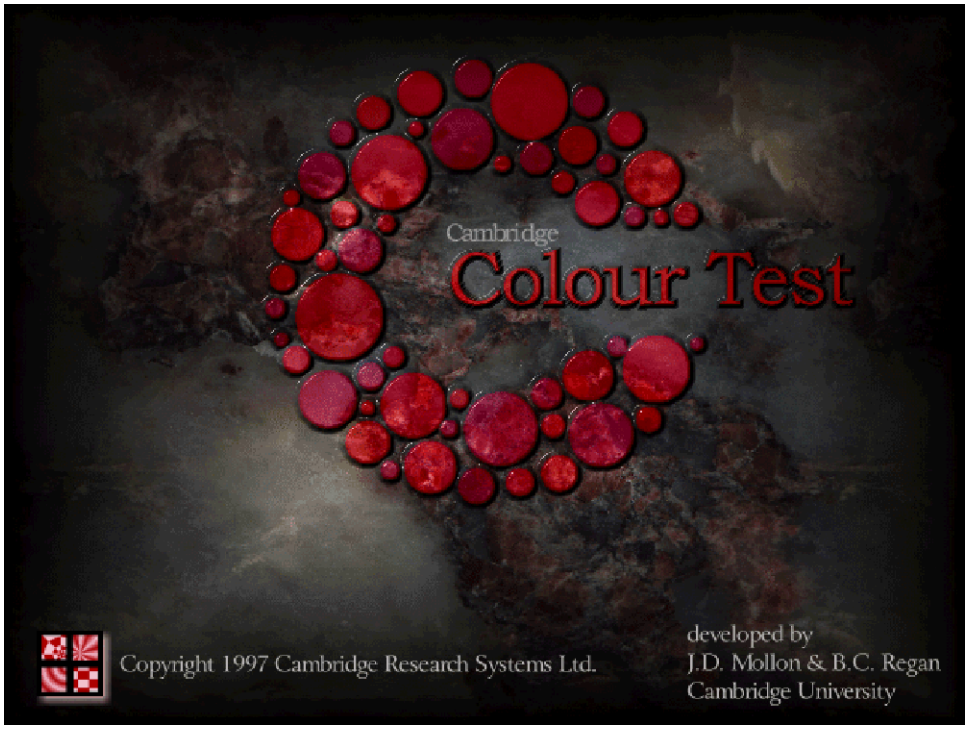
CAMBRIDGE COLOUR TEST

Handbook

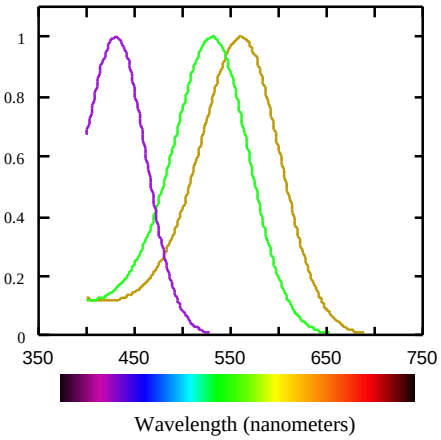


J. D. Mollon and B. C. Regan

Version 1.1, January 2000

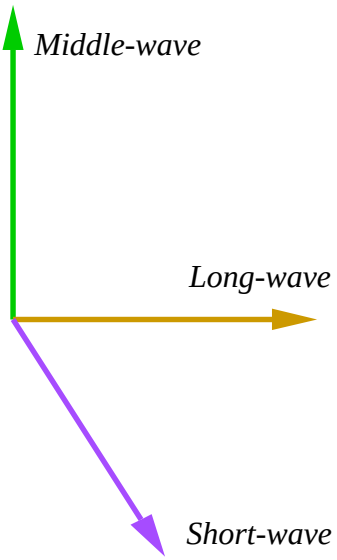
Introduction

Normal colour vision. Normal colour perception depends on the absorption of light by the three classes of cone photoreceptor in our retina. The peak sensitivities of the three cones lie in the violet, the green and the yellow-green parts of the spectrum – at wavelengths of appproximately 420, 530 and 560 nanometers. It is convenient to refer to the three types of cone as short-wave, middle-wave and long-wave respectively. Their spectral sensitivities are shown schematically in the figure below.



Any individual cone obeys the *Principle of Univariance*: although the stimulus for the cone can vary in two dimensions (radiance and wavelength), the output can vary in only one dimension – the degree of hyperpolarization of the cell. As wavelength varies, there is a variation in the probability of a given photon being absorbed, but once a photon has been absorbed, all information about its wavelength or frequency is lost. So the individual cone, or class of cones, is colour blind. Lights of two widely different wavelengths will produce the same output provided the two radiances are suitably adjusted. So to analyse colour, the visual system must compare the rates at which quanta are being caught in different classes of cone; this comparison is initiated at a retinal level, in that ganglion cells of the 'midget' and the 'small bistratified' types draw inputs of different sign from different classes of cone.

Since the normal retina contains just three classes of cone and since each class of cone obeys the Principle of Univariance, all lights can be represented in a three-dimensional space, the ordinates of which correspond to the rates of quantum catch in the short-wave, middle-wave and long-wave cones (as below).



