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Colour Under Some New Fluorescent Lamps

Garry Thomson

Fluorescent lamps have gained wide acceptance in the artificial lighting of museums and galleries. Often more confidence is placed in their colour-rendering properties than in those of the ordinary electric light bulb or the spotlight (tungsten filament lamps). But there are many types of fluorescent lamp available, most of which make no claim to good colour-rendering, and we must choose the best, according to criteria to be described.

The two main considerations are:

1. How does the light affect the colour of an exhibit?
2. How much light comes out for the electricity that goes in?

The answer to the first question will be examined here. It is not an easy one.

The second question is readily disposed of. Put crudely we measure the amount of light that is emitted by our test lamp and divide this by the amount of electrical power that we put in. The answer, called the efficacy (not efficiency) of the lamp, is measured in lumens per watt: lumens of light per watt of electricity. Large economies can be made by using lamps of high efficacy.

The reason for the immediate popularity of fluorescent lamps when they were introduced in the 1940s was that from the first their efficacy was very much higher than that of tungsten lamps. 95% of the electrical input to a tungsten lamp is converted to heat not light, giving an efficacy of about 13 lumens/watt. With one of the new fluorescent lamps you could get four or five times as much light. It became feasible for artificial light to be as bright as indoor daylight.

Recently introduced 'triphosphor' fluorescent lamps have raised that ratio to seven in some cases.

The problem

This is where the conflict arises. There is little doubt that one can select a few fluorescent lamps with good colour-rendering properties which can confidently be recommended for art galleries. Unfortunately these have up to now been the lamps of lowest efficacy. Worse than this, so few customers seem to need the best colour-rendering that there is danger of quality degenerating, prices rising or even of the best lamps being withdrawn.

At the same time new lamps are being introduced, some of them with claims of both high efficacy and good colour-rendering. These must be examined.

On the matter of economy it so happens that when a single bank or line of the old fluorescent lamps of good colour-rendering but low efficacy (for example Thorn Kolor-rite) is backed by good reflectors it will give 150 lux all the way down quite a high picture-hanging wall, say 6 m. But 200 lux is just beyond capacity: either two banks must be fitted (doubling cost) or a single bank of lamps of higher efficacy. Dimming will then be needed in either case.

Standards of good colour-rendering

We cannot measure any aspect of the colour-rendering properties of a light source unless we have some standard with which to compare it. For those 'cool' fluorescent lamps which imitate daylight, such as the Northlight or Colour Matching lamps, the standard must obviously be daylight. But what is standard daylight? It varies from clear sky to overcast, from high to low sun. The answer lies in the fact that all phases of daylight can be characterized by a single figure called the Colour Temperature. Roughly the higher the Colour Temperature the bluer the light. Numerous measurements have allowed us to specify the spectrum of daylight of a given Colour Temperature. We then compare our test lamp with daylight of nearest Colour Temperature.

This Colour Temperature scale can be extended downwards towards the warmer lights: tungsten lamps and Warm White fluorescent lamps. But now we use a set of curves smoother than daylight, the Black Body or Planckian curves, approximately representing light from a body heated to high temperatures. The Colour Temperature scale, as it falls, gives us spectra of ever increasing red and decreasing blue. Tungsten lamps themselves come very close to this scale at about 3000 K (K, standing for degrees Kelvin, is the unit of measurement). Therefore, on this widely accepted basis, tungsten lamps give good colour-rendering. This is because tungsten lamps emit a full smooth spectrum with no peaks or missing wavelengths. The eye and brain together have, in the course of evolution, developed a very efficient means of detecting the colour of objects accurately, whatever the light, bluish or reddish, within a wide range. Adjustments are made entirely unconsciously so white appears white and the other colours fall into place. This is what is known as 'colour constancy'.

Due to their peaky spectra, this does not happen with all fluorescent lamps.

Colour spaces

In general one can imagine a space containing all the colours, each colour being represented by a point in the space. It may be some kind of distorted sphere, in which all the spectral colours are found round the equator; black is at the south pole and white at the north. One familiar form of this colour space is the Munsell Atlas, where HUE designates spectral colour round the equator; the scale from black to white is VALUE and the horizontal distance out from the axis is CHROMA [1].

There are many such colour spaces, and much effort has been expended in devising a space which has the important property that two colours separated from each other by unit distance should be just perceptibly different wherever we go in the colour space. This is an unattainable ideal, but some systems come close. The one used here, known officially as the CIE 1976 ($L^\star a^\star b^\star$) colour space, is one of the best in this respect.

