Light under control!

How to evaluate and measure the quality of an illumination setup: a few examples.

Danny Pascale & Roger Breton

1. Introduction

If you are concerned about the accuracy and reproducibility of the colors you print, then you should also be with the quality of the environment in which they are seen and judged. This applies to both the color monitors and to ambient room lighting.

Most computer users are aware of the importance of a calibrated display for accurate manipulation and editing of images, and many tools are available for such calibration. At the same time, most images are viewed under inadequate lighting conditions. This is due, in part, to the relatively high cost of complete-ready-to-use light booths, to a lack of awareness about simpler lighting solutions, and to the unavailability (until now!) of affordable hardware and software tools to measure and quantify the viewing environment. The benefits of using standardized "calibrated" illumination cannot be overstated, from the capability to see printed images as they appear on your monitor all the way to being able to share this "vision" amongst the various people involved in the image reproduction chain.

The goal of this essay is to familiarize the reader with the requirements of an illumination setup to be used for judging the color of printed material, and with the various measurements that can be done to assess the setup performance. The intended audiences are graphic designers, photographers, textile designers, and anyone involved in the quality or accuracy of a printed color.

Section 2 describes our room setup and the four illumination systems we analyzed; section 3 presents the spectrums and color temperature measurements; section 4 is a description of ISO 3664 and the various other standards it refers to; section 5 presents the ISO 3664 measurements, and section 6 is the conclusion.

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2. Setup

2.1. Room description

Light can easily be "polluted". There is no benefit of installing D50 fluorescents lights in the entire room if your walls are bright orange, or if your carpet is green, or if your office partitions are blue. Rooms designed for color work should be decorated with neutral colors. ISO 3664 recommends a neutral grey with a reflectance between 10% and 60%. This may not make for a cool atmosphere within a hip media company, but it will certainly help in obtaining predictable results. Such a neutral atmosphere is also suggested for working places where only monitor work is done, since the environment colors will intermix with what is shown on screen. For rooms dedicated for image capture, walls covered with a matte black paint are recommended.

Certain rooms are dedicated solely to the comparative viewing and assessment of prints. However, it is not uncommon to also find computer stations dedicated to image editing in these same rooms; in this case, we have the additional requirement that not only should the room colors be neutral, the room illumination level should be low. How low? Quite a lot! ISO 3664 recommends a maximum of 64 lux, with a value of 32 lux or less ideally, transforming any office in what many would call a "cave". While it may be difficult to dim specific sections of open floor offices, care should be taken to minimize the contribution from external lights. High-end monitors often come with light-shields designed for this purpose. Also, again, ideally, the room lighting should be of the same color temperature as the monitor.

The room used for the measurements described in this paper has all walls painted with a light grey paint selected to approximate Munsell N8, with 80% nominal reflection. Here is the measured wall reflectance spectrum:

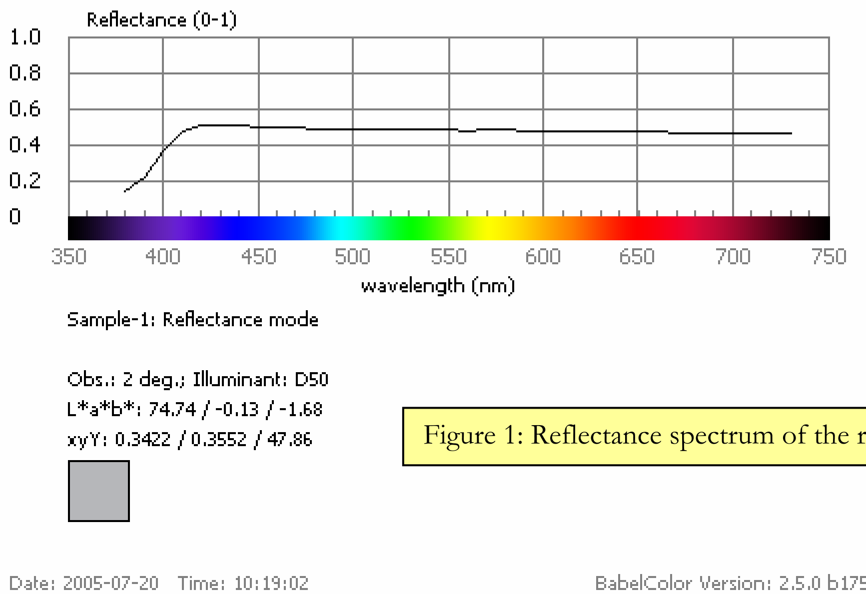


Figure 1: Reflectance spectrum of the room walls.

At 74,7%, the wall's reflection is above the recommended 60% from ISO 3664, but still way better than most working rooms; to be safe, we placed black cardboards on the wall near the measurement table The room windows are covered with black horizontal blinds, and the background light level, mostly seeping from the sides of the window blinds is below 10 lux. This is a real cave!

We took particular care to place sheets of black cardboard over any possible color contaminants, such as library shelves filled with colorful books (about color!). For similar reasons, a large green cutting mat on the measurement table was covered with black velvet.

2.2. Illumination systems

We looked at a variety of illumination systems: two fluorescent tubes designed for color rendering applications, one commercial light booth designed for both direct view and transparencies viewing, and a tungsten-halogen type bulb specifically designed to reproduce daylight. Our selection was simply based on the available material we had around us, which may be quite different than your own setup. In any case, the methods and procedures shown apply to most setups.

> Note: Our measurement may not be representative of all units manufactured under the same part number, as can be recognized by the fact that some light booth manufacturers will, on demand, try to match a replacement lamp to the batch used for original manufacturing. Also, all lamps and tubes will show a change in their properties with aging and will exhibit different output characteristics with variations of their operating voltage.

Here are detailed descriptions of each system:

1- **GretagMacbeth** (GMB) **fluorescents**, model “5000 K F40T12/50” (part no 20115020, made in Canada). Two 40 W tubes mounted in a simple commercial fluorescent holder of the type shown in the picture below. You will note that the fixture has no diffuser between the tubes and the illumination zone (the viewing table). One of the consequences of using such a fixture is non-uniformity in the color temperature of the illumination because the light coming directly from the tube is different than the light reflected by the fixture; this is discussed further in this section. We nonetheless present results for this tube-fixture combination since it is ubiquitous in many workplaces. Approximate age of tubes is 2 years and they were used about 50-60 hours.

2- **Just Normlicht fluorescents**, model “Color Control daylight 5000”, 36 W. Two tubes mounted in a commercial fluorescent holder of a similar type than the one used for the GMB tubes, but not compatible because of the tubes’ different diameter. Approximate age of tubes is 2 years and they were used about 100-150 hours.

3- **GTI light booth**, SOFT-VIEW D5000 Transparency Print Viewer, model “sofv-2m”. This booth uses custom GTI fluorescent tubes (Graphiclite D5000 color viewing lamp, F14T12, 14 W). Similar tubes are used for direct viewing and for back-lighting transparencies. Light output can be adjusted using a continuously variable potentiometer. Approximate age of tubes is 5 years and they were used about 200-300 hours.

4- **SoLux 5000 K**, MR16 type lamp, 36 degrees Flood, 12 V, 35 W (ordering code: 4735104). SoLux lamps, manufactured by Tailored Lighting Inc., comprise a patented built-in filter which enables them to generate light with a spectrum close to daylight of the same temperature. The lamp used for these measurements was mounted in a SoLux desktop **Task Lamp**. In our tests, we tweaked the color temperature by adjusting the lamp current using a DC power-supply. The lamps have been lit for less than 10 hours.

2.3. Instrumentation

All measurements made for this document were made using Eye-One Pro spectrometers manufactured by the GretagMacbeth Company. The figures were either produced by, or are screen-shots of the Spectral tools of the BabelColor software.

3. Spectrums and CCT

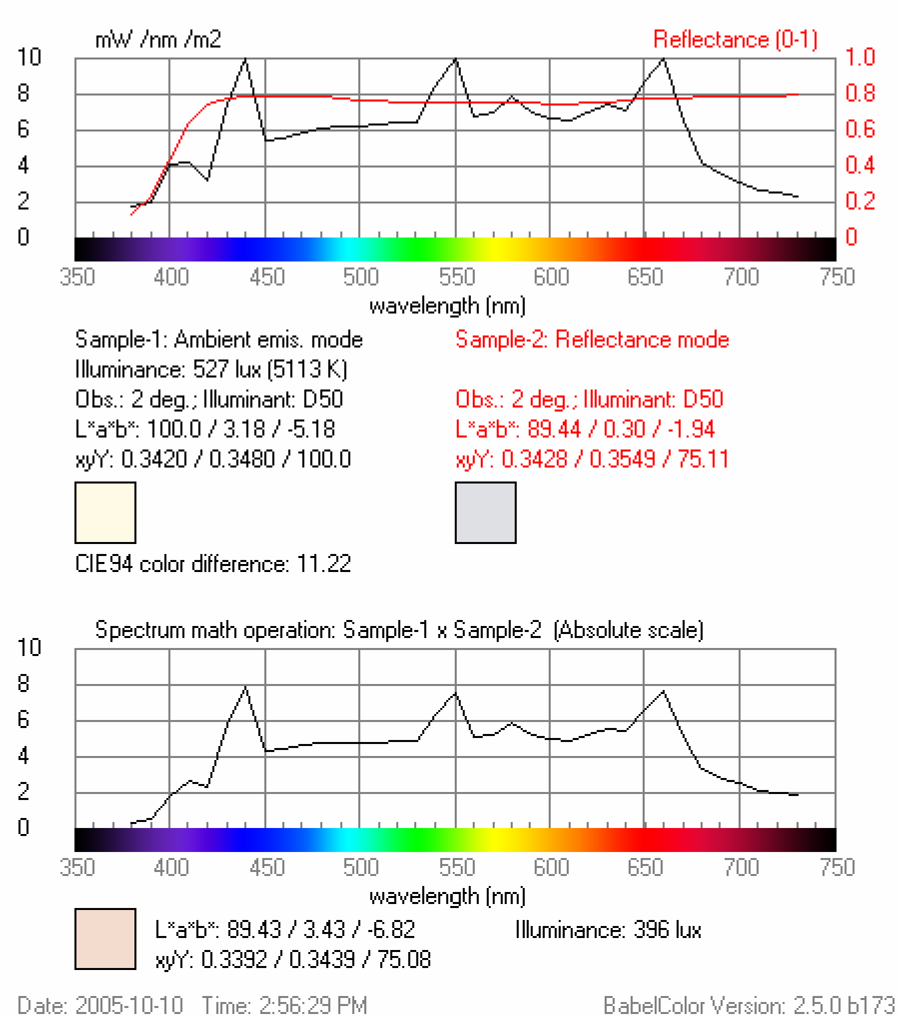
In this section, we look at the spectrum of each lamp and measure their *Correlated Color Temperature* (CCT), which is the temperature of the blackbody, measured in kelvin, which matches the perceived "whiteness" of the light. For the fluorescent tubes, we also measure the reflectance spectrum of the fixtures in which they are mounted.