Any given light will plot as a point in such a space. As the light's radiance is increased or decreased, the plotted point will move along a vector that passes through the origin. The angle of the vector – its direction relative to the three axes – corresponds to the *chromaticity* of the light. Lights that plot at the same point in the space, though they have different spectral compositions, will appear alike. However, the chromaticity of the light – the relative quantum catches it produces in the three cones – is not sufficient to tell us the colour that it will appear: for the appearance of a light depends not only on its own chromaticity, but also on the chromaticities of other stimuli in the field and on many other factors such as the recent history of stimulation.

Dichromacy. Owing to the simple nature of this space, it is possible to choose a pair of physical stimuli that yield the same quantum catches in two of the three classes of cone but differ with regard to the remaining class. By alternating between such stimuli, we can probe the integrity of one class of cones in isolation. This principle is exploited in the present

colour test, as it has been in many earlier tests. Consider, for example, a point that lies in the plane defined by the quantum catches of the middle- and long-wave cones – the plane of the paper in the present diagram. Now imagine a line passing through this point and orthogonal to the plane of the paper. Lights along the line vary only in the quantum catch they yield in the short-wave cones. The line is called a 'tritanopic confusion line', because someone who lacks the short-wave cones – a 'tritanope' – will confuse all chromaticities that lie along the line. By alternating between analogous pairs of lights, it is similarly possible to detect those who lack the middle-wave cones or the long-wave cones and who are called 'deuteranopes' and 'protanopes' respectively. About 2% of the male population are congenital dichromats of the deuteranopic or protanopic kinds.

Congenital tritanopia, unlike deuteranopia and protanopia, is not sex-linked, and it is much rarer. However, diseases and drugs that affect the receptor layer of the retina appear disproportionately to affect the short-wave cones. The acquired colour deficiency is often of a tritan type, in that thresholds for discrimination are elevated along a tritan confusion line.

Anomalous trichromacy. About 6% of men exhibit anomalous trichromacy, a congenital form of colour deficiency that is milder than dichromacy. Unlike dichromats, they require three variables in colour-matching experiments, but they make different matches from the normal observer and, in most cases, their discrimination of colours is poorer than normal. Currently, the predominant view is that the anomalous trichromat lacks either the normal long-wave or the normal middle-wave pigment, but achieves his residual discrimination in the red-green range by a neural comparison of the quantum catches in two slightly different versions of the middle-wave pigment or two slightly different versions of the long-wave pigment. Anomalous trichromats who behave as if they lack the long-wave pigment are called 'protanomalous' and those who behave as if they lack the middle-wave pigment are called 'deuteranomalous'. Characteristically, the two types of anomalous trichromat show reduced discrimination between chromaticities that are confused by the corresponding type of dichromat: their thresholds, when plotted in a normal colour space, typically form an ellipse oriented along a protan or a deutan confusion line. However, the term 'anomalous trichromacy' covers a large variety of phenotypes: some anomals may exhibit discrimination that is nearly as poor as that of the corresponding dichromat, a few enjoy colour discrimination within normal limits, while the majority have discrimination ellipses that lie somewhere between these extremes.

The basis of this phenotypic variation is not yet well understood, but some part of is likely to depend on the spectral separation of the two long-wave or two middle-wave pigments on which the anomal is thought to depend for his residual discrimination. Indeed, the distinction between dichromacy and anomalous trichromacy is nowadays less clear-cut than was traditionally held. For it is possible that some of those classified as dichromats by the Nagel anomaloscope in fact express two genes, encoding pigments with very similar spectral sensitivities, but differing very slightly in peak wavelength or optical density: under some circumstances these residual differences may sustain some limited discrimination in the red-green range.

Post-receptoral channels. The trichromatic colour vision found in Man and in the Old World primates did not evolve in a single step, and it is increasingly clear that our colour vision depends on two subsystems, which emerged at different times. These two subsystems remain morphologically distinct at early stages of the human visual system.

A phylogenetically ancient subsystem compares the signal of the sparse short-wave cones with some combination of the signals of the long- and middle-wave cones. Forming the anatomical substrate for this pathway are the 'blue cone bipolar cells', the small bistratified

type of ganglion cell, and cells of the koniocellular laminae 3 and 4 of the lateral geniculate nucleus.

A duplication of a gene on the X-chromosome is thought to have led to the newer subsystem of colour vision, sometime after the divergence of the Old and New World monkeys. This second subsystem compares the quantum catches of the long- and middle-wave pigments, which diverged from a single ancestral pigment after the duplication. Its signals are thought to be carried by the midget bipolars, the midget ganglion cells, and cells of the parvocellular laminae of the lateral geniculate nucleus.