The standard colour spaces have three dimensions, where one of the dimensions scales the lightness/darkness of the colour (Value in the Munsell system, Luminosity in most others). If this Luminosity is set aside, the two remaining parameters, known together as Chromaticity, can be represented on a plane in two dimensions, a Chromaticity Chart.

Calculating colour-rendering

The colour-rendering properties of a light source can, for our purposes, be subdivided under three headings:

1. Colour-rendering proper
2. Colour discrimination
3. Metamerism

Other scales have been devised, such as 'colour attractiveness' and 'colour preference', but these are more important to marketing than to conservation. It is interesting to note, however, that, because we can see colours more clearly under lamps of good colour-rendering, lighting at a given illuminance appears brighter [2].

1. Colour-rendering

Briefly, colour-rendering is a measure of the degree to which colours stand out too strongly or fail to stand out enough, when compared to an agreed reference light source. If a lamp emits very strongly in the lime-green region of the spectrum (as mercury vapour does at 546 nm) then greens appear unnatural. Certain fluorescent lamps emit substantially no light beyond 650 nm so that deep reds become too dark. These are two examples among many.

The mistake has often been made that one can judge colour-rendering by setting up booths, each lighted by one type of lamp and each containing the same range of coloured objects. We can then stand back so that all the booths are in view and judge which lamp gives the most natural colours.

Such a plan ignores the colour adaptation of the eye.

A photographic film has no power of colour adaptation. If we load with artificial-light film and then take photos out-of-doors they will come out strongly blue-tinted. The reverse happens with daylight film used indoors: everything acquires a red-brown cast.

The eye, however, adapts to the colour of the light, all the way from tungsten at the 'warm' end to blue sky at the 'cool' end.

When you look at that set of booths lit by various lamps, to which is your eye adapted? It is impossible to tell. Such a scheme is worse than useless because it gives false information.

There are two main methods of measuring colour-rendering quality. One, devised by B. H. Crawford working at the National Physical Laboratory, splits up the spectrum into six bands of equal colour-rendering importance. The calculation then compares the amount of light in each of these bands emitted by the test source with the amount emitted by the reference source. A measure of how much difference is significant was devised by setting up coloured objects before a group of observers and then altering the composition of the light slowly enough for the eye to adapt. The observers noted when any change in colour relations became apparent. Some of Crawford's tests were performed on National Gallery pictures. The calculation is explained in [3].

The second method, the Colour Shift method, has won, rightly or wrongly, acceptance as the official method by the Commission International de l'Éclairage (CIE) [4]. It makes use of one of the colour spaces mentioned above. Each colour that we perceive can be allotted a point in the three-dimensional space of such a chart, the third dimension corresponding to the luminance or brightness of the colour. But a colour cannot be seen unless it is illuminated by a light source and the spectrum of this light source will affect the position of the colour on the chart. The shift of the colour under the test source from its position under the reference source gives us the basis of the Colour Shift method. The bigger the shift the bigger the difference between the test and reference, and the worse the colour-rendering of the test. In practice eight colours spaced through the spectrum are used, and the average of their shifts is quoted as the colour-rendering rating for the test source, its R_a.

The two methods have agreed well in the past in selecting the best lamps, but have sometimes differed quite widely over others. The new triphosphors get much better ratings under the Colour Shift method than under Crawford. This brings our problem into focus.

2. Colour discrimination

Colour discrimination tests were devised to detect people with deficiencies in colour vision. One such test, the Farnsworth-Munsell 100-Hue Test, presents the subject with trays of discs ranging through the spectrum in colour, but in steps which are only just discernible. The subject has to arrange them in their correct order.

This test could be used in reverse: to detect lamp rather than human deficiencies by having normal subjects perform the test under different lamps. But there is a surer way.

The colour-vision properties of the normal human eye have been well studied and are embodied in the calculations of colour science.

We can take the reflectance curve of any colour we choose and carry out the calculation which places this colour in colour space. We then slightly distort the reflectance curve thus making a small change in the colour, and repeat the calculation. The colour will have slightly shifted its position in colour space as a result, and we can measure this shift.

We next repeat the process for other lamps. If the shift under a certain lamp is significantly smaller than the average we have grounds for concluding that this lamp exhibits poorer colour discrimination for the chosen colour (see Appendix).

