Anuario de Psicología
2001, vol. 32, nº 3, 5-24

Colour naming by colour blind children

Julio Lillo*
Ian Davies**
José Collado*
Elena Ponte*
Isaac Vitini*
**Universidad Complutense de Madrid*
***University of Surrey*

We compared 30 colour-blind boys to 29 colour-normal boys matched for age (5-9 years) on a colour naming task. The stimuli were good examples of Berlin & Kay's (1969) universal colour categories presented under relatively natural viewing conditions. The colour-blind boys made less than half the naming errors predicted by the standard model of colour vision; naming of primary categories (white, red, green, yellow and blue) was almost normal, while their naming of brown, grey and purple was least accurate. It seems that the phenomenal world of the colour-blind is not as different from ours as the standard theory predicts, and that the advice given to the newly diagnosed colour-blind and their parents needs tempering. The colour-blind however, probably rely more than colour-normals on lightness and saturation differences for colour discrimination and naming, and this suggests that their achievement of their limited level of naming competence will be delayed relative to colour- normals.
Key words: *Colour blindness, basic categories, dichromatic, children.*

30 niños daltónicos y 29 controles de edades similares (5-9 años) fueron comparados en una tarea de denominación de colores en la que se emplearon prototipos de las categorías universales consideradas por la teoría de Berlín y Kay (1969) y condiciones cotidianas de observación. Los daltónicos tuvieron menos errores que los previstos a partir de los modelos convencionales de la visión del color. En concreto, sus denominaciones de los estímulos pertenecientes a las categorías primarias (blanco, rojo, verde, amarillo y azul) fueron muy similares a las de los

Correspondencia: Julio Lillo. Departamento de Psicología Diferencial y del Trabajo. Facultad de Psicología. Universidad Complutense de Madrid. Campus de Somosaguas. 28223 Madrid. Correo electrónico: julillo@psi.ucm.es
Ian Davies. Department of Psychology. University of Surrey. Stag Hill. Guilford. GU2 5XH. United Kingdom. Correo electrónico: idavies@surrey.ac.uk
This study was supported by a DGYCYT agrant (PB95-0910) and ESRC grant number R000236750 and we gratefully acknowledge this support.

controles, aun y cuando tuvieron más errores que éstos ante los estímulos correspondientes a las categorías de marrón, verde y morado. El conjunto de resultados observado parece implicar que el mundo fenoménico de los daltónicos no es tan diferente del común como se predice desde las teorías convencionales, lo que no debe olvidarse cuando se proporciona un diagnóstico de daltonismo al niño afectado y a sus padres. Por otra parte, es muy probable que los daltónicos dependan más que los comunes de las diferencias en claridad y saturación cuando efectúan denominaciones y discriminaciones de color. Este hecho puede estar relacionado con sus limitaciones cotidianas para denominar colores.

Palabras clave: *daltonismo, categorías básicas, dicromático, niños.*

Introduction

For the «colour blind» the diagnosis of colour blindness is often met first by disbelief, and then by curiosity about the colour experiences of those with normal colour vision. This curiosity is reciprocated by those with normal colour vision: how do colours appear to the colour blind? Colour vision tests do not address these questions directly. Such tests show that there are discriminations colour normals make that the colour blind are unable to make, but they say little about the phenomenal world of the colour blind. The scepticism of the colour blind is compounded by the fact that they are often unaware of any practical handicap in everyday life, and the fact that it takes carefully designed tests to reveal the condition. Recent research (Smith & Pokorny, 1977; Montag, 1994; Paramei & Cavonius, 1999) provides some support to the protests of the colour blind. Under viewing conditions approximating everyday life, colour blind adults' performance is less disadvantaged than clinical applications of standard theories of colour vision would predict.

In the research we report here we compared colour naming in normal and colour blind boys under relatively natural viewing conditions in order to assess the impact of colour blindness on everyday colour naming. We also compared the mistakes made by the colour blind boys to predictions derived from the «standard model» of colour vision (Birch, 1993, chapter 4; Rigden, 1999). We expected that the mistakes children made would provide some insight into the problems faced by colour blind children, and that they might provide a handle to begin to understand the nature of such children's' colour experience. Before describing the study, we first outline the standard model of colour vision, then we show how the standard model accounts for colour blindness, and derive predictions of the colour naming errors that colour blind children should make.

The standard model[1]

People with normal colour vision are *trichromats*: all colours can be matched by a mixture of three «primary» monochromatic lights in appropriate pro-

1 See Mollon (1982) for an excellent introduction to the standard model, and Kaiser & Boynton (1996, chapters 5 and 7) for a more advanced treatment.

portions. Trichromacy is based on the normal retina having three types of light detectors (cones) that vary in their spectral sensitivity, as originally proposed by Young (1802) and Helmholtz (1924). This difference in spectral sensitivity is due to the three cones containing different photo-sensitive pigments.

The three cone types are usually known as short (blue), medium (green) and long (red) reflecting their relative peak wavelength sensitivities: about 420 nm, 535 nm and 565 nm respectively (Bowmaker & Dartnall, 1980; Stockman, MacLeod & Johnson, 1993). Figure 1 illustrates the relative cone responses to achromatic stimuli, such as white, and to examples of chromatic stimuli (yellow, blue and purple). The three cone types all respond strongly, and about equally, to white, but differentially to chromatic stimuli. Post receptor processing combines the cone outputs into an achromatic channel (dark-light) and two opponent process chromatic channels, red-green and blue-yellow, consistent with Hering's (1924) theory (see Hurvich, 1981; and Lillo, Collado, Sánchez-López, Ponte, & García, 1998), although the details of how this is achieved are not fully agreed (De Valois & De Valois, 1993; Mollon & Jordan, 1997).

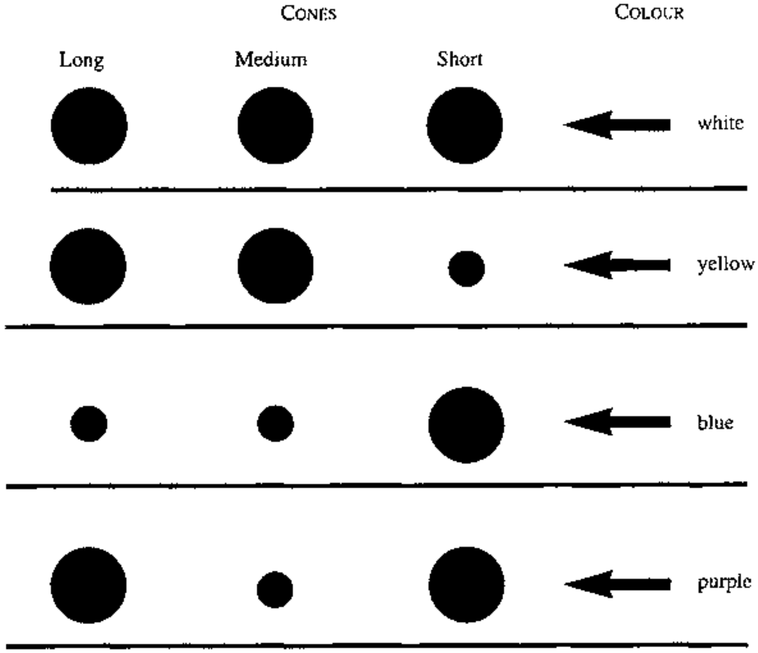

Figure 1. Colour coding and relative cone activation. Circles sizes represent relative cone responses to white, yellow, blue and purple.