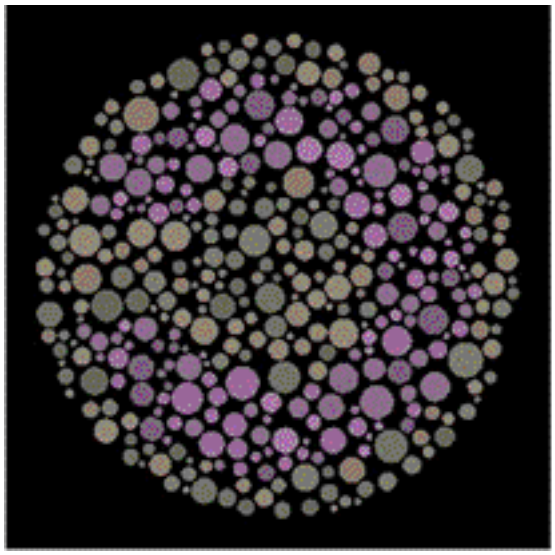
The cells of these two pathways are distinct, in morphology, in size and in immunoreactivity. So we might expect them to be differentially affected by particular diseases, toxins or drugs. If the phylogenetically older pathway is affected, we can expect thresholds to be elevated along a tritanopic confusion line. If the phylogenetically younger pathway is affected, we can expect a discrimination ellipse that is elongated in a direction intermediate between the protan and deutan confusion lines.

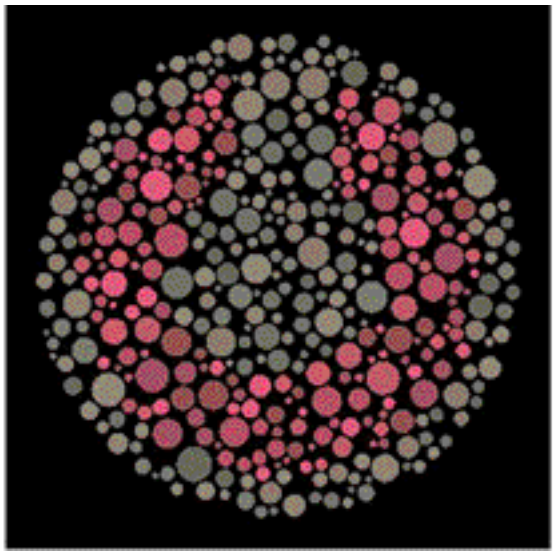
The Cambridge Colour Test

The Cambridge Colour Test provides a rapid means of screening subjects for colour vision deficiencies; but it also can be used to examine in more detail the changes in colour discrimination that occur as a result of congenital or acquired conditions. It allows the clinical investigator to monitor quantitatively over time the progression or remission of disease. Many drugs affect colour vision, and the pharmacologist will find the test well suited to monitoring the short-term or long-term course of such side-effects.

The test combines old principles and modern technology. The stimulus arrays resemble the plates of a traditional pseudoisochromatic test, such as those of Stilling or Ishihara. The target is a C shape differing in chromaticity from the background. The target and background are made up of many discrete discs, each with its own contour, and the luminances of the individual discs are randomized. These two manoeuvres ensure that the subject can detect the target only by true colour vision and cannot use edge artifacts or luminance differences. So — unlike several previous computerised tests of colour vision — the present test does not require that valuable time be spent in a preliminary equation of luminance for each subject or for each part of the visual field.

Many pseudoisochromatic plate tests use alphanumeric characters, and these have the difficulty that the subject may be rehearsed on the test in advance or may remember responses from previous testing. In the present case, the target is C-shaped and it is presented randomly in one of four orientations, the subject's task being to press one of four corresponding keys. So the subject cannot predict the identity of the target on a given trial and thus can be tested repeatedly. The task itself is cognitively simple and is readily grasped by subjects.





The advantage of computer control is that the difference in chromaticity between target and background can be adjusted dynamically according to the subject's performance. At the beginning of the test run, the target is saturated in colour; a staircase routine is then used to establish the chromaticity difference needed for the subject reliably to report the orientation of the C. In the basic "Trivector" version of the test, the targets differ from the background along one of three theoretically significant lines in colour space, the protan, deutan and tritan

confusion lines. These three types of target probe the sensitivity of the long-wave, middle-wave and short-wave cones respectively. The staircases corresponding to the three confusion lines are randomly interleaved, and occasional control trials are introduced to ensure that the subject is alert and is not malingering. The longer version of the test yields a full 'discrimination ellipse', showing the loss of sensitivity for a range of directions around the background chromaticity: in the common forms of colour deficiency, the long axis of the discrimination ellipse is indicative of the type of loss.
The native space of the Cambridge Colour test is the CIE (1976) *u',v'* diagram. It is in this metric that the step sizes of the staircases are calculated and the measured thresholds are expressed. The *u',v'* diagram is a linear transformation of the CIE (1931) *x,y* chromaticity diagram, but, in the *u',v'* diagram, equal distances more nearly correspond to equal perceptual differences. The *u',v'* diagram is far from perfectly uniform and is used here only as a practical tool; it serves better for the computation of thresholds than does the 1931 diagram, and even a non-linear transformation would be strictly valid only for the experimental conditions under which it was generated.

The software of the present test allows the user to express the data in the more familiar CIE (1931) diagram, but the computation of the staircases and the expression of the results will still be in terms of the CIE (1976) *u',v'* diagram.

