# 9. Trials of a computer-controlled colour vision test that preserves the advantages of pseudoisochromatic plates

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**Abstract**

During the last decade, computer-controlled raster displays have been widely used to identify congenital and acquired deficits of colour vision. In such tests, the subject is commonly asked to detect a target spot or a grating, and the chromaticity of the target is modulated along varying axes of colour space. The chief advantage of such tests is that the depth of chromatic modulation can be dynamically and quantitatively adjusted according to the patient's performance. The chief disadvantage lies in the difficulty of ensuring that the patient does not detect the target by edge artefacts or by differences in luminosity between target and field. To eliminate these difficulties, we have borrowed two ploys from the designers of the original pseudoisochromatic plates: first, the target is formed from discrete patches, each having its own contour, and second, the luminances of the patches are varied randomly rather than being equated. For a group of subjects, performance on the new test has been compared with performance on the Nagel anomaloscope, the Ishihara plates, and the Farnsworth-Munsell 100-hue test. The test is rapid to administer, it separates protan and deutan types with high reliability, and it gives a quantitative measure of colour discrimination. However, we draw attention to a third ploy that is embodied in some of the Ishihara plates, and this principle could be used in a modified version of the present test.

## Introduction

It is only with good reason that one should introduce a new test of colour vision that is based on a computer-controlled raster display. For many such tests have already been described (e.g., King-Smith *et al.*, 1983; Fallowfield and Krauskopf, 1984; Sellers *et al.*, 1986; King-Smith, Vingrys and Benes,

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*B. Drum, J.D. Moreland & A. Serra (eds.), Colour Vision Deficiencies X*, pp. 69–76.

1987; Heard *et al.*, 1987; Arden, Gündüz and Perry, 1988). Typically, the subject has been required to signal the presence or absence of a chromatic spot or grating on an equiluminant background, and the chromaticity of the target has been modulated along theoretically significant axes of colour space. The primary advantage of a raster display is that the depth of chromatic modulation can be dynamically and quantitatively adjusted, in order to accommodate different degrees of deficiency and to allow thresholds to be measured by adaptive methods.

However, several major disadvantages have confronted the designers of such systems:

(i) The presence of a chromatic boundary may be revealed by edge artefacts that arise either from the slight misalignment of one or more of the guns of the colour monitor or from the intrinsic pattern of phosphor dots (Vingrys and King-Smith, 1986; Heard *et al.*, 1987).

(ii) Similarly, if the chromaticity varies across the display at a high spatial frequency, the chromatic aberration of the eye may render colour boundaries visible.

(iii) Luminosity matches vary widely both among normal subjects and among those with congenital and acquired colour vision deficits. Thus luminance matches must be made for each individual subject before testing, in order to ensure that the spots or gratings used in the main test are truly equiluminant for that observer. Such a procedure is time-consuming, both because of the extra time required to make the actual measurements, and the time required to acquaint the naive subject with the additional photometric procedure.

(iv) Even if a preliminary photometric equation is made for one part of the visual field, it is likely that this equation will not hold elsewhere in the field (Livingstone and Hubel, 1988).

Analogous problems faced the designers of the first pseudo-isochromatic plates who attempted initially to test colour discrimination with solid figures of one chromaticity on a uniform background of a second, confusable chromaticity. They found that minor misalignments in the printing process produced edge artefacts which revealed the shape of the figures, and that it was not possible to equate the luminance of figure and background to the satisfaction of all.

By two manoeuvres, Stilling (1877) ingeniously solved these problems. Firstly, he broke test and background stimuli into a number of discrete patches, each with its own shape and its own limiting contour. Secondly, instead of trying to ensure that the equation of luminance survived the printing process, Stilling introduced a *variation* in the luminance of the patches in the display. Thus neither edge artefacts nor luminance differences could be used as a cue to figure/ground discrimination. In such a design the figure chromaticity is the only characteristic shared by all the patches of the figure and by none of the background patches.