> Note: Zero Kelvin, the absolute zero temperature, is about -273 Celsius (within fractions!). The kelvin and Celsius scales are simply shifted relative to one another, and a one kelvin temperature difference is the same as a one Celsius difference. For example, zero Celsius is 273 kelvin (which can also be written 273 K) and a room temperature of 22 Celsius is 273 + 22 = 295 kelvin.

GretagMacbeth fluorescents

The black spectrum (Sample-1) in the upper section of Figure 2 shows the light output of the bare GMB tubes at a distance of approximately 29 in (74 cm), as measured in ambient mode with the Eye-One ambient diffuser. A black cardboard was placed between the tubes and the fixture to make sure we did not include the "color" of the fixture's white diffuser in our measurement. The tube spectrum is expressed in units of absolute spectral irradiance density, in mw/nm/m². The illuminance is 527 lux and the CCT is 5113 K, close to the tube nominal value of 5000 K. We notice peaks at 440, 550, 580, and 660 nm which likely correspond to four of the seven phosphors used in manufacturing these patented tubes.

Figure 2: GMB bare tubes (Sample-1) and fixture reflectance (Sample-2).



Note and warning: We suggest starting the tubes and letting them stabilize for at least one hour. However, we also noticed that when we left the black cardboard, used to shield the tube from the fixture, too long, the tubes heated, and there was a shift of the measured color temperature. The cardboard also got hot and this could be a fire hazard. If you use a similar setup, let the tubes stabilize without the cardboard, then turn OFF the tubes while you place the cardboard, turn the lamp ON again, and do not leave the cardboard there more than a few minutes.

The spectrum drawn in red (Sample-2) is the reflectance of the white diffuser paint covering the fixture which holds the tubes; units are absolute and shown with a scale between zero and one. The third spectrum in the bottom of Figure 2 is obtained by multiplying the bare tube spectrum with the reflectance of the diffuser (Sample-1 x Sample-2); this is not the spectrum of the light actually reflected by the fixture, which is shown in Figure 4, but a mathematical derivation of the combination.

The color patches are computed relative to a D65 monitor, for the sRGB color space, which explains why the tube "white" (Sample-1), at 5113 K, is seen as slightly yellow. We can see that the diffuser (Sample-2) has a small bluish tint and the computed spectrum reflected by the diffuser (Sample-1 x Sample-2) an overall pink-orange tint. We also see a small increase in the blue portion of the (Sample-1 x Sample-2) spectrum; the first peak at 440 nm is higher than the 550 and 660 peaks whereas in Sample-1, the peaks are of equal height. These measurements simply show that the resulting color is a mix of the bare tube characteristics combined with the reflectance of the light fixture. The L*a*b* and xyY coordinates shown are computed for D50 and the 2 degrees Observer.

The upper part of Figure 3 shows another measurement of the bare-tube spectrum while the bottom part shows the same spectrum with an "ideal" spectrum, in fact the theoretical D-series spectrum, of the same CCT, 5113 K (rounded to the nearest 100 K. i.e. 5100 K, hence D51), and the same illuminance, 527 lux. You can notice how the phosphor peaks detract from the smoother D51 shown in green. These peaks could likely affect the performance of the illumination system in terms of daylight simulation accuracy; this will be evaluated in a later section.

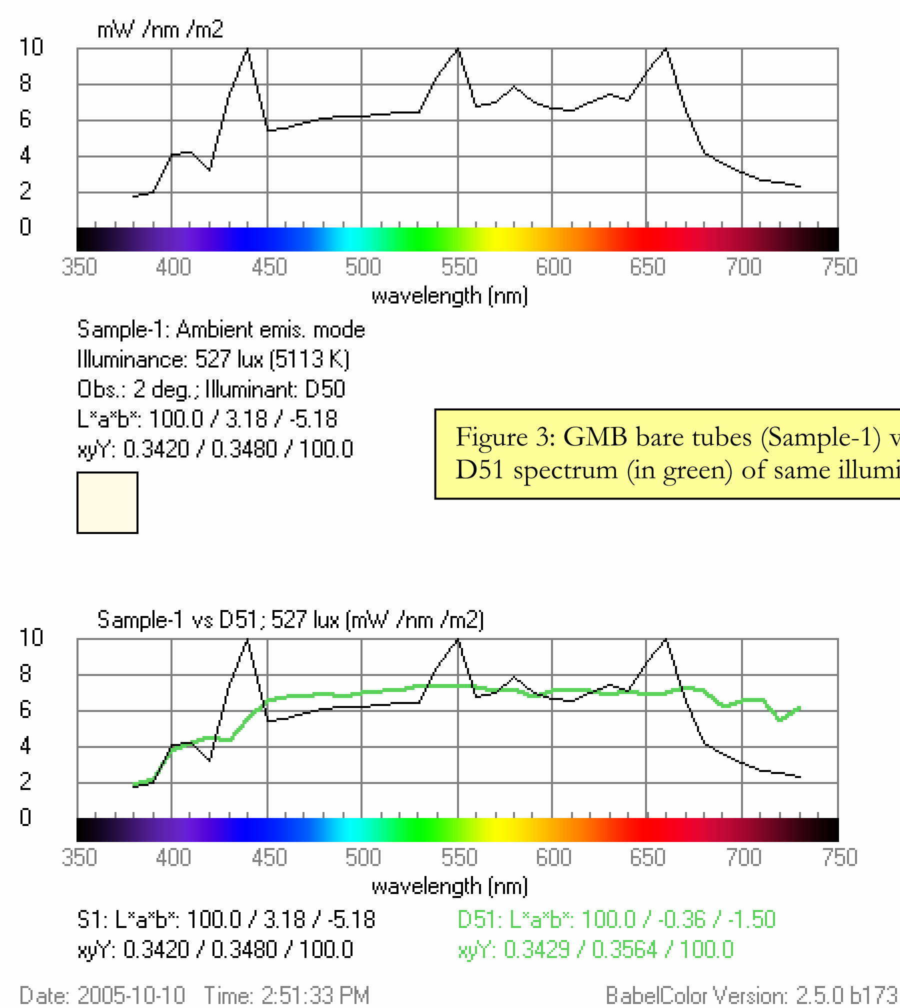


Figure 3: GMB bare tubes (Sample-1) vs theoretical D51 spectrum (in green) of same illuminance.

The black spectrum (Sample-1) in the upper section of Figure 4 shows the light output of the GMB tubes combined with the effect of the tubes' fixture at a distance of approximately 40 in (102 cm), as measured in ambient mode with the Eye-One ambient diffuser. These spectrums shapes (not their absolute levels since the measuring distance is different) should be compared with the ones of Figure 3. The CCT is slightly higher, 5294 K compared to 5113 K, due to the fixture's bluish tint. The phosphor peak at 440 nm is higher than the 550 nm and 660 nm peaks, corresponding to what was predicted in the computed (Sample-1 x Sample-2) spectrum of Figure 2. The bottom section of Figure 4 compares Sample-1 with a theoretical ("ideal") spectrum of the same CCT and illuminance.

You should not be too concerned by the dip of the measured spectrum at wavelengths higher than 670 nm; the eye is not very sensitive in this region and the effect of the difference is minimal.

We would have liked to test the GMB tubes with the fixture used with the Just Normlicht tubes but the tubes diameters are different.

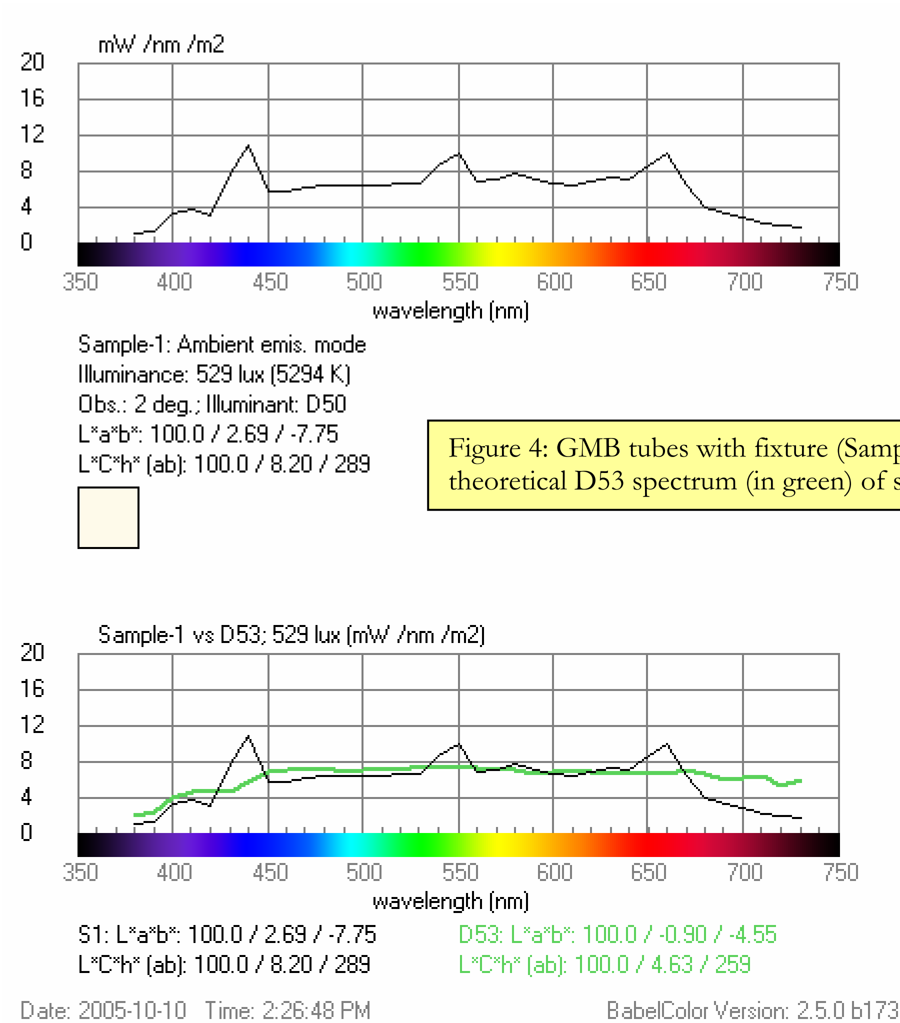


Figure 4: GMB tubes with fixture (Sample-1) vs theoretical D53 spectrum (in green) of same illuminance.

Just Normlicht fluorescents

The black spectrum (S1) in the upper section of Figure 5 shows the light output of the bare Just Normlicht tubes, with black cardboard placed between the tubes and the fixture, at a distance of approximately 32 in (81 cm); this figure should be compared with Figure 2. The measured illuminance is 490 lux and the CCT is 4842 K. Compared to the spectrum of the GMB tubes, in Figure 2, we see similar blue (440 nm) and green (550 nm) phosphors, while the red phosphors are quite different. We also note the strong presence of a blue-green phosphor in the Just Normlicht tube, at 490 nm, which makes for an overall "bumpy" spectrum.