Testing protocol

Although the Cambridge Colour Test is simple to use, there are a number of choices to be made before beginning the test, such as the viewing distance, the amount of time allowed for response, and the depth of luminance modulation employed. In this section we outline the standard procedure used in our own laboratory. The Help file provided by CRS gives instructions for use of the actual software.

The testing room. The test should be conducted in a darkened room. A full black-out is ideal, but if this is not possible, the test may be conducted in a room with thick curtains and the lights turned off. Under no circumstances should any source of light project directly on to the screen of the testing monitor. Any small light sources in the room, such as LEDs on computer monitors or printers, should be turned off or covered, as these may distract subjects during the test. If the monitor of the PC is visible to the subject, it should be switched off or covered with black card once the test has been set up and the 'Run' button clicked.

Viewing distance. Subjects should be seated in a chair at the appropriate viewing distance from the monitor screen. We recommend that the standard viewing distance for the test be fixed so that the gap in the C-ring subtends one degree of visual angle. This is appropriate if the test is being used for screening purposes with the normal population. If the monitor has been correctly calibrated, the 'Setup' screen of the Cambridge Colour Test gives the viewing distance at which the centre-to-centre separation of the circles on either side of the gap in the C-ring subtends one degree.

If the test is being used with a clinical population, and especially with patients who have reduced visual acuity, a smaller viewing distance may be used. Of course, the same viewing distance must be used for probands and controls.

Response time, response mode, and feedback. The standard time allowed for the subject to respond to a test stimulus is 3 seconds. We have found that this is appropriate for the normal

population. If the test is being used with a clinical population or with young children, the permitted response time can be increased.

We recommend the use of the four-button box supplied by CRS as the method for subject responses to be recorded. The button box automatically beeps when a button is pressed. We find that subjects like to have audible feedback when a button is pressed; therefore, if the keyboard is used for responses, the *Keyboard response beep* option in the 'Controls' submenu of the 'Setup' menu should be selected. For some clinical populations (e.g. Parkinsonian patients) it may be preferable for the experimenter to press the buttons on behalf of the subjects, with the subjects simply stating on each trial the orientation in which they see the gap (top, bottom, left, right, don't know). In this case it will probably be necessary to increase the response time allowed. The same response mode should, of course, be used for probands and controls.

Luminance modulation, neutral point, and maximum and minimum excursions along confusion lines. The software allows the tester to vary the range of the luminances of the individual patches and thus the depth of contrast modulation in the stimulus array. In our laboratory we use a standard range of six luminance levels between 2 and 16 $cd.m^{-2}$. It is not essential to maintain these absolute luminance levels, but we recommend that the highest and lowest luminances differ by a similar factor, if the test is used for screening.

The maximum excursion along the confusion lines is dependent upon the gamut of the monitor and the positioning of the neutral point. For the "Trivector" test, we use a neutral point at (u',v') = (.1977,.4689), a maximum excursion of 0.110 units, and a minimum excursion of 0.002 units in this space.

Instructions to subjects and conduct of test. If a subject has not performed the test before, he or she should first perform the short screening test (the *Trivector* test) for practice, even if the intention is to measure discrimination ellipses. Once the test has been set up, and the *Begin test* button has been clicked, the screen shows a blue C-ring on a grey background as a demonstration stimulus. Most subjects should be able to see this easily, even if they are colour-deficient, as the chromaticities of the ring and the background have been chosen to lie far away from any dichromatic confusion line in colour space.

It is important that subjects should understand the task before beginning the test. All subjects should be given essentially the same instructions. In our laboratory, subjects are handed the response box, and given verbal instructions, as follows:

> 'In the pattern of dots on the screen, can you see a ring with a gap in it? Good. The gap is facing to the (top, bottom, left, right). In the test you will see many such patterns. In each pattern, there is a ring, and the gap may be at the top, left, bottom or right of the ring. Your task is to press the button corresponding to the position of the gap. Don't press the button yet, but as an example, in this case you would press the (top, bottom, left, right) button. As you proceed, the computer will make it increasingly difficult for you to see the ring. It will make the colour of the ring more and more similar to the colour of the background, and there will come a point where you cannot see the ring or the gap. If you can't see the ring, or you can't see where the gap is, then don't press a button. The next pattern will appear after three seconds. If you think you can see where the gap is, but you aren't sure, then press the button for where you think the gap is. The test will last about four minutes. Do

you understand what you have to do? I'll turn the lights off, and then you can start, by pressing the appropriate button for the ring that's on the screen now.'

Once the "Trivector" test has been performed, the ellipse test may be performed if required. By this stage, subjects understand their task well, so it is sufficient simply to tell them that they are to perform a longer version of the test, taking about twenty minutes. We recommend that the *Pause between pairs of staircases* option be selected (in the 'Ellipse' sub-menu of the 'Setup' menu). If this option is selected, subjects should be told that they will be given, every few minutes, a record of their progress towards finishing the test.