Stilling was explicit in his insight into how to prepare successful pseudoisochromatic plates. He wrote:

> Der störende Einfluss der Buchstabenconturen ist einfach dadurch beseitigt, dass die Conturen über das ganze Feld gleichmässig vertheilt und die Buchstaben aus discontinuirlich von Grund sich abhebenden Quadraten gebildet sind. Der zweite Fehler ist dadurch völlig eliminirt, dass die sämmtlichen Quadrate des Grundes abwechselnd dunklere und hellere Töne zeigen.

We have followed Stilling's capital approach (Mollon and Reffin, 1989). We adapt his method to produce a computer-controlled test of colour discrimination that does not require luminance matches prior to testing but does retain the dynamic adjustment that is the advantage of coupling a raster display to a computer. In its appearance and in its theoretical basis, our test particularly resembles the pseudoisochromatic plates of Hardy, Rand and Rittler (1954), in which coloured targets of varying saturation are embedded in achromatic backgrounds that consist of small discs varying in lightness. In so far as our mosaic target forms a Landolt C, the present test recalls the pseudoisochromatic plates of Schaaff (1925).

## Method

The stimuli are generated by means of a Sigma Electronic Systems 5688 colour-graphics system and are displayed either on its integral Mitsubishi monitor or on a slave Barco CD351 monitor. The Sigma system allows the output of each gun of the monitor to be specified with a precision of 8 bits. A typical test stimulus is as follows. A large circular area of the screen contains many small disc-shaped patches, varying randomly in size and luminance. The majority of these discs constitute the background and are of a single chromaticity, whilst a subset of discs constitute the target and are of a different chromaticity from the background. The latter set of discs, taken as a gestalt, form a Landolt C, with the gap in the C ring at the top, bottom, right or left. The orientation of the C is randomly selected for each trial by the computer. The standard viewing distance is 1.75 m and the gap in the Landolt C subtends 1° of visual angle. The outer diameter of the C subtends 4.9° and the inner diameter subtends 2.4°.

On each trial, the task of the subject is to press one of four response buttons to indicate the orientation of the gap in the Landolt C. The stimulus is displayed until the subject responds or for four seconds, whichever is the shorter. The subject is asked to guess even if he or she cannot detect the figure; and if the subject fails to respond, the stimulus is repeated later. The computer probes chromatic sensitivity along the protan, deutan and tritan