Other, more theoretical, ways have been suggested for measuring the colour discrimination of a lamp. We need to bear in mind that a monochromatic light source, such as a sodium lamp, is unable to differentiate colours at all: they cluster at one point in colour space. At the other extreme it is not possible to make paints or dyes which appear as saturated as the pure spectral colours, even under the best light sources. The realizable colours occupy a space which is larger for the better discriminating light sources, though never extending to the whole of the colour space. Then the colour discrimination of the light source can be rated by measuring, either the volume bounded by a set of standard colours [5] or the volume containing all the realizable colours [6]. In practice the third dimension, Luminosity, can be set aside, and a measurement made of area on a Chromaticity Chart rather than volume.

This procedure appears impeccable, but produces a strange anomaly: that certain fluorescent lamps (the triphosphors, see below) are better at colour discrimination than natural daylight! This suggests that objects under triphosphor lamps are as colourful as in daylight but at lower illuminance. If true it is questionable whether a lamp which claims to upstage daylight itself is desirable. Daylight must surely remain the standard for lamps in the daylight range.

3. Metamerism

Two (or more) different colours are said to be metamers if they match under one of the common light sources such as daylight. One might say, if they match they are the same colour. But the word 'different' means that they have different reflectance spectra. Two colours with different reflectance spectra may appear the same under one light but not under another, as everyone knows who has matched textiles under artificial light only to find they fail to match under daylight.

Metamerism can be important in the restoration of textiles and paintings where a new dye or pigment is used to match an old.

A striking museum example of metamerism – not as it happens under the human eye but under the eye of the camera – is described by Sarah Staniforth [7]. An azurite and a cobalt blue pigment can be made to match in the human eye, even though their spectra differ rather widely in the deep red. But this is just the region where colour film is more sensitive than the eye. So a colour photograph of a sky painted in azurite and retouched with cobalt blue shows up the retouched areas as pinkish, since cobalt blue reflects more red.

To return to the human eye, even though both daylight and tungsten are regarded as sources of good colour-rendering, they often cause metameric trouble: colours which match under tungsten fail under daylight and vice versa. Fluorescent lamps usually cause less trouble. We must examine the new lamps in this respect.

Triphosphor lamps

If a drop of mercury is sealed in an evacuated tube and a current is passed through the small amount of mercury which has evaporated into the tube, light will be produced at certain sharp wavelengths and a reasonably efficient lamp will have been made. But some of the strongest spectral lines will be in the ultraviolet (UV) and there will not be enough in the visible range to render colours acceptably. However if the inside of the glass is coated with a suitable combination of powders which fluoresce (absorb short-wave radiation and re-emit it at longer wavelengths), these shortcomings can be overcome. We have a fluorescent lamp.

For good colour-rendering we need an even distribution of light throughout the spectrum. For high efficacy we need to concentrate on the middle of the spectrum where the eye is most sensitive. Hence the conflict.

Pursuing a novel line of thought, W. A. Thornton in the USA produced a fluorescent lamp where, by suitable choice of phosphors, almost all the light was emitted at just three wavelengths, near 450 nm, 540 nm and 610 nm. These correspond approximately to the three peaks of the human visual system.

As has been mentioned, these triphosphor lamps have been claimed to give good colour-rendering, and also what has been called 'visual clarity', meaning that objects whether coloured or not appear exceptionally clearly.

But the great selling point, which has caused all the major lamp manufacturers to market triphosphors, is their economy in the use of electricity: an efficacy of up to 90 lumens/watt (the figure for tungsten lamps is about 13).

Choice of Colour Temperature

Fluorescent lamps are available in a wide range of Colour Temperatures, from daylight range (Colour Temperature about 6500 K) to tungsten range (about 3000 K).

It is generally agreed that the daylight range, usually designated Northlight or Colour Matching, though as a group good on colour-rendering, make an exhibition room look cool and dull — like an overcast sky.

There is a range at about 5000 K, which is more suitable for museum lighting, but still a little cool for most situations.

For exhibition rooms where artificial light supplements and replaces daylight after dark there is a marked preference for lamps of Colour Temperature near 4000 K, that is to say intermediate between daylight and tungsten light.

Because warm light appears psychologically preferable at low illuminance, and because light high in red and low in blue is less damaging, tungsten lamps or fluorescent lamps in the tungsten range (3000 K) are the usual choice for sensitive material at 50 lux.

In each of these categories (except the 6500 K range, which are all of acceptable colour-rendering), lamps of both good and poor colour-rendering can be found, with the poor outweighing the good.

Colour-rendering and efficacy

It used to be quite simple: you either got good colour-rendering or good efficacy, never both.