Difficulties with subjects. If the subject cannot see the ring at the beginning, its position should be traced out on the screen (without touching the screen). Usually failure to see the ring at the beginning is due to misunderstanding, and tracing the ring is sufficient. However, if the subject still cannot see the ring once its position has been traced out on the screen, check that the problem is not low visual acuity or a field defect. The subject may be able to see the ring if he or she sits closer to the screen or further from it. If he or she still cannot see the ring, the experimenter should tell the subject where the gap is, and then, once the instructions have been given, the subject should be told to press the appropriate button. On subsequent trials the subject should be asked if he or she can see the ring, and encouraged to press the appropriate button. In our experience, subjects who have failed to see the demonstration stimulus in the "Trivector" test have also failed to see any subsequent stimuli.

Interpretation of Results

We give below the results to be expected if normal or colour-deficient subjects are tested under the standard conditions specified in the previous section. (For particular research purposes, the experimenter might wish to vary the conditions and will wish to run a control group for comparison with the experimental or patient group.)

Normals. Normal limits for performance for first examination on the basic "Trivector" test are 100 (protan), 100 (deutan) and 150 (tritan). Young adults may perform well within these limits. The "Ellipse" test for normals yields small discrimination ellipses, without a large axis ratio: the latter will typically be less than 2.0. Examples of normal discrimination ellipses are shown in Graph 1, which is an actual printout from the CRS software. The three ellipses correspond to three different background chromaticities, and the crosses represent individual thresholds for different directions relative to the background. The ellipses are fitted by a least squares method.

Protan and deutan observers. Subjects with congenital forms of colour deficiency will almost always exceed the normal limit on either the protan or deutan axis of the "Trivector" test, and typically will exceed this limit on both. The test reliably distinguishes protan and deutan types of colour deficiency, agreeing with classification by the Nagel anomaloscope. The axis of higher score should be taken to indicate the type of deficiency: if the protan score exceeds the deutan, then the classification is protan, and if the deutan score exceeds the protan, then the classification is deutan.

The test gives a quantitative measure of the subject's colour discrimination. The traditional categories of dichromats and anomalous trichromats are now known to cover a large number of genotypes; and population studies show that colour-deficient subjects vary considerably in

their colour-discrimination abilities. Subjects classified as dichromats by the Nagel anomaloscope - protanopes or deuteranopes - will typically score at least 750 on one axis of the "Trivector" test, whereas most anomalous trichromats will achieve a lower score; but there exist anomalous trichromats whose performance is very poor, overlapping with that of dichromats.

In Graph 2 we show results from the ellipse test for a protanope. Notice that the long axes of the ellipses point towards u'=0.678, v'=0.501, which are typical coordinates for the protan confusion point in this chromaticity diagram. Notice too that some data points lie at the limit of the gamut available on the monitor. Graph 3 shows corresponding results for a deuteranope. Here the long axes of the ellipses point towards u'=-1.217, v'=0.782, which are typical coordinates for the deutan confusion point in this chromaticity diagram. Note that sometimes the ellipse fitted by the program will approximate to two parallel lines in the case of subjects with poor discrimination.

Graph 4 shows a discrimination ellipse for an anomalous trichromat with relatively good discrimination. Notice that ellipses point towards the upper left, indicating that this is a subject of the deuteranomalous type.

Tritan observers. Congenital tritanopia is rare, but a number of systemic or ocular conditions, such as diabetes, glaucoma and retinal detachment, may elevate threshold on a tritan axis. In the u',v' diagram, colours confused by a tritanope lie on lines converging to the point u'=0.257, v' =0.0. So tritan confusion axes are approximately vertical in the diagram, tilting slightly anticlockwise. The software offers a special set of three centre points for using in the "Ellipse" test in cases where a tritan defect is suspected from the "Trivector" test.

In Graph 5 we show discrimination ellipses for a case of acquired tritanopia associated with multiple sclerosis. The data are for monocular viewing. This patient had been tested by us in 1992, using an earlier version of the test (Regan et al, 1994). Her more recent results are very similar to those obtained earlier, except that the axes of maximum impairment are rotated by about 10 degrees. This rotation is probably due to the fact that she has had cataracts removed in the interval.

Notes

J. D. Mollon and B. C. Regan would value feedback from users of the Cambridge Colour Test and will endeavour to answer written enquiries about the theoretical and experimental aspects of the test. They can be reached at Department of Experimental Psychology, Downing St., Cambridge CB2 3EB, United Kingdom. Enquiries about the software, its use and operation, should be directed to Cambridge Research Systems. The test is supplied for the purposes of research and neither the authors of the test nor Cambridge Research Systems accept any liability arising from errors of design or construction.

References

The Cambridge Colour Test was first described in:

Mollon, J. D. and Reffin, J. P. (1989) A computer-controlled colour vision test that combines the principles of Chibret and Stilling. *Journal of Physiology*, **414**, 5P

Subsequent field studies can be found in the following:

Reffin, J. P., Astell S. and Mollon, J. D. (1991) Trials of a computer-controlled colour vision test that preserves the advantages of pseudoisochromatic plates. In *Colour Vision Deficiencies X,* pp 69-76, Eds: Drum, B., Moreland, J. D. and Serra, A., Kluwer, Dordrecht