The standard model and colour blindness

Over 6% of European males inherit some form of «red-green» colour blindness or *Daltonism* (Fletcher & Voke, 1985; Lillo, Sánchez-López, Ponte, & García, 1998). Daltonism is due to either the central retina having just two cone pigments, in which case the person is a *dichromat*, or to having an abnormal cone pigment, in which case the person is an *anomalous trichromat*. About a quarter of those with Daltonism are dichromats, and the remainder are anomalous trichromats. There are two kinds of dichromat: deuteranopes do not have the medium wavelength cone, and protanopes do not have the long wavelength cone. In both cases the colour-blind person needs just two primaries suitably adjusted to match any colour, and their perceptual colour space is compressed along the red-green axis.

Anomalous trichromats have an anomalous photopigment in either the medium wavelength cone (*deuteranomaly*) or in the long wavelength cone (*protanomaly*). In both cases the spectral sensitivity functions of the two pigments are closer together than in the normal eye, resulting in reduced discrimination along the red-green axis of colour space.

Figure 1 illustrates why dichromats see some stimuli as equivalent, which to normals look different. Blue and purple appear different to normals because they produce different responses in the long wavelength cones, while producing similar responses in the other two types of cone. Thus, for those dichromats lacking the long wave length cone (*protanopes*), the retinal response to blue and purple is essentially the same, and they therefore have no basis for discriminating between these stimuli. By extension, it follows that every set of stimuli differentiable only in terms of the activity of a single cone type, will not be discriminable for observers lacking this cone. By using the quantitative functions relating cone responses to wavelength, the full set of confusable colours for dichromats can be derived. In combination with what we know about the semantic fields of basic colour terms, predictions can be derived for what are the most likely naming confusions for dichromats.

Predicting naming confusions

Figure 2 shows the CIE (1976) (Commission Internationale De l'Éclairage) u' v' chromaticity diagram (see appendix 1 for an outline of the system). Spectral colours lie on the horseshoe shaped circumference, and the loci of the colours used in our study are shown as landmarks. Achromatic colours (white, black and grey) lie at u' = 0.21; v' = 0.47. Full specification of a colour requires a third dimension (not shown) L* (lightness). The regions around each of the landmark colours include colours that fall in the same linguistic category as the focal colour, but the colours become increasingly less good examples of the category with increasing distance from the category focus. Members of the same colour category can vary in lightness (e.g. dark blues and light blues), and therefore colour categories are represented by volumes in the CIE space. In order to predict dichromats' naming confusions, we need to be able to specify the volumes occupied by each colour category.

Dichromats' colour confusions are represented by confusion lines radiating from a point (see Figure 3; the convergence point is different for protanopes and deuteranopes, but for illustration we just show the point for protanopes). Any pair of colours falling on the same confusion line will look equivalent to a protanope. Figure 3 emphasises one confusion line for illustration. Three points are shown (as large diamonds) representing monochromatic lights at 520 nm (green), 590 nm (yellow) and 670 nm (red). These colours are confusable by protanopes, as are all others falling on that particular confusion line. Figure 3 also shows the loci of the colours we used in our study, and the confusion lines passing through each locus. Just as for the green-yellow-red confusion line, any pair of colours falling on a confusion line will seem equivalent to a protanope, and this forms the basis for predicting naming confusions (see appendix 1 for more technical details).

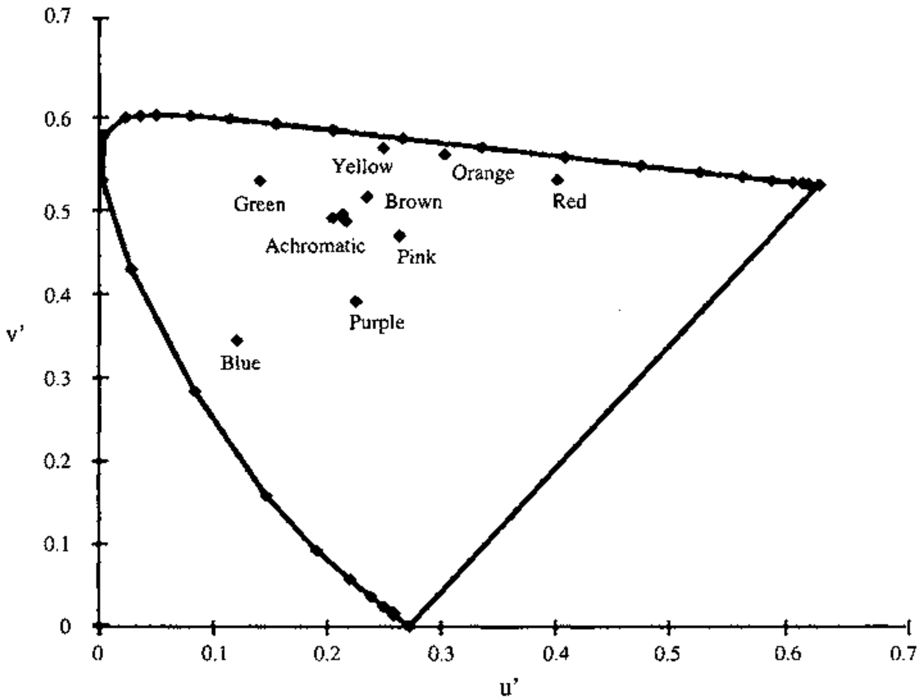

Figure 2. CIE (1976) u' v' chromaticity diagram. Spectral colours lie on the horseshoe shaped circumference, and the loci of the colours used in this study are shown. The achromatic colours (white, black and grey) have approximately the same loci (u' = 0.21, v' = 0.47) but differ in reflectance (non represented).