Table 1

Lamp	Colour Temp. Category	R_a	R_w	Crawford Class	UV Content	Best Efficacy
Old high-fidelity:						
Philips 38	Int.	90	83	C	81	45
Sylvania Cool White DL	Int.	89	83	C	127	?
Thorn Kolor-rite	Int.	89	82	C	85	45
Triphosphors:						
Philips 84	Int.	82	52	F	87	85
Sylvania Octron 4100	Int.	79	59	E	89	*c.*90
Thorn Polylux 4000	Int.	80	52	F	76	89
Wotan Maxilux 21	Int.	82	51	F	89	*c.*90
Sylvania Octron 3100	Warm	70	43	F	102	*c.*90
Thorn Polylux 3000	Warm	78	53	F	103	89
Wotan Maxilux 31	Warm	84	56	F	115	*c.*90
New high-fidelity:						
Philips 94	Int.	95	86	C	43	65
Wotan Maxilux 22	Int.	94	87	C	63	63
Philips 93	Warm	94	82	C	49	65
Best in our record for colour-rendering in the range 3000–5000 K:						
Matsushita FL 40S-N-EDL	5000	98	96	B	61	?

Notes: 'High-fidelity' lamps are those of good colour-rendering.
'Int.' Colour Temperature category is around 4000 K. 'Warm' is around 3000 K.
R_a is the overall CIE colour-rendering index, R_w is for the worst test colour of the eight.
UV content is in microwatts/lumen. If less than 75 no UV filter is required.
Efficacy varies a little by lamp size. The best value after 2000 hours was chosen.
Sylvania lamps are available in the USA, Matsushita in Japan.
Colour-rendering and UV content computed in N.G. laboratory from spectral data kindly supplied by manufacturers.

Consequently until recently there were a few lamps of good colour-rendering (R_a about 90, Crawford Class B or C) but low efficacy (40–50 lumens/watt), such as the Philips 37 and the Thorn Kolor-rite in the 4000 K range and the Philips 27 in the 3000 K range. But they did not sell as well as expected. Recently Philips have withdrawn their 37 and 27 lamps.

Concurrently triphosphors swept into the lighting scene, with very high efficacies (up to 90 lumens/watt) and colour-rendering a great deal better than most lamps. But triphosphors tend slightly to exaggerate metameric mismatches. Also, while giving an R_a often better than 80, at least one of the eight test colours gives a very low value, and the rating on the Crawford scale is poor, usually E or F.

Nevertheless, because of their unusually high efficacy, there is considerable pressure to use these lamps in museums and reap the economic benefit, especially now that good lamps are being withdrawn.

Fortunately an alternative has recently appeared. A wide range of phosphors is now available and computations to obtain optimal blends have improved. New lamps have appeared on the market with colour-rendering at least as good as the withdrawn lamps, but also with improved efficacies (greater than 60 lumens/watt). Examples are the Philips 93 and 94 and the Osram/Wotan Maxilux 22. These are the obvious choice for museums.

But they are not available in all countries, unless for large orders. The museum outlet is not sufficient to sustain a market. Thus the Philips 90 series are only available in the UK for orders of 1000 lamps and above.