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Further Reading

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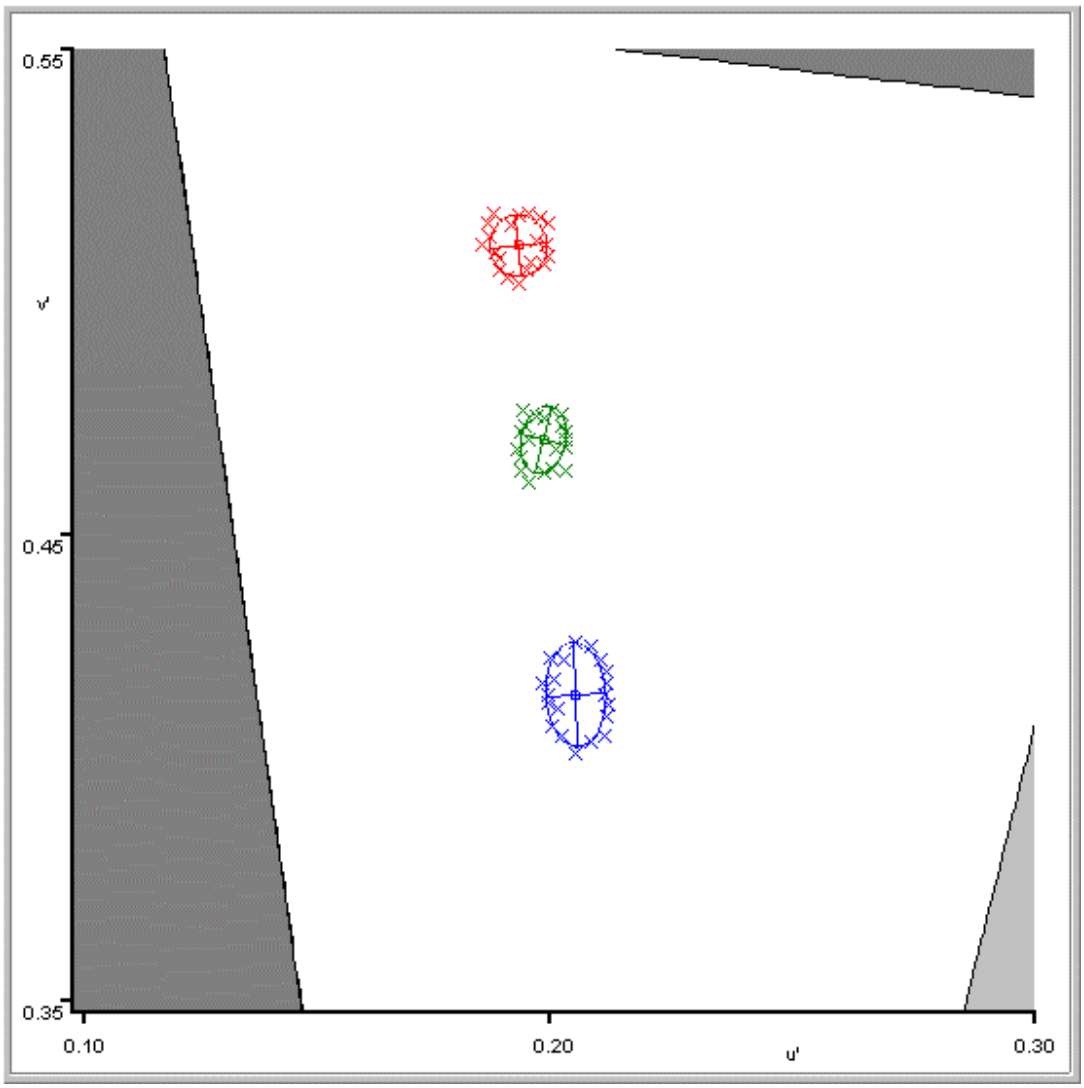
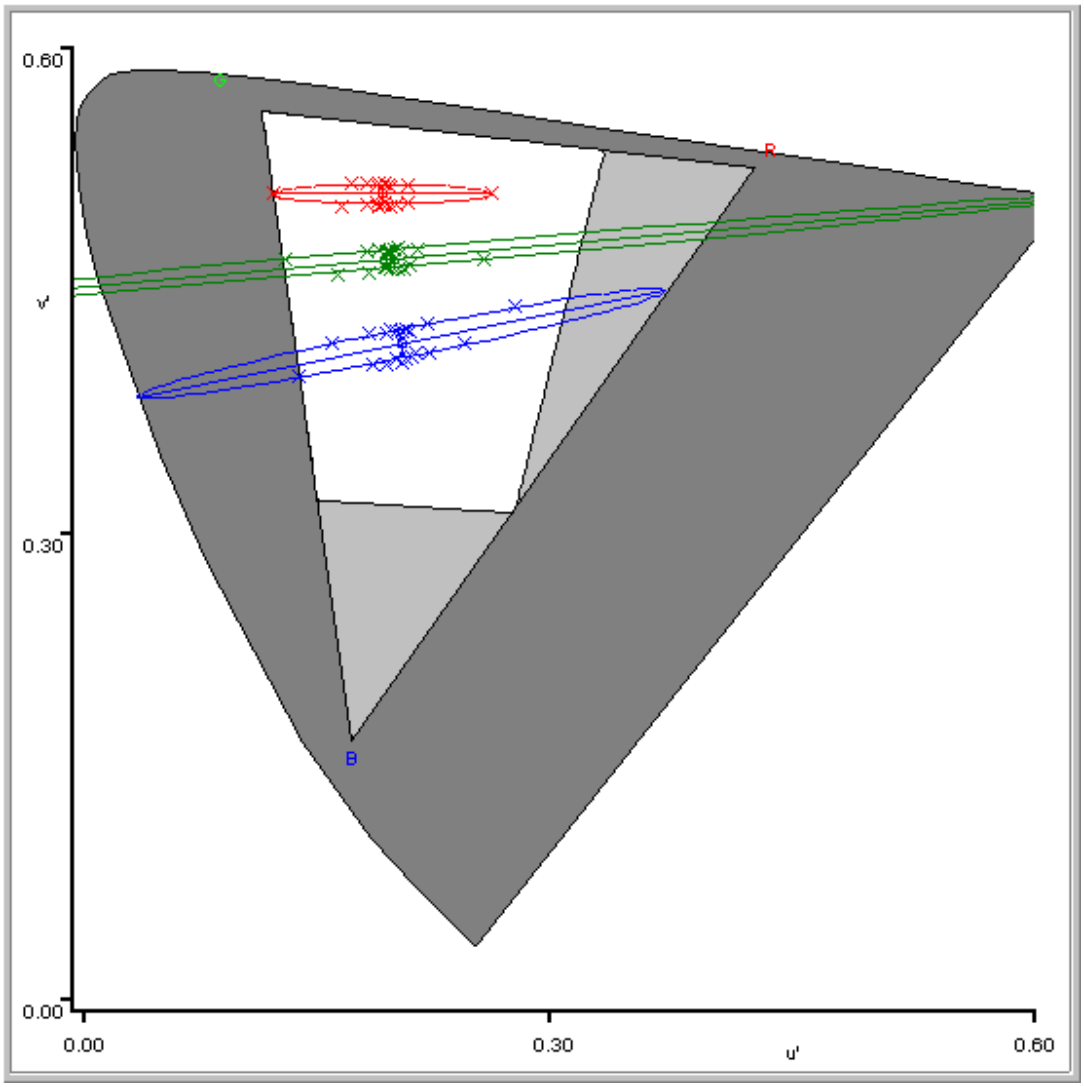
Graph 1. Results from a normal subject