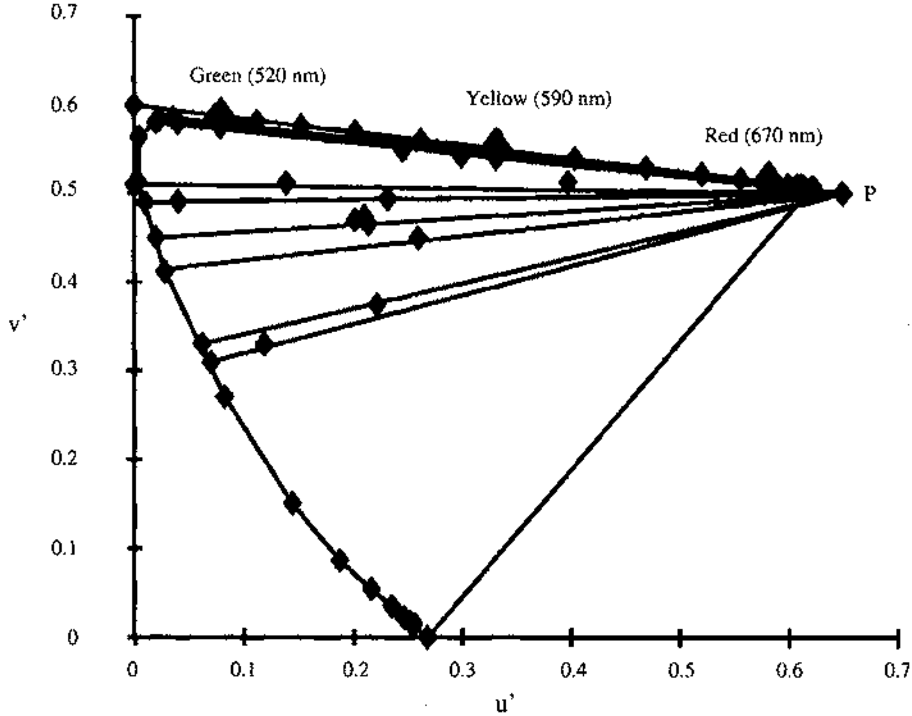

Figure 3. Protanope confusion lines in the CIE (1976) u' v' chromaticity diagram. The large data points represent monochromatic lights (red, green and yellow). The small data points represent the stimuli used in the colour naming task. Confusion lines radiate from the protanope confusion point P.

If the regions occupied by two colour categories are intersected by the same confusion line, then a naming confusion is possible. However, recall that colour categories are represented by volumes in CIE space, so a further requirement for naming confusions is that the lightness (L*) of the two categories must also intersect, otherwise lightness alone could be a sufficient cue for category identification[2]. The volumes of colour space occupied by each colour category were derived from Boynton and Olson's (1987; see also Boynton and Olson, 1990) colour naming data for English, and they are also consistent with other naming data from Catalan (Davies, Corbett & Margalef, 1995); English (Davies & Corbett, 1995; Sturges & Whitfield, 1997); Russian (Davies & Corbett, 1994); and Spanish (Lillo, Collado, Sánchez-López, Ponte, Vitini & García, 1996).

Table 1 shows the predictions of naming confusions derived from the preceding method for protanopes and for deuteranopes. The first column shows the

2 As dichromacy affects the achromatic channel the effective lightness values will differ for colour normals and dichromats. In order to allow for this we calculated lightness values for the dichromats using Smith & Pokorny's (1975) cone fundamentals. Further technical details are available from the first author.

correct name[3], and columns two and four show possible naming confusions for protanopes and deuteranopes respectively. Note that in most cases there is more than one possible confusion. For instance, the red colour could be named either *green, orange* or *brown* by a protanope, and *green, orange, brown* or *pink* by a deuteranope. For simplicity, we assume that each possible naming confusion and the correct response are equally likely, and columns three and five shows the expected percentage of correct responses based on this assumption. For instance, for the red stimulus we used, protanopes have four equally likely possible responses (*red, green, orange* and *brown*) and therefore the proportion of correct responses should be one fourth, (20%). (Appendix 1 gives more technical detail for these predictions.)

TABLE 1. PREDICTED NAMING ERRORS AND PERCENTAGE OF CORRECT RESPONSES FOR PROTANOPES AND DEUTERANOPES

Tile	*Protanopes*	*% Right*	*Deuteranopes*	*% Right*
red	green orange brown	25	green orange pink brown	20
green	orange pink	33	red pink brown grey	20
blue	red purple brown	25	purple	50
yellow	green	50		100
orange	green yellow pink	25	green yellow pink	25
purple	red blue pink brown	20	blue brown	33
pink	blue grey	33	green grey	33
brown	red green black grey	20	red green black grey	20
white		100	---	100
black	red green blue brown	20	green brown	33
grey	red green blue pink brown	17	red green brown	25
Total		33		42

The standard model and the peripheral trichromatism of macular dichromats

Tests of colour blindness use relatively small stimuli which when fixated project just onto the macula (the central retina). Smith & Pokorny (1977) showed that clinically diagnosed dichromats make less colour confusions with large stimuli than with the more usual small visual angle test stimuli. Such stimuli excite both the central and peripheral retina, and the implication is that receptors in the periphery must be providing the information for the improvement in colour discrimination.

Rods are frequent in the peripheral retinae, and it is possible that they contribute to colour vision (Montag & Boynton, 1987; Shapiro, Pokorny & Smith, 1994). However, dichromats also show enhanced colour discrimination with large stimuli at high illumination levels when the rods cease to function (Nagy & Boynton, 1979; Frome, Pientamina & Kelly, 1982), and most colour naming tasks use such illumination levels.

3 Although we use English terms, they are intended to denote whatever the appropriate term is for a given region of colour space in any particular language. English and Spanish are very similar in how colour space is partitioned.

Nagy (1980), Breton & Cowan (1981) and Montag (1994) hypothesised that the dichromat's peripheral retinae may contain some of the types of cone missing from centre. If this is the case, then macular dichromats should respond to large stimuli as anomalous trichromats do to small ones, and this is what Montag (1994) found. Dichromats' colour naming was similar to that of anomalous trichromats when large stimuli were presented with long exposure times.

The origin of colour categories

Berlin & Kay (1969) claim that there are eleven universal colour categories, and that all languages draw their inventory of basic colour terms from this universal set. English and Spanish have terms for each of the universal categories. The eleven English basic colour terms are: *black, white, red, green, yellow, blue, brown, purple, pink, orange*, and *grey* (Davies & Corbett, 1995). Kay & McDaniel (1978) argue that the eleven universal categories are each based on a perceptually salient category focus (the best example) and that this salience is based on the underlying perceptual physiology (De Valois, Abramov & Jacobs, 1966). It is assumed that the physiology confers a privileged status on the first six terms (the primary terms) although the exact basis for this status has yet to be completely determined (De Valois & De Valois, 1993; Mollon & Jordan, 1997). As well as this universal factor the theory leaves scope for cultural relativity. Languages can vary in the size of their basic colour terms inventory, and also in the position of their category boundaries.

First language learners normally share a predisposition to form colour categories around the universal foci, but must learn the particular set of terms and the positions of boundaries from those already competent in the language. Colour blind children on the other hand, do not share completely the predisposition to form colour categories around the same set of perceptually salient foci, and should thus be handicapped in acquiring competence in using colour terms. Nevertheless, they are expected to learn the language's basic colour terms, but their use of some terms will be distributed differently to colour normals across colour space, and they should be inconsistent in colour naming, as predicted by the standard theory.