Conclusions

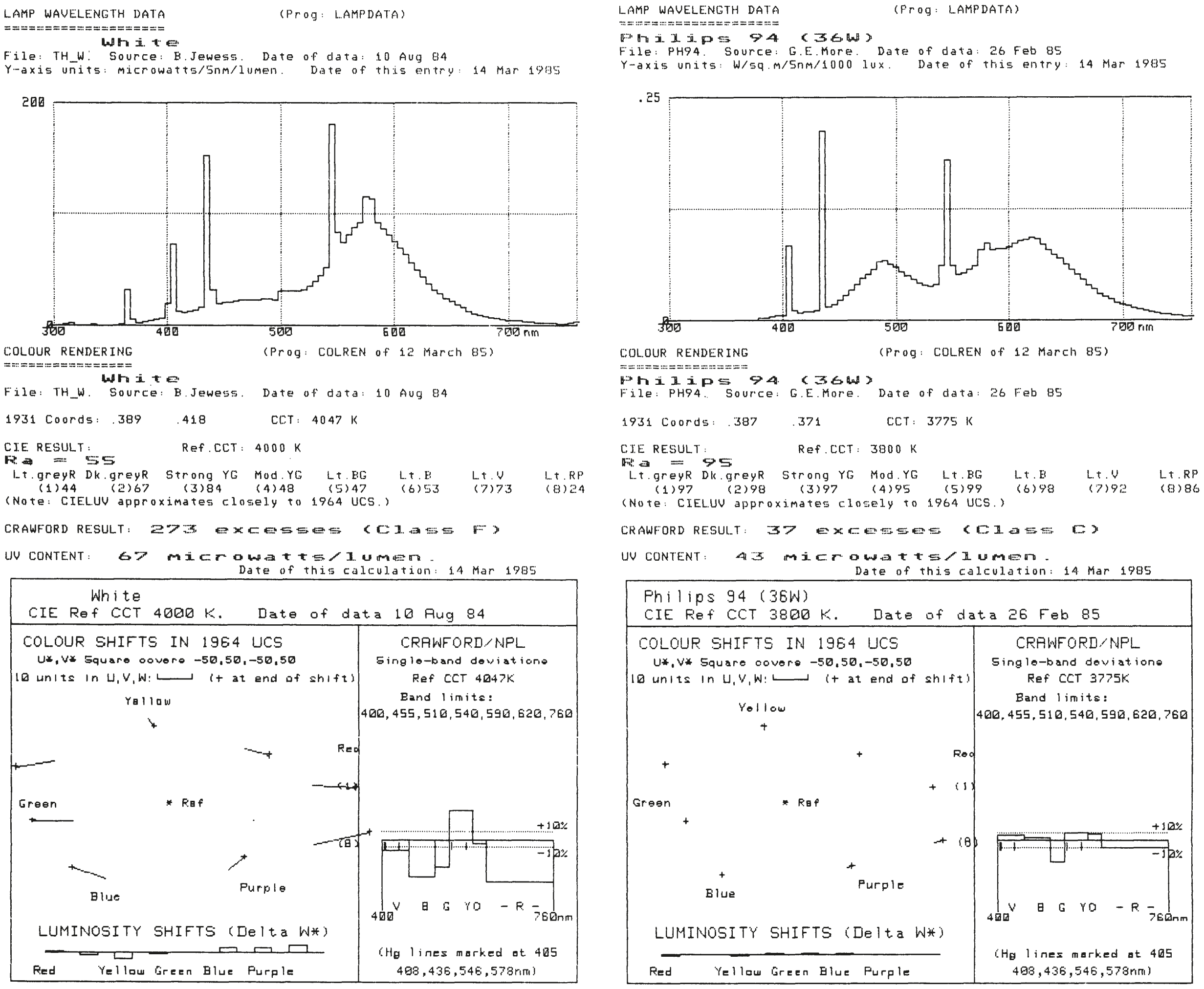
Calculations of colour-rendering quality by both the CIE Colour Shift method and the Crawford-NPL Spectral Band method have been carried out on a number of lamps, using spectral power distributions kindly provided by the lamp manufacturers. Usually these calculations agree well enough with the manufacturer's own figures, but where they differ our own figures give poorer ratings, and these have been used.

Triphosphor lamps, even those with good CIE average ratings, (R_a) all give poor results for at least one CIE test colour. They also get a bad Class on the Crawford scale (see Table 1).

Colour discrimination of triphosphors is just slightly below average by the method described in the Appendix. But against this, colour gamut methods give them an above average rating. On balance we can say that colour discrimination varies little between fluorescent lamps.

Metamerism is an acknowledged problem with triphosphors but not a major one in the museum (see Appendix).

By contrast certain new lamps devised for good colour-rendering and improved efficacy (Philips 93 and 94 and the Wotan Maxilux 22) get good ratings in general.



```
LAMP WAVELENGTH DATA              (Prog: LAMPDATA)
====================
          White
File: TH_W.  Source: B.Jewess.  Date of data: 10 Aug 84
Y-axis units: microwatts/5nm/lumen.   Date of this entry: 14 Mar 1985
```

```
COLOUR RENDERING                (Prog: COLREN of 12 March 85)
================
          White
File: TH_W.  Source: B.Jewess.  Date of data: 10 Aug 84

1931 Coords: .389    .418          CCT: 4047 K

CIE RESULT:              Ref.CCT: 4000 K
Ra  =  55
 Lt.greyR Dk.greyR  Strong YG  Mod.YG   Lt.BG    Lt.B     Lt.V     Lt.RP
    (1)44    (2)67     (3)84    (4)48    (5)47    (6)53    (7)73    (8)24
(Note: CIELUV approximates closely to 1964 UCS.)

CRAWFORD RESULT:  273  excesses  (Class  F)

UV CONTENT:   67  microwatts/lumen.
                                    Date of this calculation: 14 Mar 1985
```

```
     White
  CIE Ref CCT 4000 K.    Date of data 10 Aug 84
```

```
LAMP WAVELENGTH DATA              (Prog: LAMPDATA)
====================
Philips  94  (36W)
File: PH94.  Source: G.E.More.  Date of data: 26 Feb 85
Y-axis units: W/sq.m/5nm/1000 lux.   Date of this entry: 14 Mar 1985
```

```
COLOUR RENDERING                (Prog: COLREN of 12 March 85)
================
Philips  94  (36W)
File: PH94.  Source: G.E.More.  Date of data: 26 Feb 85

1931 Coords: .387    .371          CCT: 3775 K

CIE RESULT:              Ref.CCT: 3800 K
Ra  =  95
 Lt.greyR Dk.greyR  Strong YG  Mod.YG   Lt.BG    Lt.B     Lt.V     Lt.RP
    (1)97    (2)98     (3)97    (4)95    (5)99    (6)98    (7)92    (8)86
(Note: CIELUV approximates closely to 1964 UCS.)

CRAWFORD RESULT:  37  excesses  (Class  C)

UV CONTENT:   43  microwatts/lumen.
                                    Date of this calculation: 14 Mar 1985
```

```
  Philips 94 (36W)
  CIE Ref CCT 3800 K.    Date of data 26 Feb 85
```