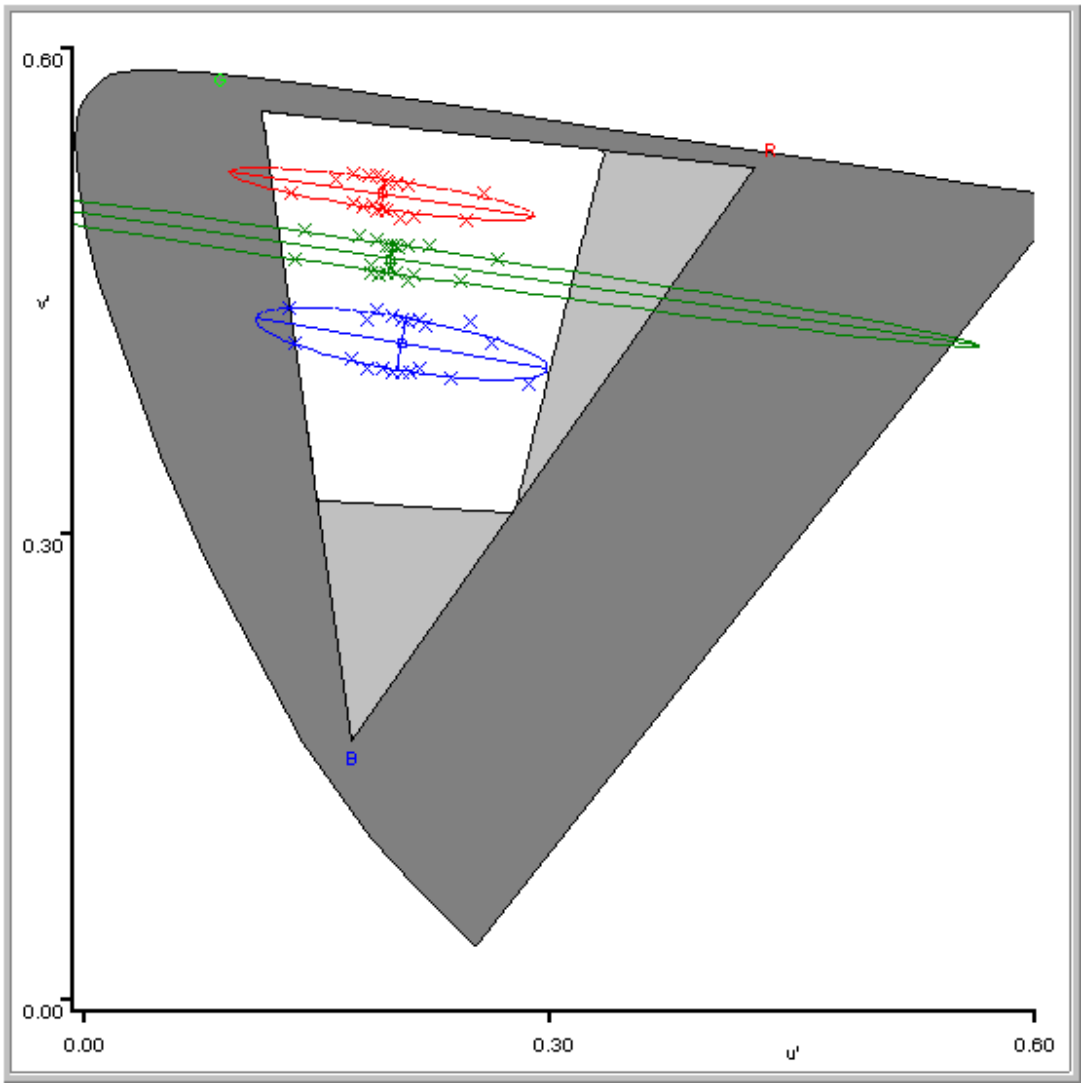
Note that this graph has been expanded to show only the central part of the *u',v'* diagram.