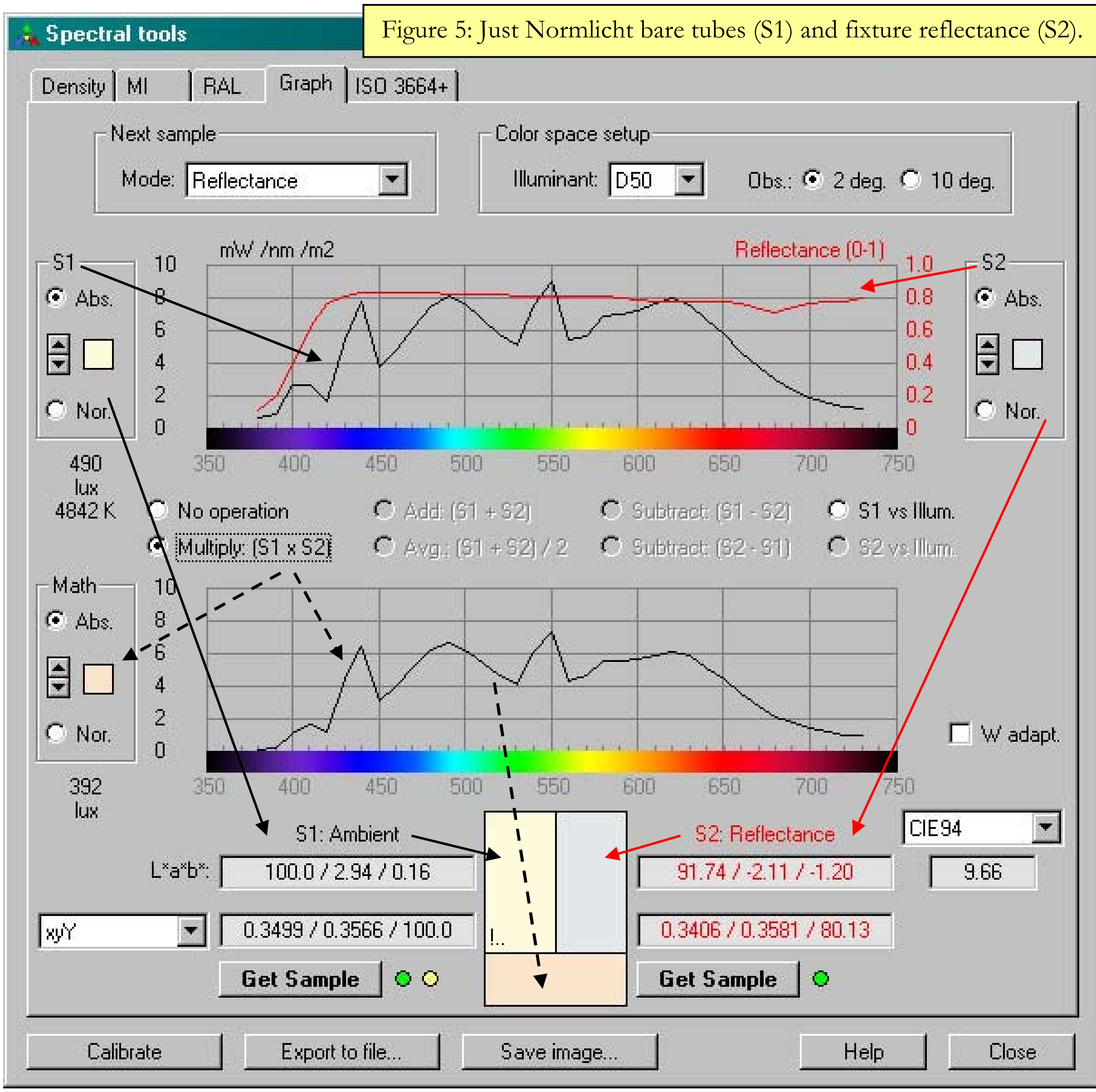


Figure 5: Just Normlicht bare tubes (S1) and fixture reflectance (S2).

Note: Figure 5 is a screen-shot of the application used for making the measurements. This is the same type of data shown in Figure 2 but this previous figure was obtained by clicking the "Save image…" button in the bottom of the screen-shot.

In Figure 5, the spectrum drawn in red (S2) is the reflectance of the white diffuser paint covering the fixture which holds the tube. This fixture's spectrum is similar to the one used in the GMB fixture, except that the spectrum of the GMB fixture had a large gentle dip between 480 nm and 650 nm whereas the spectrum of the Just Normlicht fixture has a small sharper dip around 680 nm. The third spectrum in the bottom of the figure is obtained by multiplying the bare tube spectrum with the reflectance of the diffuser (S1 x S2); the resulting spectrum has less pink (more orange) than the one obtained with the GMB tubes in their fixture.

Figure 6 shows the bare-tube spectrum in the upper part while the bottom part shows the same spectrum with a theoretical spectrum of the same CCT and illuminance. We notice four main peaks on the tubes spectrum, at 440, 490, 550, and 620 nm, which detract from the ideal D48 shown in green (4842 K was rounded to the nearest 100 K, i.e. 4800 K). When compared to Figure 3, we could think that having more pronounced non-uniformity in the Just tubes spectrum compared with the GMB tubes spectrum could translate to less daylight simulation accuracy; this will be measured and discussed in section 5. Also, compared to the GMB tubes, we note a more pronounced dip in the red tail of the Just Normlicht spectrum relative to the theoretical illuminant (drawn in green).

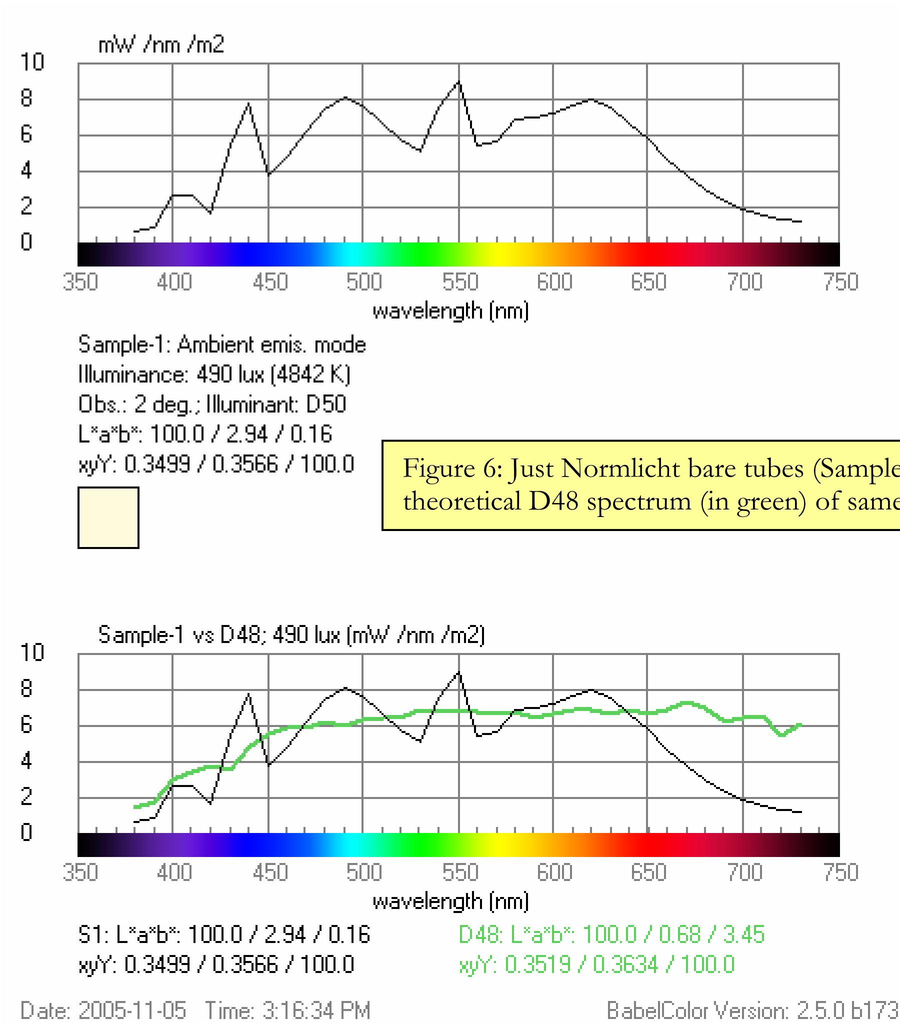


Figure 6: Just Normlicht bare tubes (Sample-1) vs theoretical D48 spectrum (in green) of same illuminance.

SoLux 5000 K lamp

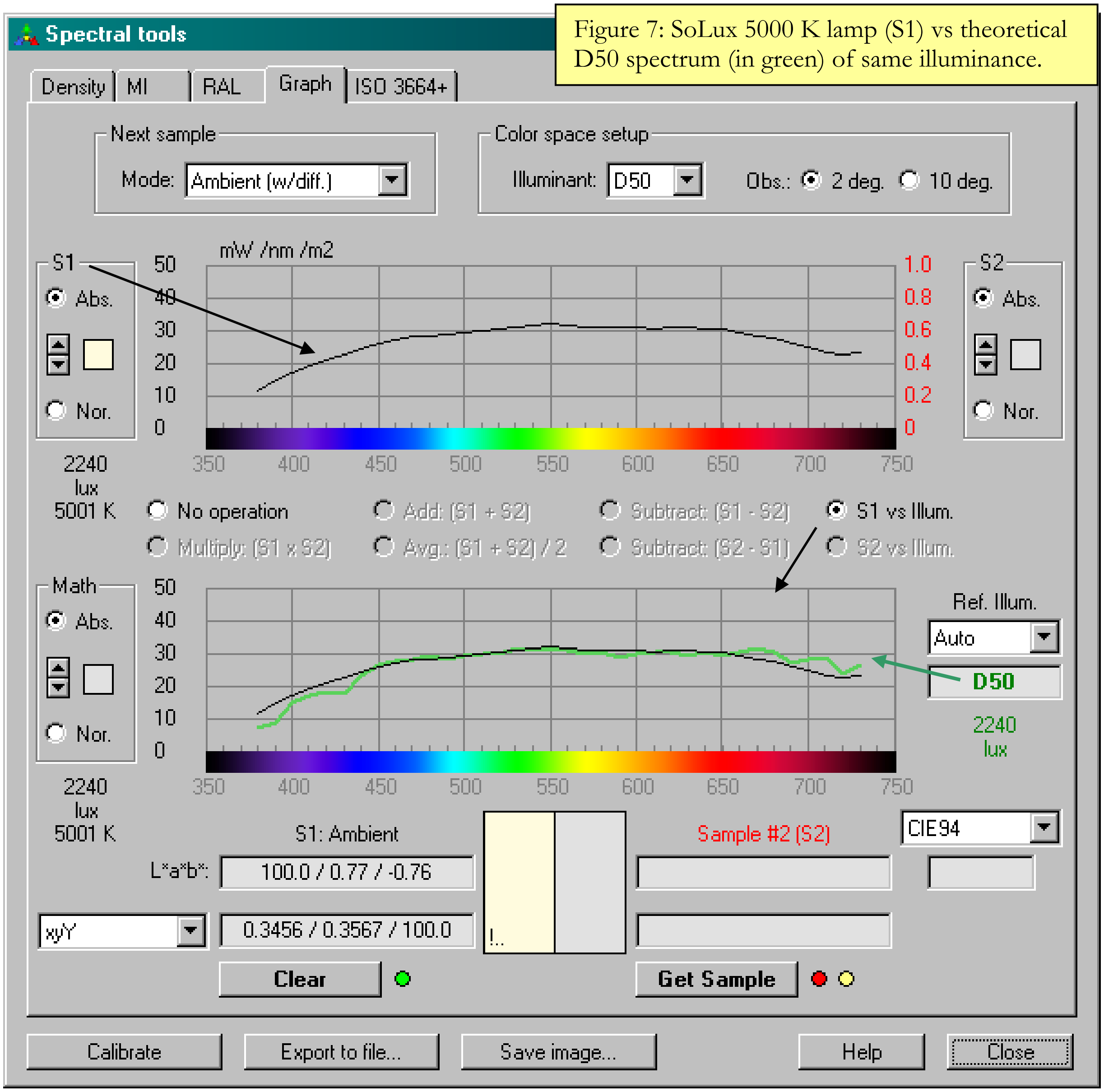


Figure 7: SoLux 5000 K lamp (S1) vs theoretical D50 spectrum (in green) of same illuminance.