Figure 1 Colour-rendering of two fluorescent lamps.

'1931 Coords' give the (x, y) coordinates of the lamp on the 1931 Chromaticity Chart. 'CCT' and 'Ref. CCT' are the Correlated Colour Temperatures of the lamp and reference source respectively. R_a is the average Colour-rendering Index for the eight test colours (which follow) on the CIE Colour Shift method. R = red, Y = yellow, G = green, B = blue, V = violet, P = purple. On the left side of the diagram a portion of the Chromaticity Chart used (1964 Uniform Chromaticity Scale) is shown. The eight colour samples appear anticlockwise from (1) (Lt. grey R) to (8) (Lt. RP). In each case a line terminated with a cross joins the position under the ref. illuminant to the position under the test lamp (the cross). The longer the line the worse the shift. The third dimension of colour space, Luminosity, is shown on a scale below. Shifts in this dimension are usually low. On the right, under the heading 'Crawford/NPL' is a spectral diagram of the six band ratios. A ratio above the line indicates too much of that colour in the test source. But if the band ratio comes between the tolerance limits of ±10% indicated by dotted lines it is not significant. All outside these dotted lines are added up to give an 'excesses' figure. The higher the excesses the worse the lamp. Crawford Classes are as follows: A (0 excesses), B (1 to 32), C (33 to 64), D (65 to 128), E (129 to 256) . . . The left diagram is for a 'White' fluorescent of rather poor colour-rendering. The right diagram is for a good lamp.

We would like to be able to recommend that museums and galleries use only lamps with $R_a = 100$, Crawford Class A. But this would exclude all fluorescent lamps. To be realistic, experience shows that even the most discriminating of museum visitors do not require this standard (if they did no museum would tolerate coloured walls!). Lamps of rather poor colour-rendering are often declared satisfactory, though they should not be.

We therefore suggest that lamps for museums and art galleries should pass the following test:

R_a greater than 90 Worst *R* greater than 80

Crawford Class A, B or C

Of the lamps examined this singles out the Philips 93 and 94 and the Osram/Wotan Maxilux 22. There will be other lamps (in the USA and Japan and possibly in Europe) not tested by us which will conform to this recommendation. One Japanese lamp we tested from Matsushita got the highest rating of all (see Table 1).

Depending on availability the cost of the Philips 93 or 94 may be up to double that of an old high-fidelity lamp.

Appendix

Colour-rendering

The colour-rendering calculations were carried out in two ways by computer, the first (the Colour Shift method) following the standard CIE method described in [4], the second (the Spectral Band method) following the method described by Crawford [3]. Two examples of the computer output appear in Fig.1.

Colour discrimination

In order to relate the test closely to colours commonly found in paintings, three reflectance curves taken on National Gallery paintings for the colour change programme were used:

Blue (azurite): sky in No.658, Imitator of Campin.

Green ('copper resinate'): dark green drapery in No.658.

Red (red lake): pink drapery in No.288, Perugino (see Fig.2 and Table 2).

For each light source the position of each of these colours in $L^*a^*b^*$ colour space was calculated. Each of the three colour reflectance curves was then slightly changed (by 1 to 5 units of just noticeable difference) successively in five regions of the spectrum: the whole spectrum (W), the red end (R), the green middle region (G), the blue end (B) and a region between blue and green where triphosphor lamps are low in power (BG) (Fig.2). The positions of the changed colours in $L^*a^*b^*$ space was next calculated, and from these the shifts.