The current study

The main aim of the current study was to investigate colour naming by dichromatic boys, using procedures based on Montag (1994). Using boys aged from 5 to 9 years old necessitates various changes from the methods used by Montag. First, the most reliable method for diagnosing dichromatism in adults is to use an anomaloscope (Kaiser & Boynton, 1996: 429). However, this procedure requires too much patience and concentration for young children, and so we used a battery of standard colour vision tests instead. Second, Montag required his subjects to name 215 colour samples twice, thus allowing him to map colour naming across colour space with high resolution. Again we decided that this would be beyond the capacity of our children, and instead we tested them with just eleven colour samples, the focal exemplars of Berlin & Kay's (1969) eleven universal categories. Although we had less data per subject than Montag, we had a relatively large sample (30) of colour blind children. This is the first time dichromatic colour naming data have been reported for a sample of this size, of children this young.

Method

Subjects

There were three groups of subjects: protanopes (n=12); deuteranopes (n=18) and controls (n = 29). All lived in Alcorcón, a city near Madrid (Spain) and they were first language Spanish speakers. They were selected from 1631 boys aged between 5 and 9 years who were screened for colour blindness.

Apparatus

The test battery consisted of a simplified version of the Ishihara test (Birch, 1993, p 74), the City University Colour Vision Test (CUCVT, Fletcher, 1980) and the TIDA (Test para Identificación de los Daltonismos; Lillo, 1996). A child was considered as a dichromat if the following three criteria were met: (1) anomalous responses were made to at least 22 out of the of the 24 Ishihara plates; (2) six or more (out of ten) protan or deutan responses on the CUCVT; (3) a rating of severe on the TIDA. Pilot work with adult observers showed that these are conservative criteria: all adults meeting them were confirmed as dichromats by the anomaloscope, and some adults diagnosed as dichromats by the anomaloscope failed to meet the triple criteria.

TABLE 2. SPECIFICATION OF THE STIMULI. COLOUR-AID CODE, CIE u' v' AND REFLECTANCE

Color-Aid Code	*Correct response*	*u'*	*v'*	*Reflectance*
RO-HUE	red	0.400	0.510	17.43
YGC-HUE	green	0.139	0.512	23.96
BC-HUE	blue	0.119	0.330	10.34
Y-HUE	yellow	0.246	0.549	68.50
YO-HUE	orange	0.299	0.542	48.67
V-HUE	purple	0.222	0.374	06.14
R-T4	pink	0.260	0.450	56.64
O-S3	brown	0.232	0.494	07.47
White	white	0.202	0.470	83.31
Black	black	0.210	0.471	03.71
GRAY 4	grey	0.214	0.466	20.79

The stimuli for the colour-naming task consisted of 11 five-centimetre square coloured tiles presented on a grey background (20% reflectance). They were viewed from 35 cm and they projected a visual angle of 8°, which ensured that their image extended beyond the macula to include some of the peripheral retina. The colours were taken from the Color-Aid range, and Table 2 shows their Colour-Aid identification, the name used by normal observers, the CIE u' v' (1976) chromaticity co-ordinates and standard reflectance.

Procedure

Testing was carried out where possible in natural light with an illuminance level between 250-400 lux and a colour temperature between 4000-6500 Kelvin. If the light parameters fell outside these values, natural light was mixed with the light from an incandescent blue light bulb. The CIE chromaticity index was always 100% (the optimum value).

All children were individually tested on the colour-naming task. The tiles were shown one at a time, in a random sequence, on the grey background. The tiles were viewed binocularly, from 35 cm. The experimenter required the child to respond with one colour name, and no object colour names (such as banana or tomato) were allowed.

Results

Correct responses

Table 3 shows the proportion of children in each sample that named each tile correctly, and the total proportion of correct responses for each group. It can be seen that both colour blind groups' total correct scores are over 0.70 (70%), about double the number predicted in Table 1. Moreover, the distribution of errors

TABLE 3. PROPORTION OF RIGHT RESPONSES FOR EVERY GROUP AND TILE

Tile	*Protanope*	*Deuteranope*	*Control*
red	0.83	0.94	1.00
green	0.92	1.00	1.00
yellow	1.00	1.00	1.00
blue	0.92	0.94	1.00
orange	0.75	0.72	0.97
purple	0.58	0.56	1.00
pink	0.58	0.94	0.90
brown	0.50	0.44	1.00
white	0.83	0.89	0.97
black	0.67	0.72	0.97
grey	0.33	0.44	0.93
Total	0.73	0.78	0.95

across categories is not well predicted by the model. The correlations between the predicted number of correct responses and the actual number are just 0.43 and 0.42 (not significant) for the protanope and deuteranope groups respectively.

All groups make relatively few errors in naming the primary chromatic colours (red, green, yellow and blue). The colour blind groups make more errors than the control group, but no differences were significant. In contrast, the colour blind groups tend to make more errors than the controls in naming the secondary chromatic colours (orange, purple pink, and brown) and two of the achromatic colours, black and grey (minimum $\chi^2 = 6.2$; d.f = 1, $p < 0.05$).

Types of error

Table 4 shows the names given in error to each of the tiles, and the frequency with which each error was made, for protanopes and deuteranopes separately. We also distinguish between predicted errors and unpredicted errors. For example, protanopes make eight errors in response to the grey tile: four *green* responses, three *pink* responses and one *brown* response. These kinds of response are predicted by the model, as indicated by the data falling in the predicted error column. On the other hand, protanopes make a single error for green, and this is an unpredicted error as indicated by *yellow* 1 in the unpredicted column. The majority of errors (over 80% for both colour blind groups) fall in the categories predicted by the model. Thus although the model does not predict well the absolute number of errors, or the distribution of errors across categories, it does a reasonable job of predicting which errors will not be made.

TABLE 4. FREQUENCY OF PREDICTED AND NON PREDICTED NAMING ERRORS FOR EACH TILE, FOR PROTANOPES AND DEUTERANOPES

Tile	*Protanope*		*Deuteranope*	
	Predicted	*Non-predicted*	*Predicted*	*Non-predicted*
red	green 2		orange 2	
green		yellow 1		
yellow				
blue	purple 1		purple 1	
orange	yellow 3		yellow 5	
purple	blue 5		blues 7 brown 1	
pink	blue 1 grey 2	red 1 white 1		red 1
brown	black 5	purple 1	red 1 green 4 black 5	
white		green 1 yellow 1		yellow 1 pink 1
black	green 1 brown 1		green 1 brown 1	blue 2
grey	green 4 pink 3 brown 1		green 6 brown 2	purple 1 pink 1

Discussion

Children diagnosed as dichromats name focal colours more accurately than predicted by the standard model. Overall they make about 70% correct responses compared to the standard models prediction of about 30%. Nevertheless, the majority of the naming errors they make are consistent with the standard model's predictions, even though the distribution of predicted names does not fit the quantitative predictions well (correlations of about 0.4).

