reported a 'pulling in the eyes' when the colour had chromaticity in the lower right-hand side of the CIE 1976 UCS diagram. The setting that maximized comfort is shown by a cross and the limits at which the unpleasant sensation began are shown by the arrows, which also give the direction from which the limits were approached.

Figure 4h represents the optimum settings for a series of 26 children examined using the colorimeter. Note that the settings are scattered throughout the chromaticity diagram but are more common away from red. The avoidance of shades of red is also seen in adults with migraine[6] when using a colorimeter having gamut similar to that shown in *Figure 3b*.

The above observations would seem to support the claims of Irlen[3] that certain children are subject to perceptual distortions of text and that for some children but not others the distortions can disappear when the text has a particular colour. The colour differs from one person to another and yet can be specific and consistent.

References

1. Burnham, R. W. A colorimeter for research in colour perception. *Am. J. Psychol.* **65**, 603–608 (1952).
2. Boynton, R. M. and Nagy, A. L. La Jolla analytic colorimeter. *J. Opt. Soc. Am.* **72**, 666–667 (1982).
3. Irlen, H. *Reading by the Colors: Overcoming Dyslexia and other Reading Disabilities through the Irlen Method.* Avery Publishing Group, New York, USA (1991).
4. Wilkins, A. J. and Neary, C. Some visual, optometric and perceptual effects of coloured glasses. *Ophthal. Physiol. Opt.* **11**, 163–171 (1991).
5. Hunt, R. W. G. *Measuring Colour.* Ellis Horwood, Chichester, UK (1987).
6. Chronicle, E. P. and Wilkins, A. J. Colour and visual discomfort in migraineurs. *Lancet* **338**, 890 (1991).