For example, Table 2 shows that, under daylight, the shift in colour space when the Campin blue sky was changed slightly in the red (R) was 1.5 units, in the green 2.9 and the blue 2.5.

All these results were then normalized to make the average of each column = 100, so as to combine all the results and find the standard deviation. It can then be seen that most of the variation in colour shift for different light sources is not significant, and certainly the average value for each light source (the average of any row) puts no source significantly better or worse than another on average. But it is interesting that signifi-

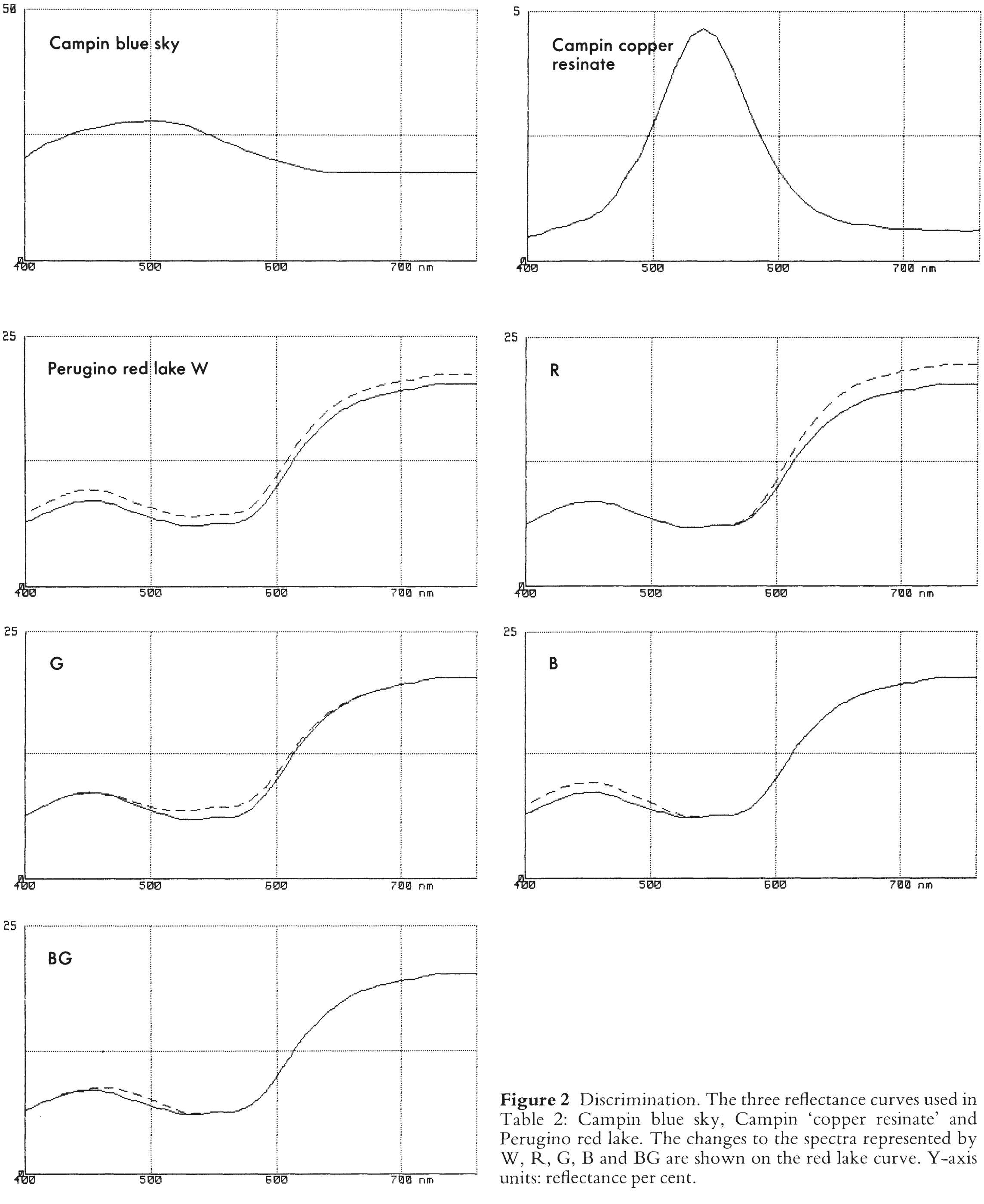


Figure 2 Discrimination. The three reflectance curves used in Table 2: Campin blue sky, Campin 'copper resinate' and Perugino red lake. The changes to the spectra represented by W, R, G, B and BG are shown on the red lake curve. Y-axis units: reflectance per cent.