Our results are consistent with Montag's (1994) data, and are clearly different to dichromats' naming performance under standard experimental viewing conditions. For instance, with small stimuli at constant luminance adult dichromats make the confusions predicted from the appropriate dichromat confusion line (Lillo, Vitini, Ponte & Collado, 1999).

Our data go some way to supporting the claims of many colour blind people that they are only rarely aware of any practical consequence of their abnormal colour vision. Natural colour categories are defined by a combination of hue, lightness and saturation. For instance, *yellow* is defined partly as a light colour, and *red* by being a relatively saturated colour (low saturation *reds* are *pink*). Thus tests of colour naming based on hue alone, withhold potential information for category naming, which is potentially of more importance to the colour blind than for those with normal colour vision. For instance, Paramei, Bimler & Cavonious (1998) showed how dichromats used relative lightness to guide colour naming.

The dichromats' performance was particularly accurate for *white, red, green, yellow* and *blue*. These are five out of the first six terms in Berlin & Kay's (1969) hierarchy of colour terms. *Red, green yellow* and *blue* also have special status as the linguistic labels for the unique hues (Mollon & Jordan, 1997). Focal examples of these categories, as used in our study, are saturated colours, and they are mutually as perceptually distant as it is possible to be. Thus it is likely that as well as information for relative lightness, dichromats may be using saturation to guide naming. With a larger range of stimuli ranging over more lightness and saturation levels, it is likely that dichromats' naming performance would deviate more from normals than that found here.

If colour blind children have to rely more than colour normals on lightness and saturation differences to learn to use colour names acceptably, this may slow learning relative to colour normals. Thus, arriving at even the level of competence achievable by the colour blind may be delayed relative to colour normals' arrival at their peak competence. In our data, the colour-blind five-year-olds made the most errors of any age group (mean = 3.2) whereas the colour-normal five year olds made virtually no errors. However, although theses data are consistent with colour-blind children being delayed in achieving their final level of competence, the sample size was too small to warrant generalisation (N = 3).

Our results also suggest that the information given to the newly diagnosed colour blind and their parents needs to be changed. Red-green colour blindness is often mistakenly interpreted to mean that the colour blind will be unable to tell reds from greens, and that their difficulties will be restricted to these regions of colour space. However, the standard model makes clear that dichromats' potential confusions can occur in most regions of colour space: dichromats cannot discriminate any pair of colours falling on the appropriate confusion line (see Figure 3). Even those working with the standard model can sometimes misinterpret it to give misleading advice. For instance Rigden (1999) in trying to illustrate what the phenomenal colour world of the colour blind is like, shows (Figure 3) the perception of red for a protanope to be light and desaturated, whereas one of the clearest aspects of protanopia is that red will appear as a very dark colour to them.

Under the viewing conditions of every day life that we tried to partially emulate in this study, dichromats' colour naming will be less abnormal than suggested by common interpretations of the standard model. Furthermore, the dichromats' perceptual confusions will be less extensive than the standard model implies. The improvement relative to the standard model will be greatest for saturated colours, and of course the best exemplars of most chromatic categories are usually the most saturated members of the respective categories. Colour coding also tends to use the best examples of colour categories as the codes, and we would expect dichromats under good illumination and with free viewing to be able to use such colour coding successfully. There will still be functions which dichromats should not perform, because of the possibility of having to make safety critical decisions under nonoptimal viewing conditions such as poor illumination or under time pressure. However, parents of the colour blind should not steer their children away from all careers where some degree of colour judgement is required unless there is an institutionalised requirement for normal colour vision, such as that for airline pilots.

Implications for learning colour naming

Learning of colour names by colour-normal children usually takes several years from first use of colour terms through to general competence in their use. Bornstein (1985) first pointed out this learning period was extended relative to other lexical classes, and it has been the subject of recent investigations by Braisby & Dockerell (1999) and Sandhofer & Smith (1999). The latter characterise the acquisition process as learning a succession of mapping systems. Children first learn that colour terms form a more or less closed lexical class –a word-word map; then learn to produce appropriate colour terms in response to stimulus properties - a word-property map; and only then learn to abstract the property of colour, in order for instance, to match objects by shared colour. The dichromats in our study had all reached competence in word-word mapping. In all cases their responses were Spanish colour terms. However, we can not rule out the possibility that learning word-word mapping is delayed relative to colour-normals without extending the sample to younger ages.

Colour-normal children tend to achieve competence in colour naming with the chromatic primary colour terms first (red, green, yellow and blue in English), followed by the achromatic primary terms (black and white), followed by the derived terms (purple, pink, orange, brown and grey (e.g. Cruse, 1977; Davies, Corbett, McGurk & MacDermid, 1998; Pick & Davies, 1999). This order probably occurs because this reflects the relative exposure of the learner to the different terms. Primary colour terms are the most frequent in the language; children's books and television often use primary colours; and carers and teachers choose primary colours and terms as first training examples. In turn, this prevalence may reflect some aspect of the neurophysiology of colour vision which makes primary colours highly salient (see e.g. Kay & McDaniel, 1978).

When colour-normal children start to use colour terms they often over extend a term by applying it to perceptual neighbours of the correct referents of the term. Pink colours may be named red or orange colours may be named yellow. Feedback from others provides the basis for narrowing a term's use to standard useage. Such learning relies on a fundamental similarity between the learner's and the teacher's perception of colour. Feedback and reinforcement for using colour terms is based upon this equivalence of the 'internal colour space': only colours that the teacher deems to be red will be accepted as instances of the term red, and so on for other terms. For a dichromat however, this equivalence is weakened. Under standard laboratory conditions, colour space is compressed along the red-green axis, and many colours that are discriminably different to the colour-normal are perceptually equivalent for the dichromat (see confusion lines in Figure 3). On the face of it, this compression may be reduced under the free viewing conditions used in this study, but some of the discrepancies with the classical model may be due to processes outlined in the conjectures below.

Consider a simple case where a confusion line passes through the domain of two basic colour terms, say red and green in English. It is likely that the child will be reinforced some of the time for labelling a green green, and a red red. But, as these two colours are perceptually equivalent for the dichromat, they will also use the two labels wrongly: green-red and red-green pairings will occur, which will not be reinforced. The child will be faced with an insoluble problem: there will always be residual uncertainty in colour name pairings, unless some additional way of resolving the uncertainty can be found.