The spectrum (S1) in the upper section of Figure 7 shows a measurement of the light output of the SoLux lamp in its fixture at a distance of 36 in (about 1 m), on axis. As mentioned previously, the lamp current is adjusted, using a DC power supply, to fine-tune its color temperature. You should be aware that using a higher voltage will seriously affect the lamp lifetime. Figure 7 should be compared with Figures 2 and 5. The measured illuminance is 2240 lux and the CCT is 5001 K. The green spectrum in the bottom section of the figure is the spectrum of an ideal D50 Illuminant. The match is excellent, with no peaks such as the ones seen with fluorescent bulbs.

In the above figure, D50 was automatically selected as the "ideal" illuminant because it is the closest rounded illuminant to the 5001 K CCT. However, we could also have imposed D50 as the "Reference Illuminant" for comparison purposes.

GTI SOFT-VIEW D5000 light booth

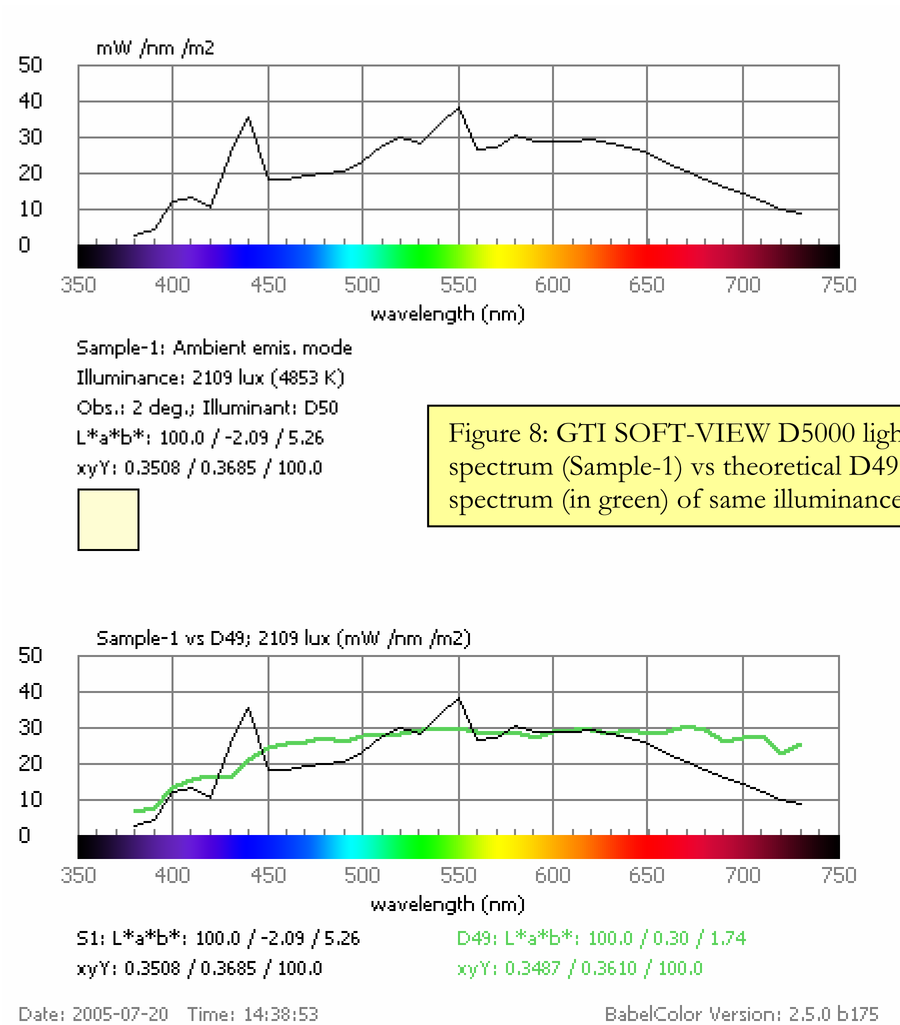


Figure 8: GTI SOFT-VIEW D5000 light booth spectrum (Sample-1) vs theoretical D49 spectrum (in green) of same illuminance.

The spectrum in the upper section of Figure 8 shows the light output of the GTI light booth as measured in the center of the booth vertical viewing plane. We adjusted the illuminance to a value around 2000 lux, corresponding to the “P1-Critical comparison” conditions called for in ISO 3664 (discussed in the next section); we did not verified if the color temperature varied for lower illuminance levels. The measured illuminance is 2109 lux and the CCT is 4853 K, significantly cooler than the GMB tubes but similar to the Just Normlicht tubes. This spectrum is reproduced in black in the bottom section of Figure 8 and the green spectrum corresponds to a theoretical D49 illuminant of the same illuminance.

We notice two peaks on the tubes spectrum, at 440 and 550 nm, which correspond to the same phosphors in the other tubes, and we see much smaller ones at 520 and 580 nm. There is also a fall-off in the red spectral region starting at 630 nm, but not as dramatic as with the GMB and Just Normlicht tubes. The same spectrum is seen when setting the booth to transparency viewing (using the back-light); this is expected, since the same tubes are used, and it also indicates that the back-light diffusing material is quite neutral.

4. ISO 3664 Description

The **ISO 3664** standard **—** *Viewing conditions - Graphic Technology and Photography* **—** is mostly a collection of other standards and accepted procedures to which it makes reference, and from which it selects particular conditions in regards to its specific target audience. ISO 3664 defines five viewing conditions:

- (**P1**) Critical comparison of PRINTS
- (**P2**) Practical appraisal of PRINTS
- (**T1**) Direct viewing of TRANSPARENCIES
- (**T2**) Viewing of TRANSPARENCIES by projection
- **Color monitors**

Table 1 on the next page gives the requirements for each condition.

P1 is recommended when comparing an original and its reproduction, or when comparing a sample print with a production run. The higher illumination level enables better judgment for evaluation of higher density zones. However, if is also recommended to make a comparison with the P2 conditions, or the actual conditions that will be used to view the images, to get an overall view of tone reproduction.

P2 is recommended when one wants to make a judgment on individual prints. This viewing condition is not recommended for comparing prints against one another, with the exception of comparing a print with its image shown on a monitor. The lower illumination level of P2 makes this task easier. You should be aware that such a comparison, monitor vs print, should only be performed when the monitor and print viewing light have the SAME *white point*, usually D65 or D50.

T1 and **T2** are dedicated to transparencies viewed either on a light table or by projection. Some light booths, such as the GTI unit used in our study, can be set for either P1/P2 or T1 conditions. It is important to mask the transparency edge with an opaque black mask in order to maximize tonal differentiation in the image dark tones.

You will notice in Table 1 that the reference display illuminant for the **Color monitors** condition is D65. Many prefer using D50 for their monitor white point, as recommended in ISO 12646. The difference stems from the different target applications. ISO 3664 is dedicated to applications where the display and the hardcopy are viewed independently, and ISO 12646 is dedicated to applications where direct comparison is made between the monitor and the hard copy. As noted above, if you intend to compare your prints with you monitor images, you should calibrate your monitor to D50.

All the viewing conditions of ISO 3664 are controlled using the white point chromaticity and either the *illuminance* (in lux), for illuminated set-ups (P1 and P2) such as light booths, or the *luminance* (in cd/m2), for transparencies and color monitors. In addition, for all viewing conditions except color monitors, the characteristics of the viewing condition can be further assessed by measuring the *Color Rendering Index* (CRI), its daylight simulator *Quality Grade* measured using a *Metamerism Index* (MI), and its uniformity.

Table 1: Requirements for the viewing conditions of ISO 3664.

<table>
<tr><th>Viewing condition</th><th>Ref. Illuminant</th><th>u'v' tolerance (note 1)</th><th>Illuminance / Luminance</th><th>CRI (CIE 13)</th><th>MI (CIE 51)</th><th>Illumin. uniformity</th><th>Surround luminous refl./ lum./ illumin.</th></tr>
<tr><td>P1</td><td rowspan="4">D50</td><td rowspan="4">0,005</td><td>2000 lux ± 500 lux (should be ± 250 lux)</td><td rowspan="4">Gen. index ≥ 90
Special indices ≥ 80</td><td rowspan="2">Visual : C or better; (should be B or better)
UV : < 4</td><td rowspan="2">up to 1m x 1m : ≥ 75%
for larger surfaces : ≥ 60%</td><td rowspan="2">< 60% (neutral and matte)</td></tr>
<tr><td>P2</td><td>500 lux ± 125 lux</td></tr>
<tr><td>T1</td><td>1270 cd/m2 ± 320 cd/m2 (should be ± 160 cd/m2)</td><td rowspan="2">Visual : C or better; (should be B or better)
UV : < 4</td><td rowspan="2">≥ 75%</td><td rowspan="2">5-10% of the luminance level
(neutral and extend at least 50mm on all sides)</td></tr>
<tr><td>T2 (note 4)</td><td>1270 cd/m2 ± 320 cd/m2</td></tr>
<tr><td>Color monitors</td><td>D65 (note 2)</td><td>0,025 (note 2)</td><td>> 75 cd/m2 (should be > 100 cd/m2)</td><td>N.A.</td><td>N.A.</td><td>N.A. (note 3)</td><td>neutral and dark gray or black
(should be ≤ 32 lux)
(shall be ≤ 64 lux)</td></tr>
</table>

Note 1: The chromaticity coordinates, *u'* and *v'*, are determined using the CIE 1976 Uniform Chromaticity Scale (UCS) equations and a 10 degrees Observer (CIE 1964); the tolerance is a radius with its center on the reference illuminant.

Note 2: In ISO 12646, the reference illuminant for the monitor is D50 and the chromaticity tolerance is a 0,010 radius.

Note 3: Although not specified by ISO 3664, BabelColor performs uniformity measurements on color monitors on up to five positions in accordance with ISO 12646.

Note 4: Not supported in BabelColor.

4.1. Color Rendering Index

The procedure used to determine the *Color Rendering Index* (CRI) is defined in the following document:

CIE 13.3-1995: Method of Measuring and Specifying Colour Rendering Properties of Light Sources.