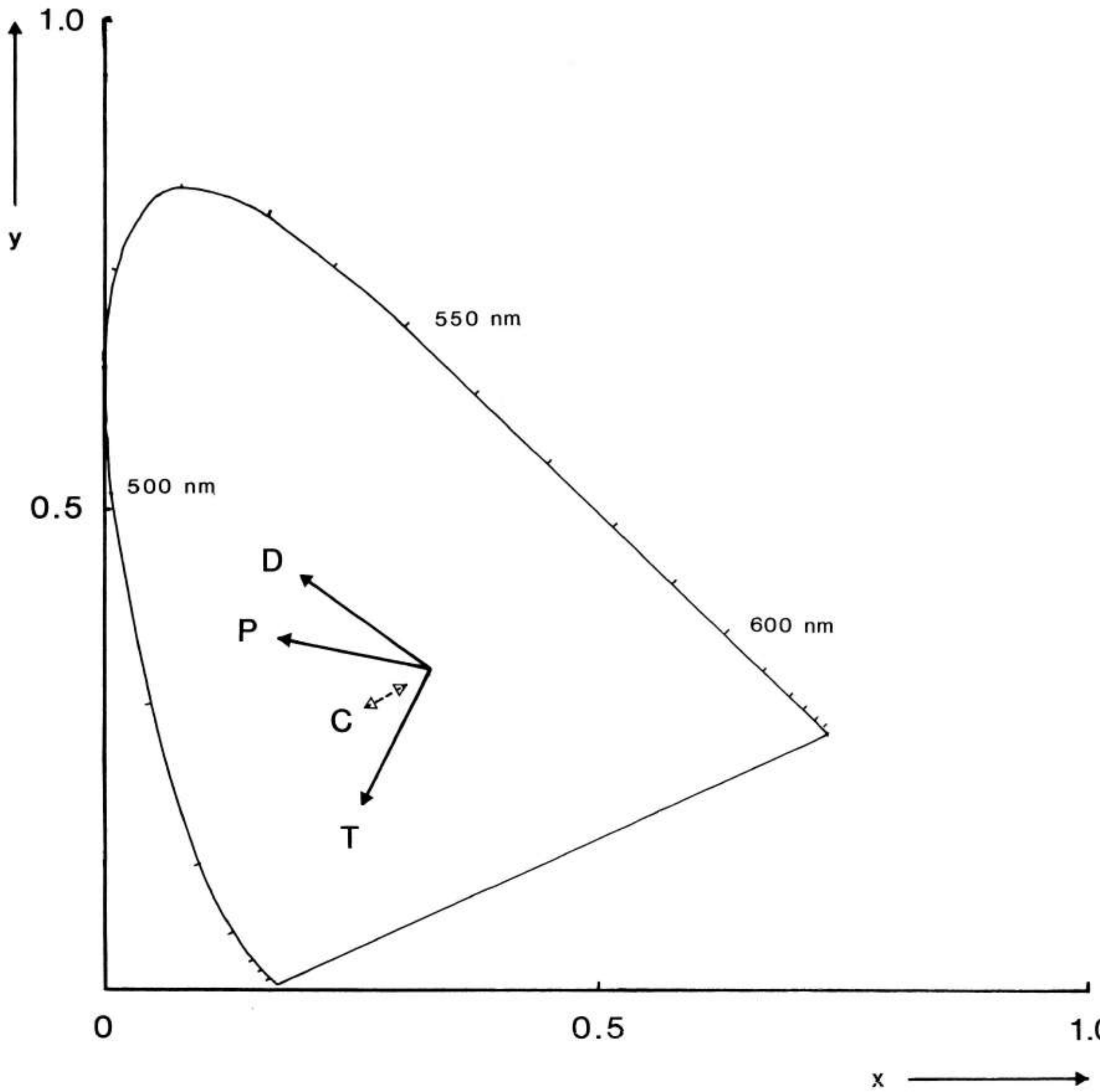


*Fig. 1.* The CIE chromaticity diagram, showing the three directions along which the chromaticity of the test stimulus is modulated. The lines radiate from $x = 0.33$, $y = 0.33$, and the arrowheads mark the maximum excursion available. On control trials (see text) the test chromaticity is chosen to lie randomly along the dashed line, within the limits indicated by the arrowheads.

confusion lines, adjusting the chromaticity of the Landolt C on each trial according to a staircase procedure (Cornsweet, 1962). The chromaticity of the background patches is held constant throughout ($x = 0.33$, $y = 0.33$). Figure 1 shows the test directions in the CIE chromaticity diagram. Testing on the protan, deutan and tritan axes is randomly interleaved. On each axis, the separation between the background and target chromaticities is initially large, and is decreased after each correct response on that axis and increased after each error. The test is terminated after 11 reversals on each of the three individual staircases; and the mean of the last 6 reversals is taken as the threshold estimate for a given confusion line. The step size is computed in units of the CIE $u'v'$ uniform chromaticity space and is a function of the number of reversals completed and of the separation of test and background chromaticities. A small subset of trials, randomly intermixed with the test trials, are control trials, on which the chromaticity of the target does not lie on any of the dichromatic confusion lines (see Fig. 1); these control trials serve to detect malingering or gross pathology and also serve to give the subject occasional clear cases when he or she is near threshold on the test trials. The test typically takes four minutes to complete.

In a preliminary study, a number of normal subjects and subjects with congenital colour-vision deficiencies have been examined with this test, and also with the Farnsworth-Munsell 100-hue test, the Ishihara plates, and the Nagel anomaloscope (Schmidt and Haensch). Each subject was classified by the anomaloscope as protanopic (N = 11), deuteranopic (N = 9), protanomalous (N = 7), deuteranomalous (N = 13), or normal (N = 11) according to the matching range, the mid-point, and the relative luminance settings. All subjects were male.