There are a number of strategies dichromatic children might use to try to minimise their incorrect use of colour terms. First they might learn about 'environmental regularities'. For example, they could respond to the relative frequency with which they encountered colour terms. Faced with the choice between two terms, each of which is sometimes reinforced, they could bias their selection in favour of the term they encounter more often, or the term which was reinforced most often. They could further refine this strategy by detecting local context; perhaps green is more likely to be acceptable in the natural world (because of the prevalence of plants) rather than in doors. A second strategy might be use general knowledge of objects to either bypass property-name mapping, or to augment it. Faced with a choice between red or green, knowing that the object was, say, a post-box (in Britain), allows the child to reliably select the red response. And the reliability need not be perfect in order to contribute to some uncertainty reduction.

Little is known about how dichromatic children learn colour terms. However, some of the data from the present study is consistent with the conjectures just outlined. The primary chromatic colour terms are the most frequent in the language, and it is these terms that the children use correctly most often. If this occurs partly because of response bias, then these terms should also have high false positive rates. In Table 4 it can be seen that the most common error pattern is for a primary term to be used to name a non-primary colour (55 out of 84 errors). Note, of course, that such response bias does not help them in the context of the study, because each of the eleven colours is equally likely. Nor does response bias account fully for the difference between the primary and non-primary terms. Combining correct responses and false positives into a single index –A', a non-parametric index of accuracy– still leaves performance with primary terms greater than for non-primary terms: A' for primary terms ranges from 0.94 to .99; and for non-primary terms from 0.86 to 0.94 (see e.g. Wickens, 1992: p. 73 for an account of this measure).

Summary

Under free viewing conditions, dichromats make less colour naming errors than predicted by strict application of the standard model of colour vision. This is particularly so for good examples of most of Kay & McDaniel's primary colour categories (white, red, green, yellow and blue). They have particular difficulty with black (the remaining primary category), purple, grey and brown. Dichromats probably use available lightness and saturation information to guide their naming, but there may also be information in the signals from the peripheral retina that is not available in the signals from the central retina. It is probable then that in every day life dichromats' colour experience, and certainly their performance with colour, will not be as different from colour normals as clinical applications of the standard theory suggest.

References

Berlin B. & Kay P. (1969). *Basic Color Terms: Their Universality and Evolution*. Berkeley Los Angeles: University of California Press.

Birch, J. (1993). *Diagnosis of Defective Colour Vision*. Oxford: Oxford Medical Publications.

Bornstein, M. H. (1985). On the development of color naming in young children: Data and theory. *Brain and Language, 26*, 72-93.

Boynton, R. M. & Olson, C. R. (1987). Locating basic colors in the OSA Space. *Colour Research and Application, 12*, 94-105.

Boynton, R. M. & Olson, C. X. (1990). Salience of chromatic basic color terms confirmed by three measures. *Vision Research, 30*, 1311-1317.

Bowmaker, J. K & Dartnall, H. J. A. (1980). Visual pigments of rods and cones in a human retina. *Journal of Physiology, 298*, 501-511.

Braisby, N. & Dockerell, J. (1999). Why is colour naming difficult? *Journal of Child Language, 26*, 23-47.

Breton, M. E & Cowan, W. B. (1981). Large-field trichromacy in deuteranopes. *Journal of the Optical Society of America. 71*, 1220-1223.

Cruse, D. A. (1977). A note on the learning of colour names. *Journal of Child Language, 4*, 305-311.

Davies, I. R. L. & Corbett, G. G. (1994). The basic color terms of Russian. *Linguistics, 32*, 65-89.

Davies, I. R. L. & Corbett, G. G. (1995). A practical field method for identifying probable basic colour terms. *Languages of the World, 9*, 25-36.

Davies, I. R. L, Corbett, G. G. & Bayo, J. (1995). Colour terms in Catalan: an investigation of eighty informants, concentrating on the blue and purple regions. *The Journal of the Philological Society, 93* (1), 17-49.

Davies, I. R. L., Corbett, G. G., McGurk, H. & MacDermid, C. (1998). A developmental study of the acquisition of Russian colour terms. *Journal of Child Language, 25*, 395-417.

DeValois, R.L,. Abramov, I. & Jacobs, G.H. (1968). Analysis of response patterns of LGN cells. *Journal of the Optical Society of America, 56*, 966-977.

DeValois, R. L. & DeValois, K. K. (1993). A multi-stage color model. *Vision Research, 33*, 1053-1065.

Fletcher, R. J. (1980). *The City University Color Vision Test* (2nd ed.) London: Keeler.

Fletcher R. & Voke J. (1985). *Defective Colour Vision: Fundamentals diagnoses and management.* Bristol: Adam Hilger Ltd.

Frome, F, Pientanida, T. & Kelly, D.H. (1982). Psychophysical evidence for more than two cone types in dichromatic colour blindness. *Science, 215*, 417-419.

Helmholtz, H. (1924). *Physiological Optics* edited by J. P. C. Southall, Rochester, New York: Optical Society of America.

Hering, E. (1924/1964). *Outlines of a Theory of the light sense.* (L. M. Hurvich & D. Jameson, Eds. And trans.) Cambridge Mass.: Harvard University Press.

Hunt, R. W. G. (1987). *Measuring Colour.* New York: John Wiley & Sons.

Hurvich, L. M. (1981). *Color Vision.* Sunderland. MA: Sinauer Assoc.

Hurvich, L. M. & Jameson, D. (1957). An opponent-process theory of color vision. *Psychological Review, 64*, 384-404.

Kaiser, P. K. & Boynton, R. M. (1996). *Human Color Vision.* Washington DC: Optical Society of America.

Kay, P. & McDaniel, C. K.(1978). The linguistic significance of the meaning of basic color terms. *Language. 54*, 610-646.

Lillo, J. (1996). Manual del Test de Identificación de Daltonismos (TIDA). Madrid: TEA.

Lillo, J., Collado, J. A., Del Valle, R. & Sánchez-López, M. P. (1995). Color, contraste y diseño ergonómico (I): La percepción del color. *Factores Humanos, 9*, 47-57.

Lillo, J., Collado, J. A., Sánchez-López, M. P., Ponte, E., Vitini, I. & García, C. (1996). *Alteraciones en la percepción del color e integración escolar (Informe Final).* Madrid: CIDE.

Lillo, J., Sánchez, P., Collado, J., Ponte, E., & García, C. (1998). TIDA: A children test to assess dysfunctions in the perception of colour. *Psychology in Spain, 2*, 48-56.

Lillo, J; Vitini, I., Ponte, E. & Collado, J. (1999). Daltonismo, pseudoacromatismo y categorías verbales. *Cognitiva, 11*, 3-22.

Mollon, J. D. (1982). Colour vision and colour blindness. In H. B. Barlow & J. D. Mollon (Eds.), *The Senses* (pp. 165-191). Cambridge: Cambridge University Press.

Mollon, J. D. & Jordan, G. (1997). On the nature of unique hues. In C. Dickinson, I., Murray & D. Carden (Eds.), *John Dalton's Colour Vision Legacy.* London: Taylor & Francis.

Montag, E. D. (1994). Surface color naming in dichromats. *Vision Research, 34*, 2137-2151.