This method is defined and maintained by the Commission Internationale de l'Éclairage (CIE) which is headquartered in Vienna (Austria). The CRI is a number between 0 and 100, with 100 being the best value, which defines how well colors are rendered by a light source in comparison with a reference illuminant, or standard. This standard can be either a thermal radiator (*blackbody*) or a D-series (daylight) illuminant.

The CRI, even though relied on by many, and often quoted as a measure of quality by lamp companies in particular, should not be considered simply at its face value. With the possibility of selecting a reference in a large array of illuminants, it is not too difficult to find an illuminant for which the computed CRI is over 90. To prevent any abuse, the reference illuminant should always be given in association with the CRI. Also, even though the color rendering properties of illuminants as different as a blackbody at 2856 K (Illuminant A) and D65 (daylight, 6500 K) are not the same, they will both result in a CRI of 100 if the test source matches the "selected" reference.

Because of its limitations, many feel that a good CRI alone is not enough (some critics are even harsher!). However, it can be shown that by combining a CRI value to a *Quality Grade*, as obtained with CIE 51.2 (and CIE S 012), described below, one can obtain a more accurate assessment of its viewing environment.

4.2. Metamerism Index / Quality Grade

The procedure used to determine the *Metamerism Index* (MI) and *Quality Grade* is defined in the following document:

CIE 51.2-1999: A Method for Assessing the Quality of Daylight Simulators for Colorimetry.

This index is not the same as the ones used when evaluating the color stability of reflectance samples or textiles, such as the Hunter Lab Metameric Index, although it is similarly based on measuring metameric differences using the CIELAB color difference formula.

The computation of this MI is based on the average color difference of five pairs of virtual metamers (i.e. theoretical or mathematically defined reflectance curves which correspond to the same tristimulus values in some conditions). These metamers have been defined in such a way that the computed color difference is zero for all pairs if the illuminant under test has the same spectrum as the ideal illuminants; in all cases, the Observer is 10 degrees (CIE 1964). This ideal illuminant is D50 for ISO 3664 but CIE 51 also covers the use of the D55, D65, and D75 illuminants. A different set of metamers is assigned by the standard for each reference illuminant.

The difference between CIE 51 and CIE 13 is that CIE 13 compares a single set of patches with two illuminants, the "measured" light and the "ideal" illuminant, while CIE 51 compares pairs of metamers with the "measured" light. The average color difference from the five pairs, the MI, is used to assign the Quality Grade, a letter between "A" and "E", with "A" being the best grade. The assignation table for the Quality Grade is:

Quality grade	MI (CIE S 012)
A	≤ 0,25
B	> 0,25 to 0,50
C	> 0,50 to 1,00
D	> 1,00 to 2,00
E	> 2,00

Table 2: Quality grade vs average MI (i.e. a Metameric Index based on a CIELAB color difference) as specified in CIE S 012 and CIE 51.

As you can see, an "A" grade requires an average color difference of 0.25 or less, which is quite a challenge to meet. In practice, grade "B" is excellent, while grade "C" is still acceptable.

The MI test specifically called for in ISO 3664 is CIE 51. The MI test performed here is based on

> **CIE S 012 /E:2004:** Standard Method of Assessing the Spectral Quality of Daylight Simulators for Visual Appraisal and Measurement of Colour,

a more recent standard which addresses the same concerns as CIE 51, and effectively replaces it.

The metamers of CIE S 012 are basically identical to the ones of CIE 51; however, their spectrums have been extended to 380 and 780, from the 400 to 700 nm range of CIE 51. The MI is computed in the same manner for CIE 51 and CIE S 012, and the quality grade categories are the same.

CIE 51 and CIE S 012 not only describe how to measure a visible index, but an Ultra-Violet (UV) index as well. In practice, most spectrometers designed for the graphic industry cannot do measurements in the range required for the UV index, and thus, only the visible index is computed.

4.3. Illumination uniformity

For P1 and P2 conditions, the uniformity should be higher than 75% for areas up to 1m by 1m. For small light booths, this would mean the entire lighted area. For an illuminated table, it can be viewed the other way around, as the area where the illumination is within 75% of the maximum value, even if this area is smaller than the viewing table.

If the lighted area is larger than 1m by 1m, uniformities as low as 60% are accepted.

For T1 and T2 conditions, the uniformity shall be higher than 75% over the entire illuminated zone.

While a uniformity criterion is not specified for color monitors in ISO 3664, such a specification exists in ISO 12646. It calls for 90% uniformity within the central zone defined by a rectangle extending between 25% and 75% of the visible area of both axes.

4.4. Surround reflectance / luminance

These requirements simply insure that the measurements and visual evaluations performed are not overly affected by the environment. They should be verified but will not be discussed furthermore in this paper.

5. ISO 3664 Measurements

The parameters of Table 1 in the previous section were measured for the two fluorescent fixtures and our light box. We did not measure the uniformity of the SoLux lamp since this is a pointless exercise for a point light! However, we did measure the other characteristics of this lamp.

GretagMacbeth fluorescent

Figure 9 on the next page shows the measured characteristics of the bare GMB tubes relative to the P2 viewing condition; a black cardboard was inserted between the tubes and the fixture in order to measure the output from the tubes only. The tube-to-table distance was 29 inches (74 cm) and the zone that met the 75% uniformity criteria, corresponding to the *Brightness uniformity* data, was measured to be about 29 inches large by 20,5 inches deep (74 cm x 52 cm). As shown in Figure 9, because the measuring zone was defined to meet the uniformity test, this test has a PASS rating.

The *Brightness*, the *Meas. Temp.* (CCT), the *Chromaticity*, the *CRI* with individual *Special indices*, and the *MI/Quality Grade*, corresponding to the central position, as selected in the *Brightness uniformity* group, are also shown. This information is available for the five positions shown in the *Brightness uniformity* group.

The chromaticity test, measured in u'v' coordinates, has failed. This is another way of indicating that the CCT is slightly high; however, all other results for this position have a PASS rating.

The eight *Special indices* from which the CRI is determined are shown; to meet the requirement, they should all be equal or superior to 80. In addition, the CRI, which is the average of these eight values, should also be higher than 90%. This goal is met.

The "C" *Quality Grade* is adequate without being great. The MI value, as well as the individual differences for the five metameric pairs, was obtained from an exported measurement report, using the "Export to file…" button. In this case, the MI value for the center position is 0,93, near the bottom limit of the C grade zone defined in Table 2 (Grade "C" is valid up to an MI of 1).

Figure 10 shows the measured characteristics of the GMB tubes mounted in their fixture relative to the P2 viewing condition. The tube-to-table distance was 40 inches (102 cm) and the zone that met the 75% uniformity criteria, corresponding to the *Brightness uniformity* data, was measured to be about 29 inches large by 25 inches deep (74 cm x 64 cm). The figure shows the results corresponding to the central position.

By comparing the data of Figure 9 and 10, and the exported report data of each test, we see a few effects of the diffuser:

a- The diffuser increases the color temperature by 200 K. In fact, with the fixture, we measure a CCT of 5310 plus or minus 40 K over the zone which covers our 75% brightness uniformity criteria, with the maximum roughly in the zone center. This indicates that our fixture is far from being a uniform diffuser.
b- The chromaticity offset is increased. This goes in pair with the increased CCT due to the bluish tint of the fixture diffuser.
c- The CRI and MI are essentially the same.

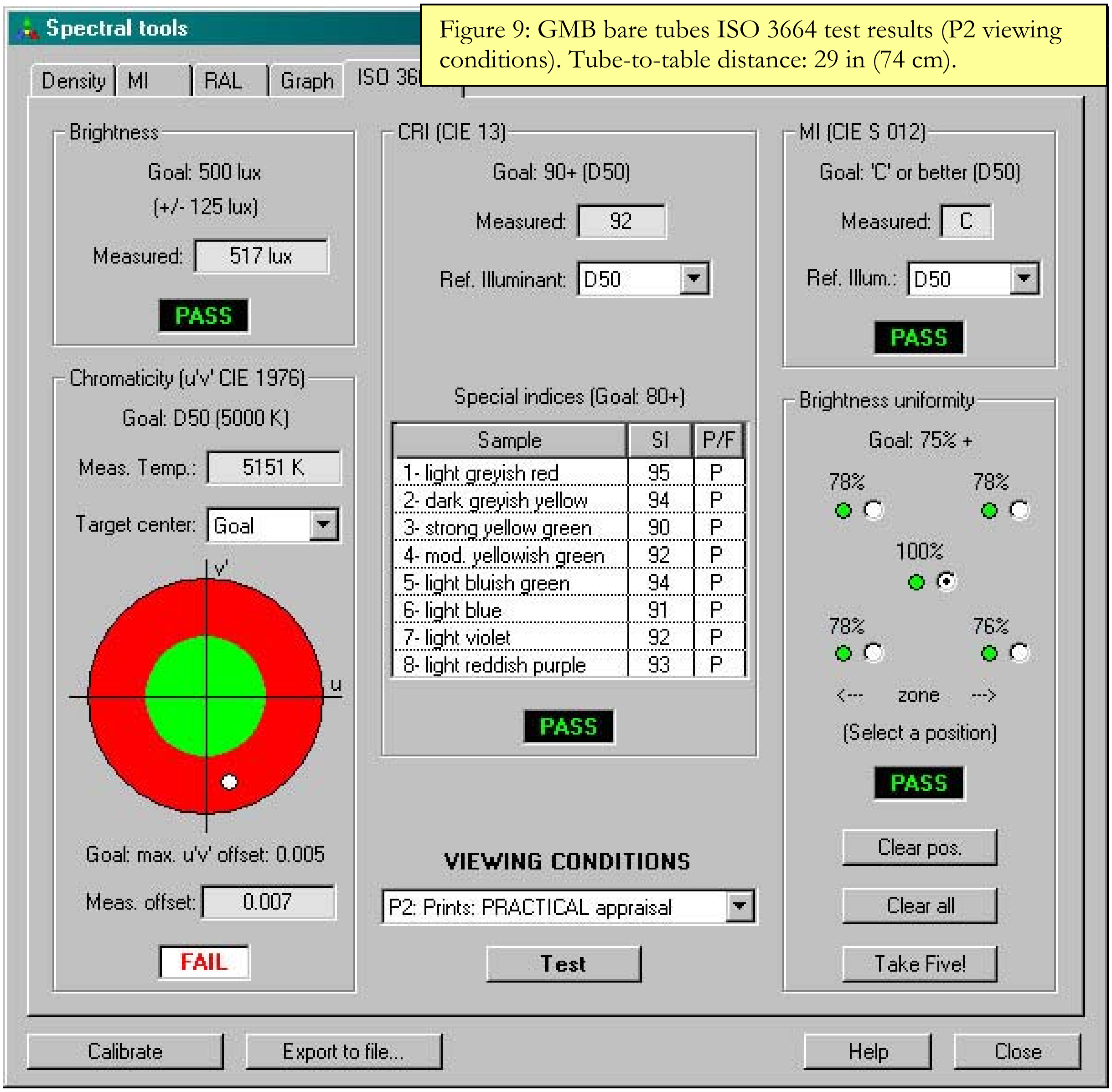


Figure 9: GMB bare tubes ISO 3664 test results (P2 viewing conditions). Tube-to-table distance: 29 in (74 cm).