A Lovibond fibre-optics tintometer was used to make calibrations of the chromaticities and the maximal luminances of the phosphors of the monitors; and a PIN 10 silicon photodiode was used to establish the functions relating phosphor output to input signal for each gun. Both the monitors exhibited independence of guns, as assessed by additivity tests.

## Results

Figure 2 shows the performance of the test in identifying and classifying colour deficiency. Discrimination threshold along the protan confusion line is plotted against threshold in the deutan direction. The ordinates of the Figure are expressed in terms of distance in the CIE $u'$, $v'$ space multiplied by $10^3$. For the normal subjects in our sample, the range of thresholds did not exceed 10 units on either ordinate, except for one subject who scored 13 on the protan axis; the latter subject exhibited a Farnsworth-Munsell score of 100 and a matching range of 5 units on the anomaloscope. The maximum possible score on the new test is 120 and many dichromats remain at this ceiling on one of the two dimensions.

With one exception, a threshold greater than 10 units on one or both axes was exhibited on the new test by all those subjects classed as abnormal by the anomaloscope: the exception was a simple deuteranomalous observer who showed a narrow matching range (4 units) on the Nagel anomaloscope and a score within the normal range (68) on the Farnsworth-Munsell test.

As can also be seen from Fig. 2, the new test achieves a complete separation of the protan and deutan types of subjects, the reference classification being that given by the Nagel anomaloscope.

As a group, the deuteranopes are clearly distinct from the deuteranomals, and similarly the protanopes are distinct from the protanomals, but in each case there is some overlap of individual scores.

For the protan subjects (dichromatic and anomalous) there was a correlation of 0.57 between the total error score on the Farnsworth-Munsell