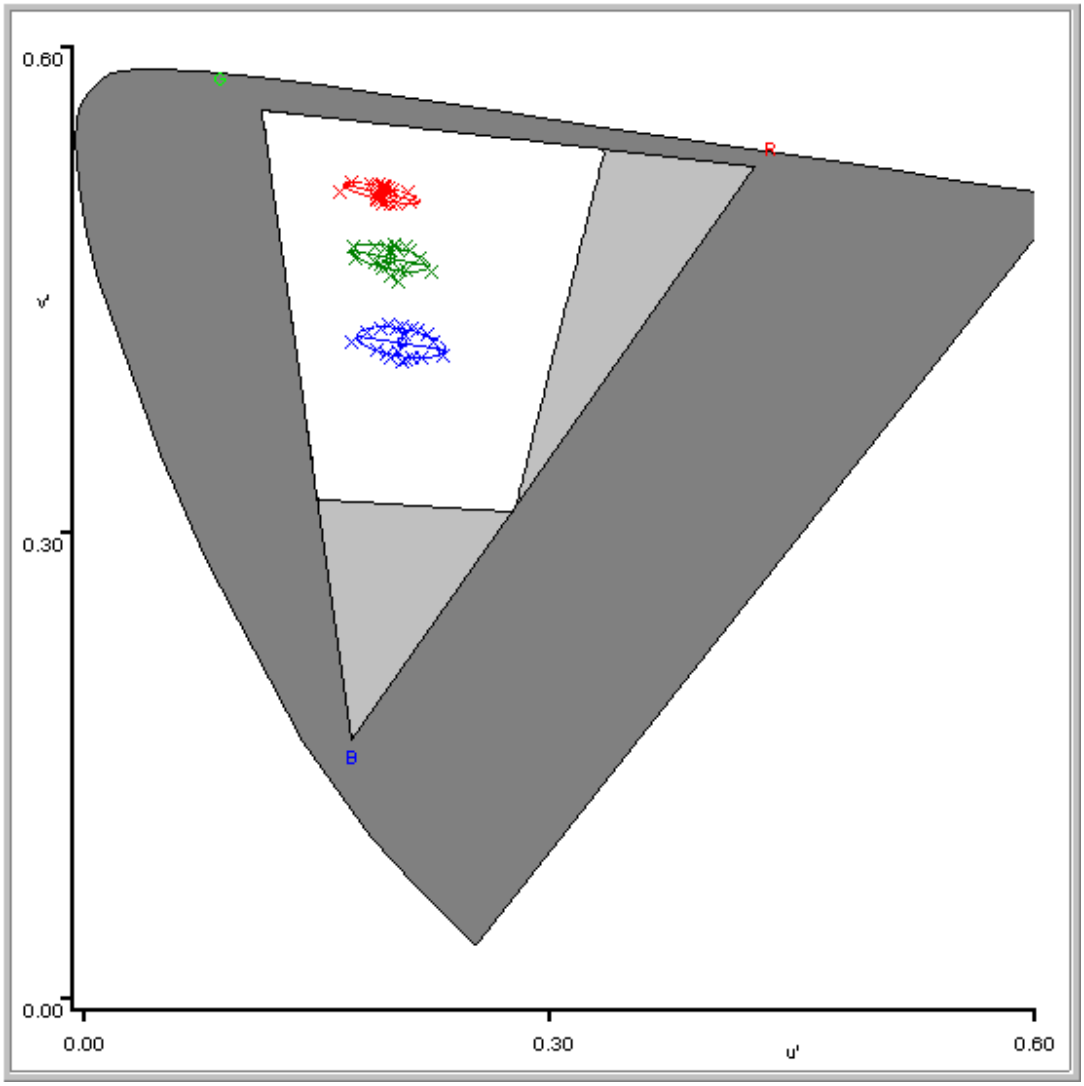
Graph 2. Results from a protanope



Graph 3. Results from a deuteranope



Graph 4. Results from an anomalous trichromat with relatively good discrimination



Graph 5. Results from a case of acquired tritanopia