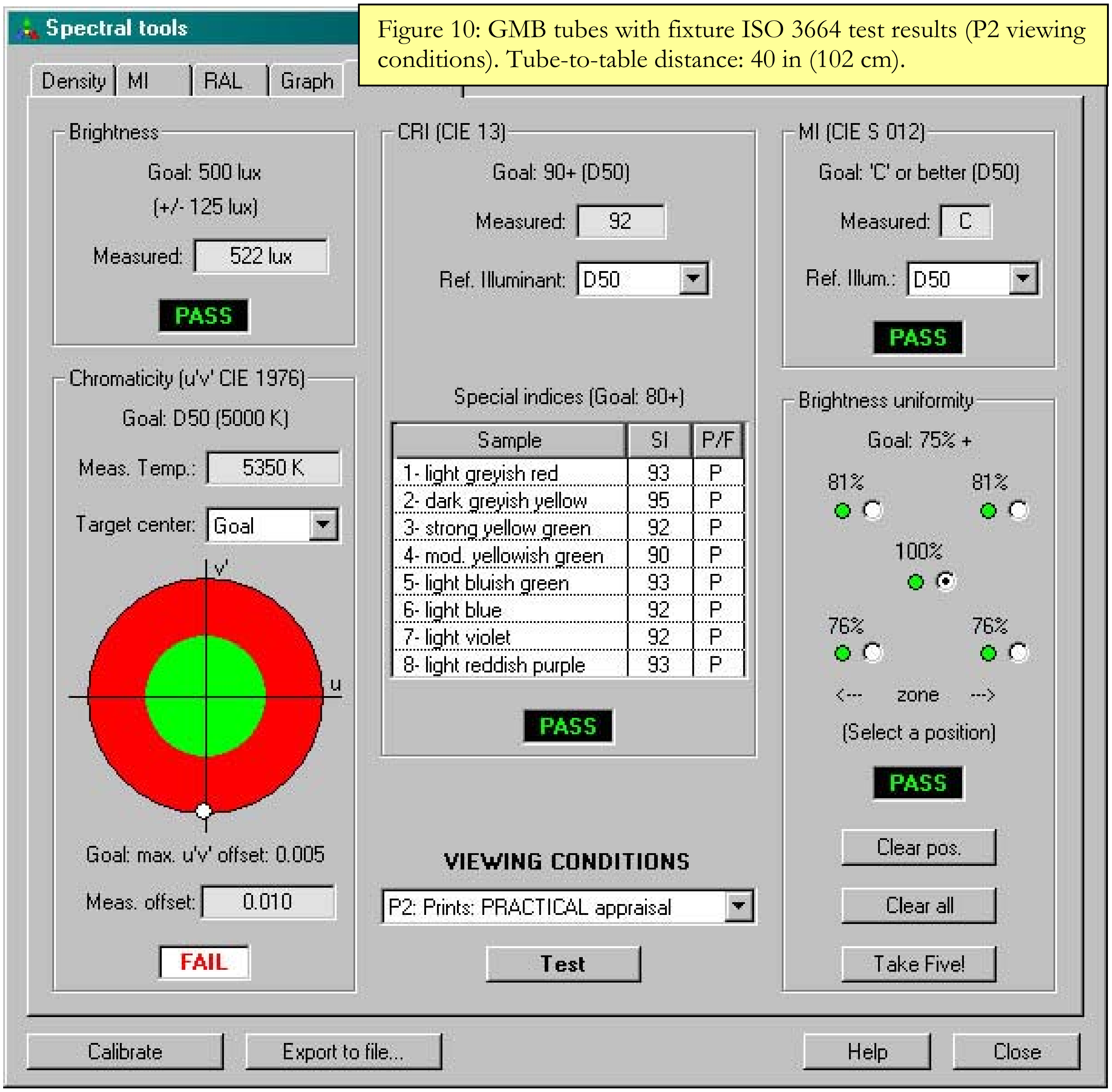


Figure 10: GMB tubes with fixture ISO 3664 test results (P2 viewing conditions). Tube-to-table distance: 40 in (102 cm).

Just Normlicht fluorescent

Figure 11 below shows the measured characteristics of the bare Just Normlicht tubes relative to the P2 viewing condition. The tube-to-table distance was 32 inches (81 cm) and the zone that met the 75% uniformity criteria, corresponding to the *Brightness uniformity* data, was measured to be about 31 inches large by 22 inches deep (79 cm x 56 cm). The figure shows the results corresponding to the central position. All results for this position also have a PASS rating.

The special indices and the resulting CRI are better than the ones obtained with the GMB tubes.

The quality grade is adequate without being great. The MI, obtained from the exported measurement report, is 0,73, in the middle of the C grade zone defined in Table 2 and slightly better (lower) than the one obtained for the bare GMB tubes.

Let's go back for a moment to Figures 3 and 6, which presented the spectrums of the bare GMB and Just Normlicht tubes. With both the CRI and quality grade slightly better than the ones obtained with the GMB tubes, it seems that there is a slight advantage in the continuously-bumpy spectrum of the Just Normlicht tube compared to the flatter-but-with-spikes spectrum of the GMB tubes. However, to GMB's defense, it must be added that non-uniform spectrums are generally more prone to generate metameric mismatches.

Figure 12 shows the measured characteristics of the Just tubes mounted in their fixture relative to the P2 viewing condition. The tube-to-table distance was 46 inches (117 cm) and the zone that met the 75% uniformity criteria, corresponding to the *Brightness uniformity* data, was measured to be about 32 inches large by 27 inches deep (81 cm x 69 cm). All results for this position also have a PASS rating.

By comparing the data of Figures 11 and 12, and the exported report data of each test, we see a few effects of the diffuser:

a- The diffuser increases the color temperature by about 250 K. This is similar to what was observed for the GMB tubes (with a different fixture).
b- The chromaticity is shifted slightly, but is still within the acceptable range.
c- The MI is slightly higher (0,90 instead of 0,73). The value with fixture is essentially the same for the GMB and Just Normlicht tubes.

In this case, the fixture improves the color temperature of the bare tubes.

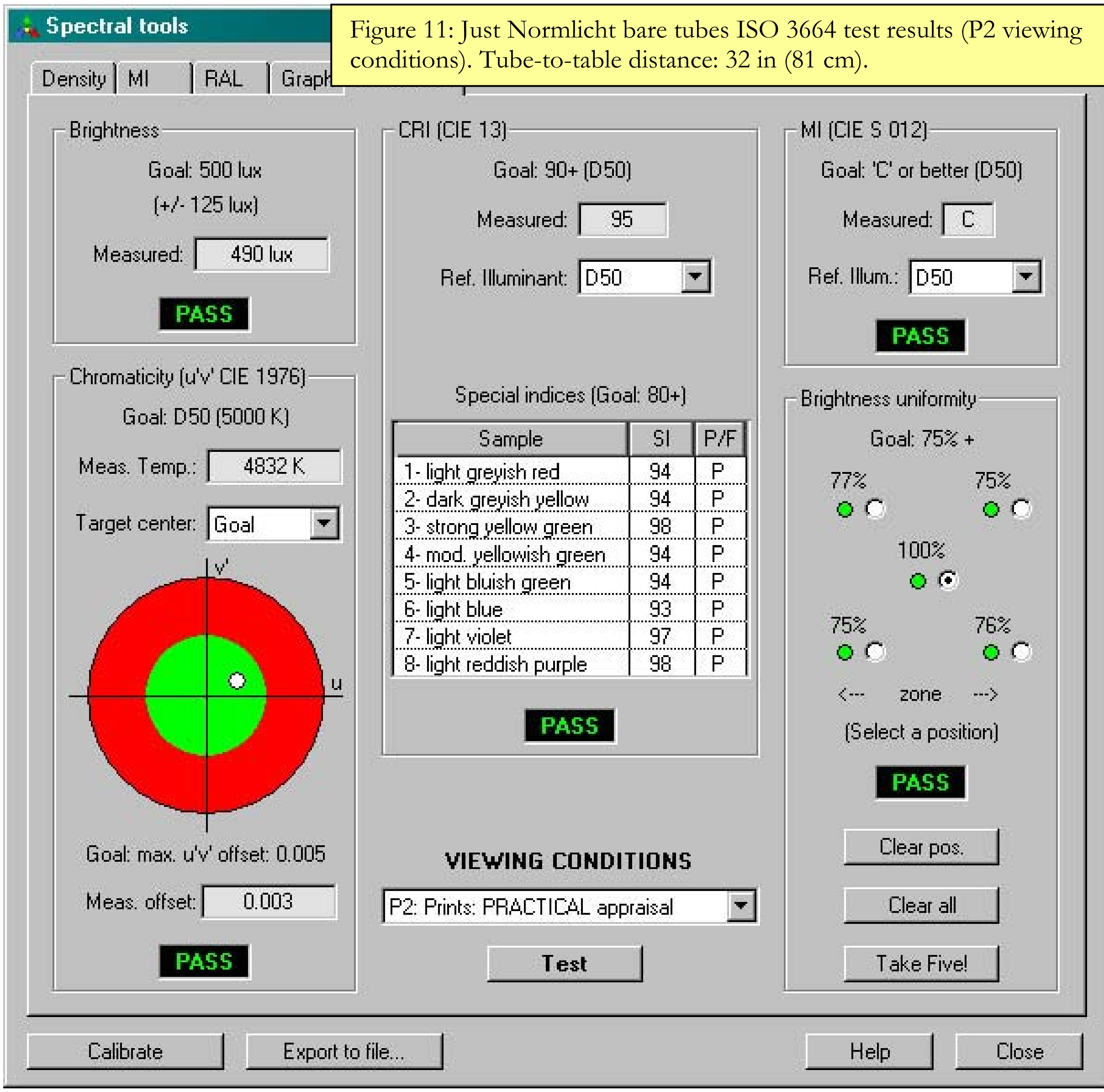


Figure 11: Just Normlicht bare tubes ISO 3664 test results (P2 viewing conditions). Tube-to-table distance: 32 in (81 cm).