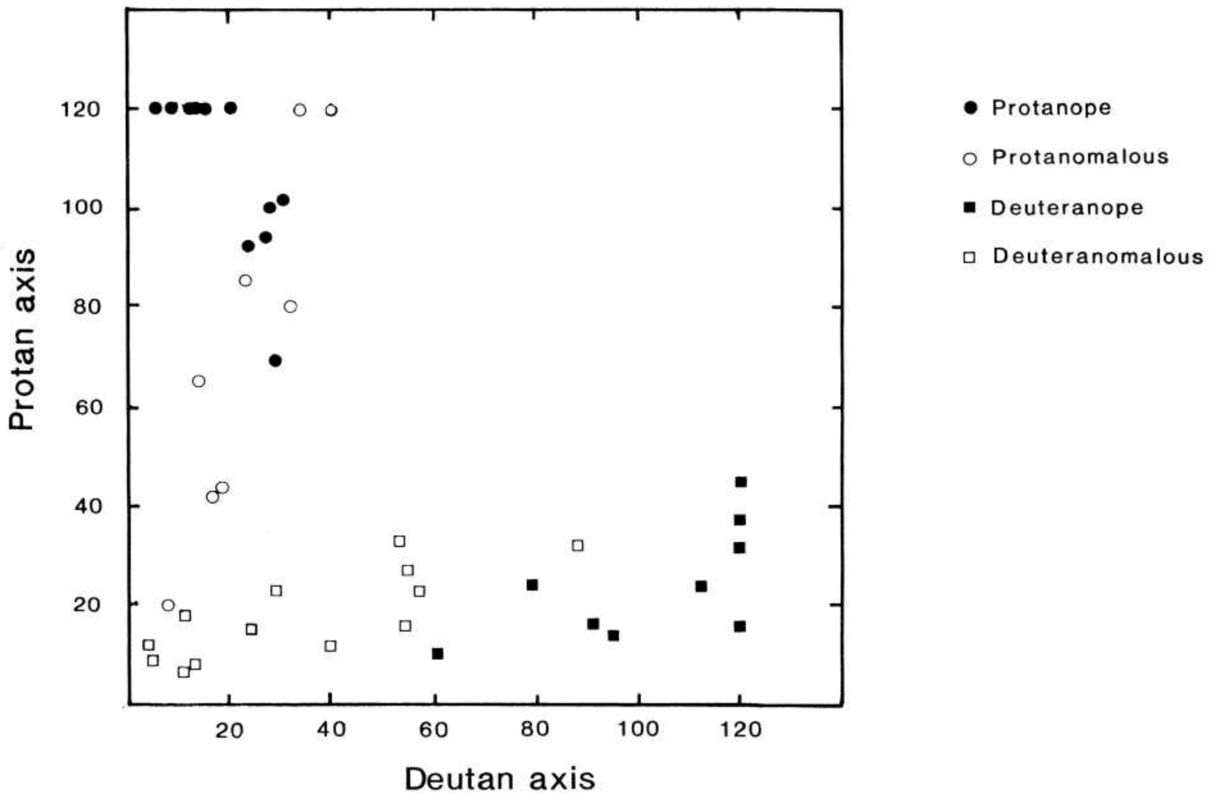


*Fig. 2.* Performance of colour-deficient subjects on the new test. Subjects are classified according to their performance on the Nagel anomaloscope. Threshold on the protan axis of colour space is plotted against threshold on the deutan axis. The units correspond to distance in the CIE $u'$, $v'$ space multiplied by $10^3$.

100-hue test and the protan error score on the new test. For deutan subjects, there was a correlation of 0.76 between the total score on the 100-hue and the deutan score on the new test.

## Discussion

The test described here is probably more rapid to administer than previous tests that use raster displays, since the preliminary equation of luminosity is eliminated; it sidesteps the problems presented by edge artefacts and the variations in relative luminosity across the visual field; it successfully separates protan and deutan subjects; and it has a face validity as a colour test, in that it gives a direct quantitative measure of discrimination in three directions of colour space. Nevertheless, the present form of the test is provisional and several modifications to the test recommend themselves.

One modification would be to incorporate in the test the third stratagem that Ishihara added to the two stratagems of Stilling. It has only occasionally been acknowledged (e.g., Clark, 1924) that the majority of the Ishihara screening plates depend on a principle different from the principle of the Stilling and H-R-R plates. The latter plates, like the present test, simply measure chromatic discrimination: a figure of one chromaticity is presented on a field of a different chromaticity, and in different plates there are differences in the size and direction of the chromatic distance between figure and field. But many of the most sensitive of the Ishihara plates (the 'transformation' plates and the 'hidden digit' plates) do not test the threshold for chromatic discrimination. Rather they measure the relative salience of the outputs of the two subsystems of human colour vision — the ancient mammalian subsystem that compares the short-wave cone signal with some combination of the long- and middle-wave signals, and the phylogenetically recent subsystem that compares the signals of the long- and middle-wave cones (Mollon, 1989; Mollon and Jordan, 1988). Ishihara's plates offer two alternative perceptual organizations to the visual system, one indicated by the ancient subsystem, the other indicated by the newer subsystem. The colour-deficient observer, whether anomalous or dichromatic, reveals himself by favouring the perceptual organization indicated by the phylogenetically ancient subsystem of colour vision. Thus, in the case of the transformation plates, the chromatic difference between the background and the 'correct' digit is well above threshold for many deuteranomalous observers, but the alternative pattern is reported because the signals of the ancient subsystem are disproportionately salient in the perceptual world of the deuteranomalous — as has been shown in another context by Müller, Cavonius and Mollon, (1990). Since the present display can emulate any pseudoisochromatic plate, it would be possible to incorporate the third stratagem of Ishihara and to titrate one subsystem against the other. It is the third stratagem that is most likely to increase the separation between normals and simple deuteranomals on a test of this type.

A second simple modification of the test might allow it to be used for testing infants. A subset of the discs of the array would form a chromatic grating and the background would be formed of achromatic discs. In successive frames the grating would be moved to the right or the left and the subject's eye movements would be monitored. Owing to the two stratagems incorporated in the present test — the use of discrete discs with independent contours and the randomization of luminance — the tester could be confident that the subject's eye movements were being controlled by the pattern of chromaticities and not by luminance artefacts. It remains, however, an empirical question whether optokinetic nystagmus could in fact be driven by a stimulus of this kind.

## Acknowledgements

We thank Dr. M. Webster, Dr. S. Shevell and Gabriele Jordan for comments on the text. This work was supported by MRC grant G8807036N.

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