Montag, E. D. & Boynton, R. M. (1987). Rod influence in dichromatic surface color perception. *Vision Research. 27*, 2153-2162.

Nagy, A. L. (1980). Large-field substitution Rayleigh matches of dichromats. *Journal of the Optical Society of America, 70*, 778-784.

Nagy, A. L. & Boynton, R. M. (1979). Large-field color naming of dichromats with rods bleached. *Journal of the Optical Society of America, 69*, 1259-1265.

Paramei, G. V., Bimler, D. L. & Cavonious, C. R. (1998). Effect of luminance on color perception of protanopes. *Vision Research, 38*, 3397-3401.

Paramei, G. V., & Cavonious, C. R. (1999) Colour spaces of color-normal and abnormal observers reconstructed from response times and dissimilarity ratings. *Perception & Psychophysics* (in press).

Pich, J. & Davies, I. R. L. (1999). La adquisición de los términos para el color en niños castellano y catalano-parlantes. *Infancia y Aprendizaje, 85*, 95-112.

Rigden, C. (1999). «The eye of the beholder» - Designing for colour-blind users. *British Telecommunications Engineering, 17*, 2-6.

Sandhofer, C. M. & Smith, L. B. (1999). Learning color words involves learning a system of mappings. *Developmental Psychology, 35*, 668-679.

Shapiro, A. G., Pokorny, J. P. & Smith, V. C. (1994). Rod contribution to large-field color matching. *Colour Research and Application, 19*, 236-245.

Smith, V. C. & Pokorny, J. P. (1977). Large field trichromacy in protanopes and deuteranopes. *Journal of the Optical Society of America, 67*, 213-220.

Stockman, A., MacLeod, D. I. A. & Johnson, N. E. (1993). Spectral sensitivities of human cones. *Journal of the Optical Society of America, 10*, 2491-2521.

Sturges, J. & Whitfield, A. (1997). Salient features of Munsell colour space as a function of monolexemic naming and response latencies. *Vision Research, 37*, 307-313.

Wickens, C.D. (1992). *Engineering Psychology and Human Performance* (2nd Ed.). New York. Harper & Collins.

Young, T. (1802). On the theory of light and colours. *Philosophical Transactions*, 12-48.

APPENDIX

THE CIE SYSTEM: CHROMATICITY DIAGRAMS AND CONFUSION LINES

The CIE (Commission Internationale de l'Eclairage) 1931 defined a standard method to measure colour that is still used today. The measurement instrument (the standardised colorimeter) models the human retinae's sensitivity to wavelength by using three calibrated filters to measure how much energy there is in the long (X), medium (Y) and short (Z) wavebands. For achromatic stimuli (black, white and grey) the three chromatic values are approximately equal (X=Y=Z), and when these values are normalised (transformed to chromatic proportions) their values are approximately 1/3 (x = y = z = 0.33). As (x, y z) are proportions of the total stimulus energy they must sum to one (x + y + z = 1), and it is common to specify only two (x and y) and the third (z) can be calculated (z = 1 – x + y).

Every colour can be represented by a point in a chromaticity diagram like Figure 1; there is a third dimension (lightness or reflectance) not shown here, which is based on physical intensity weighted by the sensitivity of the retina. Thus each point in the (x, y) diagram represents a range of possible stimuli varying in lightness. For instance, the achromatic point represents white through to black with decreasing lightness. Each point on the curved part of the perimeter represents a monochromatic stimulus (spectral colours), while each point on the straight perimeter line represents non spectral colours such as purple. Every point within the perimeter represents a group of metameters: a

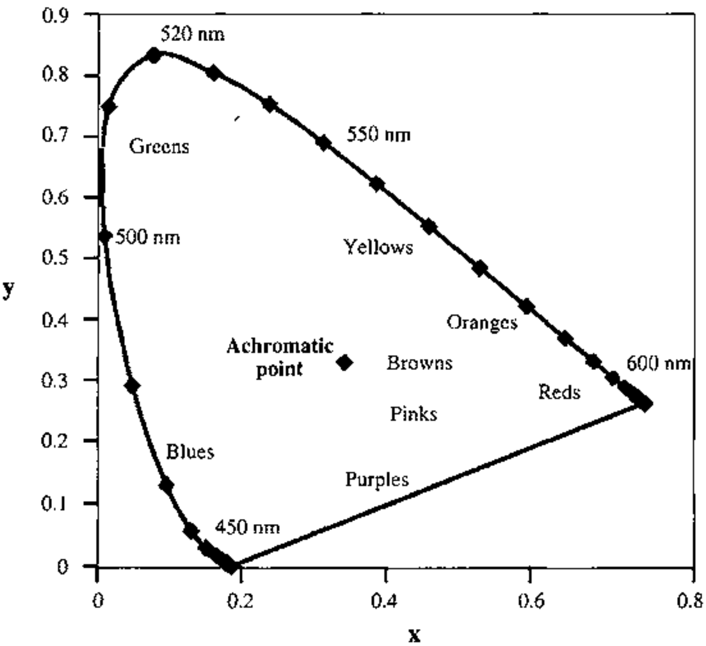

Figure 1. CIE xy Chromatic Diagram. Monochromatic colours fall on the perimeter (e.g. 450 nm is blue). Each point in the diagram represents a possible colour.

group of physically different stimuli that are perceptually indiscriminable to standard observers.

As Figure 2 shows, the CIE (x, y) chromaticity diagram can also be used to specify which stimuli are indiscriminable to dichromats, (this is only strictly true for small stimuli). Figure 2 shows the protanope convergence point: this is the theoretical stimulus that would activate the long wavelength cone (protocone) but not the other two types of cone (see Birch, 1993, chap. 4 for more detail). Two stimuli will be metamers for a protanope if they fall on a line radiating from the confusion point, and they have equivalent intensities. Pokorny and Smith's (1975) cone function fundamentals can be used to establish equivalent intensities. The convergence point for deuteranopes is the theoretical point where just the medium wavelength cone (deuteracone) is activated, and all colours falling on the confusion lines radiating from this point, and of equivalent intensities, will be metamers for deuteranopes.

Although the CIE (x, y) diagram is useful for many purposes, distances in the diagram do not correspond to perceptual distances. For some purposes it is useful to use a diagram where perceptual similarity is represented by distance in the diagram, and this can be achieved by transforming the co-ordinates to (u', v') (see Hunt, 1987, for the formula). This CIE (1976) uniform chromaticity diagram is what we use in this paper.