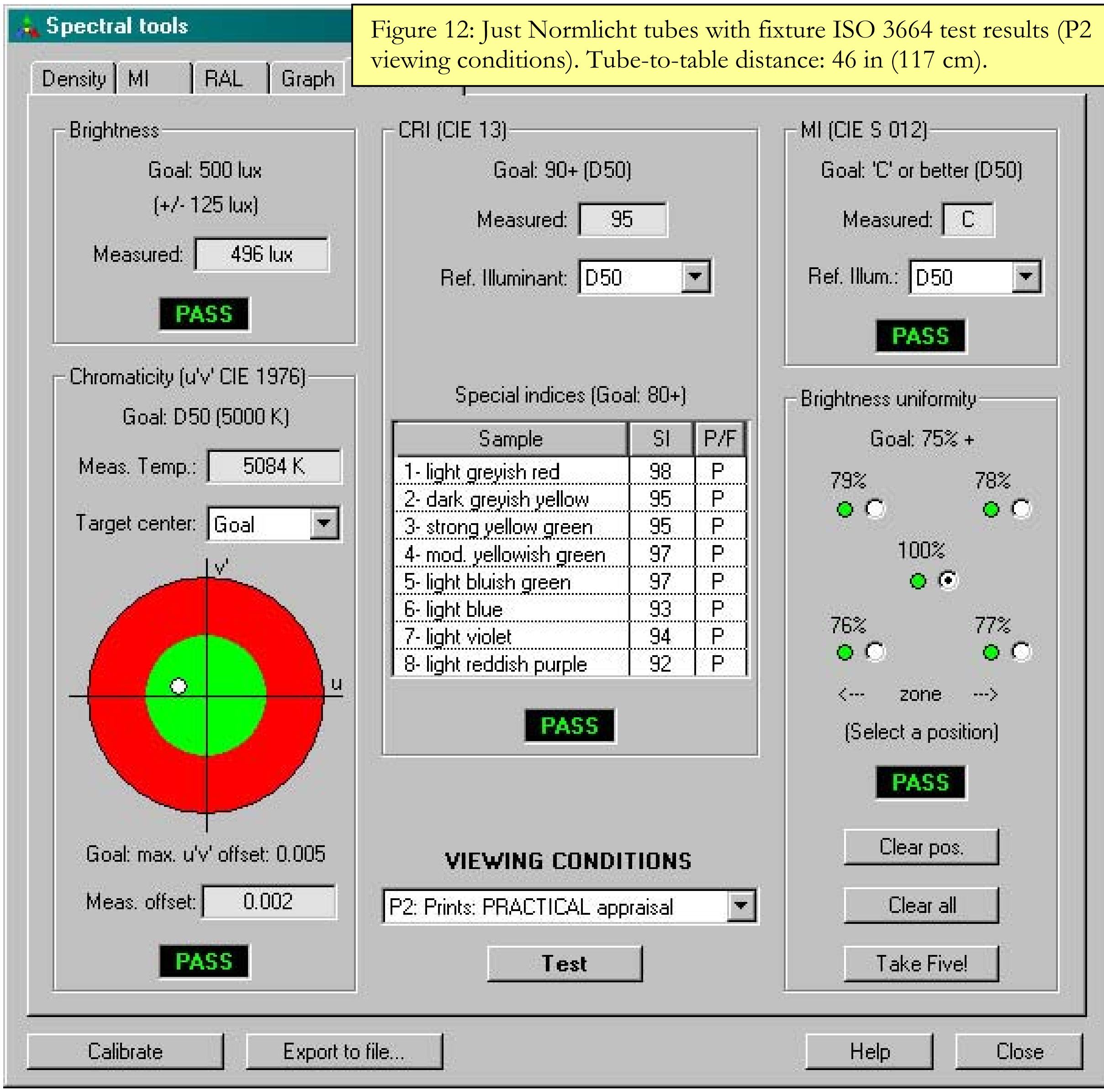


Figure 12: Just Normlicht tubes with fixture ISO 3664 test results (P2 viewing conditions). Tube-to-table distance: 46 in (117 cm).

GTI SOFT-VIEW D5000 light booth

Figure 13 below shows the measured characteristics of the GTI light booth set for the P1 viewing condition. Because of its particular illumination geometry, a horizontal top light illuminating a vertical viewing plane, it is impossible to achieve the degree of uniformity required by ISO 3664 and we only took our measurements in the center of the viewing surface for this viewing condition.

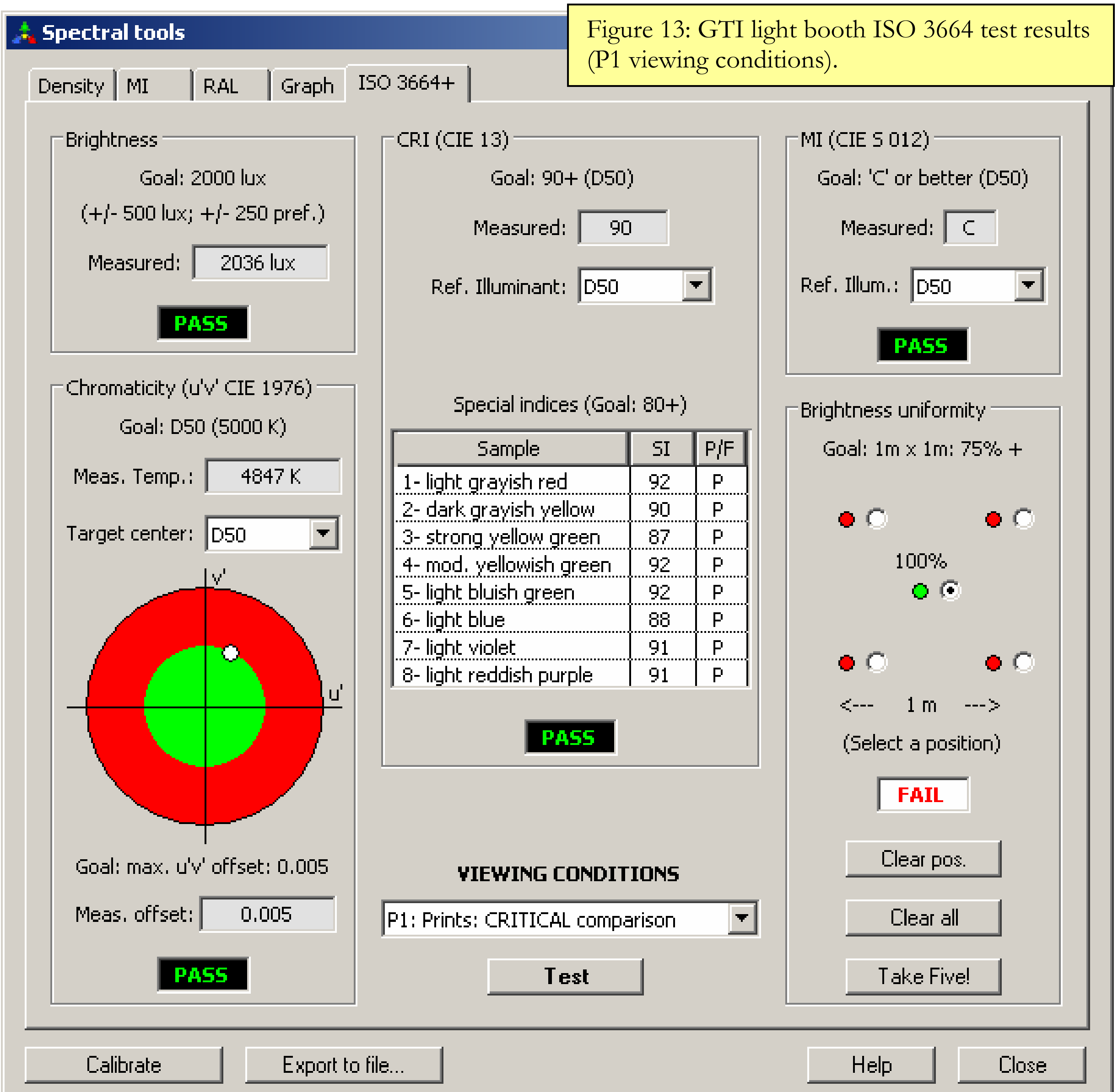


Figure 13: GTI light booth ISO 3664 test results (P1 viewing conditions).

The CRI and Quality Grade are on the limit but still good; the MI from the exported report, is 0,93, very similar to the values obtained with the GMB and Just Normlicht tubes. The 4847 K color temperature (and chromaticity) is on the cool side (more orange).

Figure 14 shows the measured characteristics of the GTI light booth set for the T1 viewing condition. For the brightness uniformity test, we defined the zone as between 25% and 75% of the illuminated area (knowing very well that ISO 3664 calls for the entire zone where light is emitted, and it would not have passed if we had done so).

The results are very similar to the ones obtained in the P1 condition, and the slight difference in chromaticity could be attributed to the different tubes used for back-lighting. We noted, in the exported report, that the MI is better in the center of the viewing zone, at 0,67, than on the edges (average MI of 0,79 for the four corners).

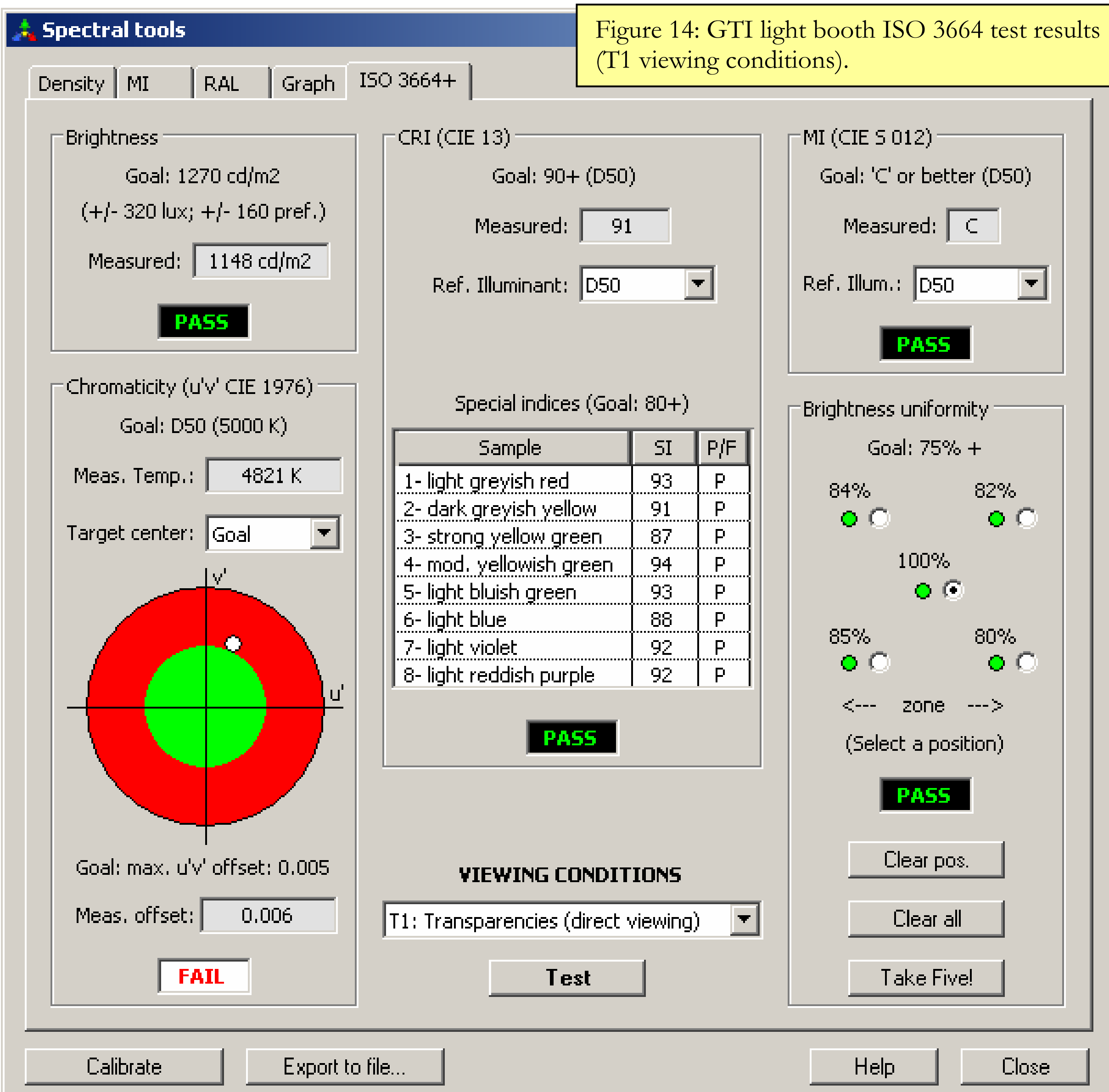


Figure 14: GTI light booth ISO 3664 test results (T1 viewing conditions).