Table 2

Colour shifts

	Campin blue sky					Campin 'copper resinate'					Perugino red lake				
	W	R	G	B	BG	W	R	G	B	BG	W	R	G	B	BG
Daylight (D65)	2.00	1.50	2.90	2.50	1.10	3.90	2.00	2.20	4.90	1.70	2.40	2.20	3.60	2.70	.96
Planckian 4000 K	2.10	1.80	2.90	2.50	1.10	3.70	2.30	2.20	4.70	1.90	2.30	2.50	3.40	2.80	.96
Tungsten (Illum.A)	2.10	2.10	2.80	2.50	1.20	3.50	2.70	2.20	4.40	2.10	2.20	2.70	3.10	2.80	1.00
Thorn Kolor-rite	2.10	1.80	3.10	2.70	.85	3.90	2.30	2.30	5.20	1.50	2.30	2.50	3.60	2.90	.75
Philips 84	2.10	1.60	3.30	2.80	.71	4.10	2.10	2.40	5.50	1.50	2.30	2.30	3.80	3.00	.62
Thorn White	2.00	1.20	3.20	2.80	.71	3.70	1.40	2.50	5.40	1.40	2.30	1.90	3.70	3.00	.62
Philips 94	2.10	1.70	2.90	2.60	1.00	3.70	2.20	2.30	4.80	1.90	2.30	2.40	3.30	2.80	.91
Philips 93	2.10	1.90	2.90	2.60	1.00	3.60	2.40	2.30	4.70	1.80	2.20	2.50	3.20	2.90	.90

Colour shifts in terms of the average for each column

	Campin blue sky					Campin 'copper resinate'					Perugino red lake				
	W	R	G	B	BG	W	R	G	B	BG	W	R	G	B	BG
Daylight (D65)	96	88	97	95	115	104	92	96	99	99	105	93	104	94	114
Planckian 4000 K	101	106	97	95	115	98	106	96	95	110	101	105	98	98	114
Tungsten (Illum.A)	101	**124**	93	95	**125**	93	**124**	96	89	**122**	96	114	90	98	119
Thorn Kolor-rite	101	106	103	103	89	104	106	100	105	87	101	105	104	101	89
Philips 84	101	94	110	107	**74**	109	97	104	111	87	101	97	110	105	**74**
Thorn White	96	**71**	107	107	**74**	98	64	109	109	81	101	80	107	105	**74**
Philips 94	101	100	97	99	104	98	101	100	97	110	101	101	95	98	108
Philips 93	101	112	97	99	104	96	110	100	95	104	96	105	92	101	107

Standard deviation = 10.3. Range of non-significant variation (2 standard deviations either side of mean) = 79 to 121.

Bold figures below 79 indicate significantly poorer than average discrimination, those above 121 significantly better.

Simulated small changes were made in the reflectance curves of the three pigments (blue sky, 'copper resinate' and red lake) as follows: W = white, R = red, G = green, B = blue, BG = blue-green (see Fig.2).

Example: An area of pink drapery on the Perugino is next to a slightly redder area. The difference between the two is visible because the shift is greater than 1 (actually 2.2. See 'Perugino red lake' under R, daylight row). But will it be more or less visible under other illuminants? The other figures under R vary a little. Is this variation significant?

In the lower table all shifts have been recalculated by normalizing each shift to its average in the column. The standard deviation then shows that no shift is significant in the range 77 to 123. Therefore this particular shift is not noticeably different under any of the illuminants.

cantly low shifts occur to the Campin blue and the Perugino red with the triphosphor (Philips 84) and the lamp representing poor colour-rendering (Thorn White). These poor values are for the blue-green region where both lamps are low in power. On the other hand tungsten light appears to discriminate better than average in the red, which might have been expected, but also in the blue-green. These results oppose any suggestion that tungsten light is poor at discriminating blues (it should be recalled that tungsten light is usually used at lower illuminance than other sources).

Metamerism

A mere difference in Colour Temperature is enough to provoke metamerism, even under light sources of good colour-rendering, as when attempts are made to match metameric pairs under both daylight and tungsten. But such pairs should match under any light sources of good colour-rendering at the same Colour Temperature.

Calculations rather similar to those for discrimination were carried out on two matching blues made up from azurite and cobalt blue. They did not, however, show up any particular fault in triphosphors.

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