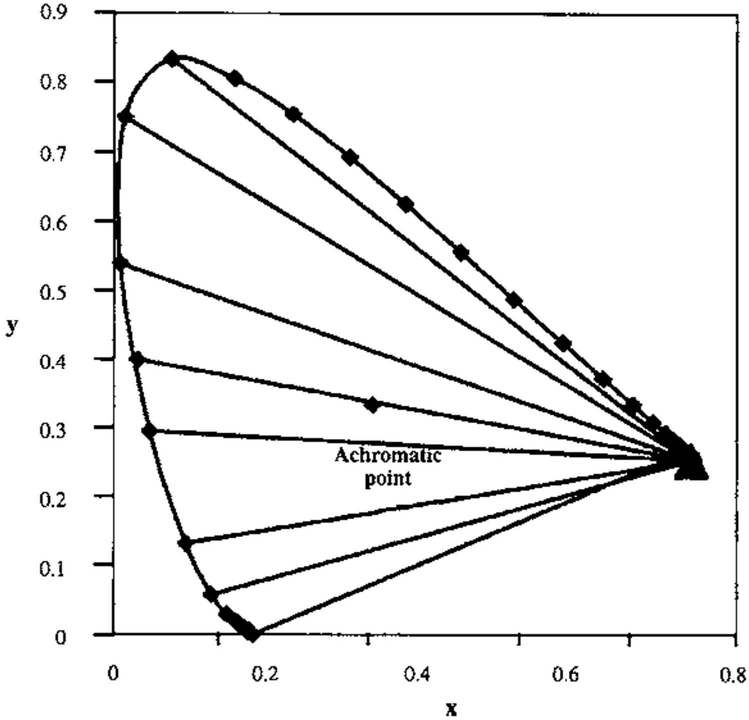

Figure 2 . CIE xy Chromatic Diagram. Every stimulus that falls on the same confusion line are metamers for protanopes.

Figure 3 illustrates how dichromat's naming confusions can be predicted using the prototypical green as an example. The green and red regions of colour space are shown as two wedges radiating from the achromatic point. The inner enclosed region represents all the colours in the OSA (Optical Society of America) colour atlas. The intersection of the OSA regions and the wedge shows those OSA stimuli that were named green or red by at

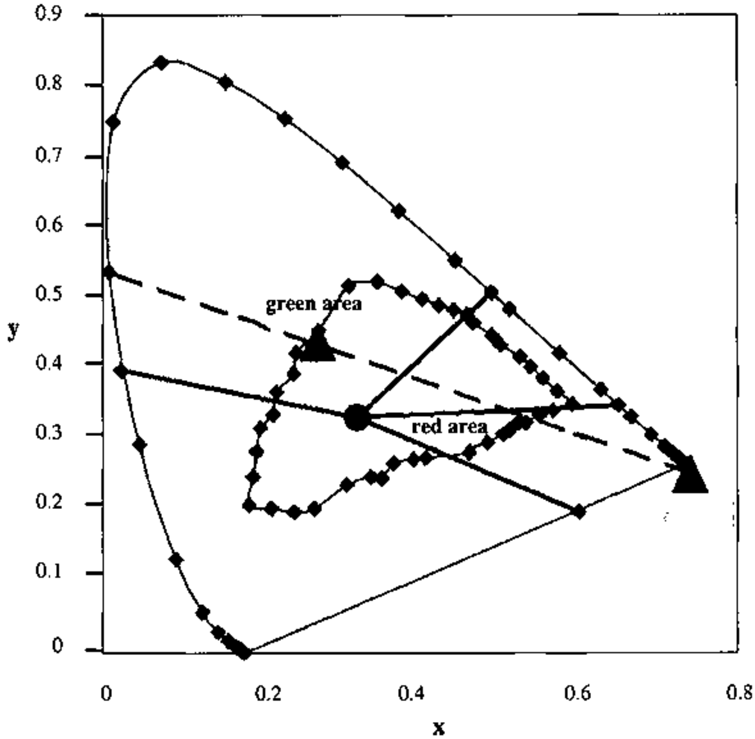

Figure 3. Illustration of prediction of dichromat naming confusions. The upper wedge radiating from the achromatic point encloses green colours, and the lower wedge encloses red colours. The intersections of the wedges with the closed inner area contains all OSA stimuli that were named, respectively, green or red by at least four out of seven Boynton & Olson's (1987) observers. The protanope confusion line for the green prototype links the prototypical green locus to the convergence point (large triangles). This line crosses the green and red chromatic areas.

least four of the seven participants in Boynton and Olson's (1987) naming task. The protanope confusion line on which the prototypical green stimulus falls is shown radiating from the protanope convergence point (triangle bottom right). It can be seen that the confusion line crosses the red and green regions of OSA space, and therefore, the green is confusable with all colours lying on the line, provided they match in reflectance.

Table 1 shows the dominant wavelengths for the nine chromatic categories (red, green, yellow, blue, orange, purple, pink, brown) together with their reflectance and saturation ranges. The domain of each colour name is a volume in colour space defined by u', v' and by lightness or reflectance. Our predictions of possible naming confusions were derived as follows. (1) For each stimulus the confusion line from the stimulus locus to the appropriate convergence point was drawn. (2) Boynton & Olson's (1987) naming data were used to map colour names onto the chromaticity diagram. (3) The reflectance of the stimulus was compared to the reflectance range of the colour category again taken from Boynton & Olson (1987). We predict a possible naming confusion if the confusion line crosses the colour category region in the diagram and the reflectance ranges match.

TABLE 1. DOMINANT WAVELENGTH, SATURATION AND REFLECTANCE RANGES FOR EACH BASIC COLOUR CATEGORY

Category	*Range dominant wavelengths (nm)*	*Saturation range (CIEuv)*	*Reflectance range*		
			Standard	*Protanope*	*Deuteranope*
Blue	476.0__ 495.5	Medium & high	03.3 - 61.8	03.8 - 67.7	03.0 - 58.1
Green	494.0__ 575.5	Medium & high	03.9 - 65.9	04.2 - 66.2	03.8 - 65.7
Yellow	572.5__ 585.5	Medium & high	30.5 - 74.9	27.5 - 73.2	32.4 - 76.0
Orange	586.5__ 614.5	High	12.7 - 63.5	09.1 - 43.9	15.1 - 76.0
Red	610.5__–496.5	High	04.7 - 17.3	03.4 - 13.1	05.6 - 19.9
Purple	–529 __ 472.5	Medium & high	03.5 - 32.1	03.5 - 31.8	03.5 - 32.2
Brown	579.5__–503.5	Low, medium & high	03.8 - 20.2	03.6 - 19.2	03.9 - 20.9
Pink	598.0__–555.0	Medium & high	17.9 - 60.2	15.7 - 56.7	19.3 - 62.5
White	–	Low	50.0 - 100	50.0 - 100	50.0 - 100
Black	–	Low	00.0 - 15.0	00.0 - 15.0	00.0 - 15.0
Grey	–	Low	05.8 - 70.8	05.8 - 70.8	05.8 - 70.8

Reflectance ranges for normal and colour blind differ because the «missing» cone contributes to effective reflectance in the normal observer. Relative saturation is represented by distance from the achromatic point and are indicated by high (towards the perimeter), low (near the center) and medium (between high and low).