Solux 5000 K lamp

Figure 15 shows the measured characteristics of the SoLux lamp set for the P1 viewing condition. We adjusted the distance at which the measurement was taken, about 22 inches(56 cm), to match the P1 brightness requirement. Because this is a single lamp bulb, it is impossible to achieve the degree of uniformity required by ISO 3664 and we only measured the brightness in the beam center; the fall-off is quite rapid as soon as you go off-center.

The results are quite remarkable, with a CRI of 98 and a "B"Quality Grade. The actual MI value, the color difference average for five metamers obtained from the exported report, is 0,28, just over the 0,25 limit of the "A" grade (individual results shown on next page).

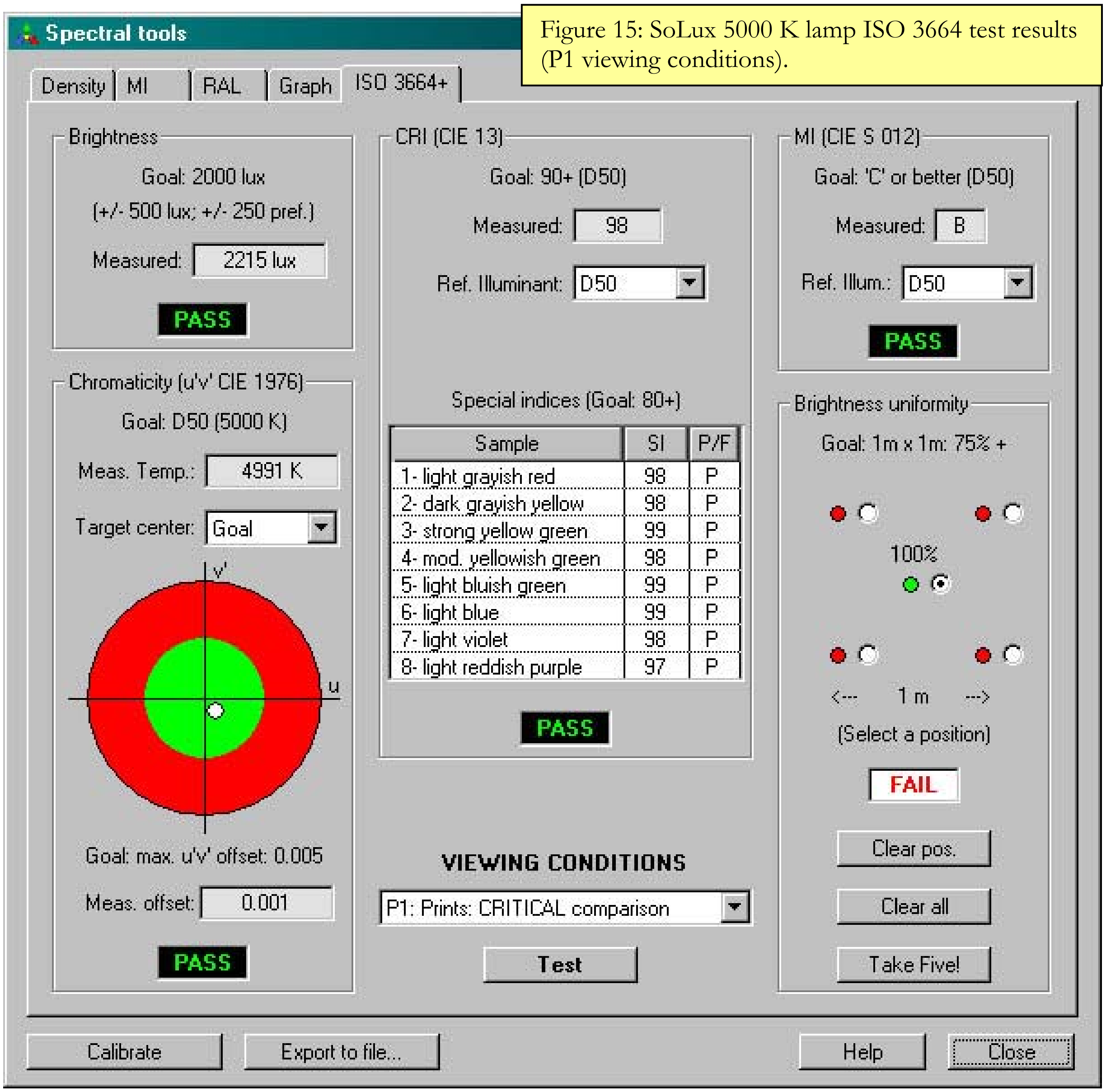


Figure 15: SoLux 5000 K lamp ISO 3664 test results (P1 viewing conditions).

The individual color differences (CIELAB, 10 deg. Observer) for the five CIE S 012 metamers are:

Metamer #	Munsell equivalent	DeltaE*ab
metamer-0	5,6YR 5,6/11	0,20
metamer-1	1,0RP 2,5/4,7	0,17
metamer-2	9,6Y 3,5/3,7	0,23
metamer-3	8,7PB 5,6/4,4	0,45
metamer-4	5,3RP 4,5/5,8	0,36
Average (MI):		**0,28**

Note: Munsell equivalent values are approximate and correspond to patches viewed under Illuminant C.

As we mentioned previously, we tweaked the lamp voltage to match the nominal D50 CCT. Also, it should be noted that we inserted the bulb in a lamp designed by the same company that designed the bulb. It seems they take particular care in managing the light emitted in the back of the bulb and how it mixes with the light emitted in the front, which is not the case in all commercial fixtures (some fixtures are designed to leak a lot of light to the rear, to minimize the lamp "spot" effect). Many users will simply insert the lamp in the MR16 socket of a generic fixture and press the "ON" switch, without doing any fine tuning (or having the possibility of doing so!). To test how the lamp would react in such an environment, we inserted another 5000 K lamp of the same batch into a generic third party "rail type" lamp holder with "electronic" transformer. We obtained the nominal CCT within a few degrees (=4998 K); the chromaticity offset (=0,004), CRI (=94) and MI (=0,41) were slightly worse than the measurements with the 5000 K lamp mounted in our Task Lamp; note that the Quality Grade is still considered a "B", which is quite good.

During our measurement sessions, we also obtained a "A" Quality Grade for an over-driven (in terms of current) 4700 K lamp (another model from SoLux, ordering code: 35003). In this particular case, the average MI was 0,24, just at the edge of the "A" to "B" transition, the chromaticity offset was 0,004, the CCT was 4820 K, and the CRI was 96. Should this "A" grade lamp be considered better than the 5000 K "B" grade of the Task Lamp which measurements are shown in Figure 15? In this case, we consider the overall results of the Task Lamp setup as better (with better chromaticity, better CRI, and no significant difference in Quality Grade). We suggest not putting too much emphasis on a single parameter and looking at all data, including the background data on which a criteria is established; in effect, an average MI of 0,24 is very close to 0,28 even though they correspond to different grades ("A" for 0,24, "B" for 0,28).

In practice, the three setups described above and summarized in the table below are very adequate for D50 illumination; it is just that one is slightly more accurate than the others.

Setup	CCT	Chromaticity error	CRI	MI / QG	Notes
5000 K lamp in Task Lamp	4991 K	0,001	98	0,28 / B	Tweaked DC current
5000 K lamp in generic rail holder	4998 K	0,004	94	0,41 / B	Generic electronic transformer
4700 K lamp in Task Lamp	4820 K	0,004	96	0,24 / A	Over-driven DC current

Note: The algorithm used to determine the CCT is very sensitive to slight variations in the chromaticity coordinates it uses for input; also, there exists a range of chromaticity that will correspond to the same CCT. Because of this, we usually place more importance in the other parameters of the table above.

6. Conclusion

You should not expect a "This is the best light source you should buy!" type of conclusion here. As the title indicates, this is a "How to…" paper and not a product review.

However, looking strictly in terms of simulating D50, the SoLux lamp is certainly the most accurate lamp we have tested. And even though there are light booths which provide equal or better D50 simulation, the cost/performance ratio of SoLux lamps is hard to beat for desktop applications! But an illumination setup is more than just matching a light source; how about having a large uniform illumination zone at a prescribed illuminance level? This is much more difficult to achieve with SoLux lamps than with fluorescent tubes.

As we have seen, both the GMB and Just Normlicht tubes have similar performance in terms of daylight simulation, with a very small advantage in chromaticity and CRI for the mounted Just Normlicht tubes, an advantage that may well have been for the GMB tubes if we had mounted them in another fixture. In any case, while these tubes strive to give you an "ideal" D50, they exhibit slightly different color temperatures, a difference which is compounded, again, by the respective fixtures we had available. Is it better to select a slightly cooler or hotter color temperature? This is a matter of personal taste, compatibility with your supplier or customer, and cost.

The facts that, in all fluorescent lights, individual phosphors are combined to achieve a given spectrum, and that these phosphors are characterized by individual peaks, can only lead to different metameric properties for these tubes. When we compared printed images with both setups, the visual assessments did differ; some colors better matched the colors seen on our monitor under one illumination system than the other.

You can save money by buying individual fluorescent tubes, but we saw that a fixture can affect the light characteristics. For instance, if the light from the bare tube and the reflected light from the fixture are spectrally different, it is likely that the color temperature of the light in the viewing plane will be non-uniform, unless the fixture incorporates a diffuser which thoroughly mixes the two spectrums (or that the fixture is far away). Knowing how to measure the effect of a fixture is a step in the right direction.

If money is no object, buying a complete light booth from a single supplier is another solution. There again, there are differences between manufacturers, and differences between models from a given manufacturer. You can see endless debates in web forums on the respective advantage of products from one company relative to another company's products. If you look at each manufacturer's specification, they all meet the same generic requirements of CIE 13 and CIE 51/CIE S 012. We have seen that the difference is in the details, and these details can explain many of the subjective comments that can be read. Meeting a standard only means that a product is within a defined performance range, but there is no formal statement that images will look exactly the same when viewed under illumination systems of different manufacturers, even though this may be thought so by the unaware user.

Assessing a system performance on CRI alone is useless. Combining the CRI with the chromaticity, the color temperature and, particularly, the Quality Grade, as determined with CIE S 012 (or CIE 51), is a much better procedure. These parameters are the basis of ISO 3664; while meeting this standard's minimal requirements is sufficient for most professional tasks, understanding how they interact and seeking optimum values will help you improve the reproducibility and quality of your work.