New Requirements on D50 Illumination in ISO/DIS 3664:1998 and the Implications

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Abstract

ISO/DIS 3664:1998 imposes new requirements on D50 illumination in an attempt to tighten the tolerances on D50 sources. This paper intends to discuss a few potential problems and some implications in implementing the newer standard regarding D50 sources.

Introduction

In response to the demand for tighter control on D50 sources and viewing conditions, a joint working group composed of members of ISO/TC6 (Paper, board and pulps), ISO/TC42 (Photography) and ISO/TC130 (graphic technology), revised ISO 3664:1975, "Viewing Conditions for Graphic Technology and Photography", after reviewing current industry practices, and come to a newer version of the standard, the ISO/DIS 3664:1998. For D50 illumination, the earlier version, ISO 3664:1975, imposes a chromaticity tolerance and a Color Rendering Index (CRI) requirement.[1] The chromaticity tolerance is defined by a 0.08 unit radius circle on the CIE 1976 Uniform Chromaticity Scale (UCS) diagram. For color rendering properties, it requires the general CRI (Ra) to be no lower than 90, and each individual CRI (1 to 8) to be no lower than 80. The newer version of the standard reduces the chromaticity tolerance to a 0.05 unit radius circle on the CIE 1976 UCS diagram; maintains the same requirement on CRI; and in addition, requires the CIE Metameric Index (MI) assessment.[2] The standard requires the MI to be no lower than "C" in the visible region (MI_{vis}) for all viewings, and the MI lower than 4 in the UV region (Mi_{uv}) for reflection viewing only. It is the intention of this paper to examine these new changes as well as the original requirements on D50 illuminations by testing a few practical examples.

Chromaticity Tolerance

ISO 3664:1975 defines the chromaticity tolerance by a 0.08 unit radius circle on the CIE 1976 UCS diagram. ISO/DIS 3664:1998 defines that by a 0.08 unit radius circle. First of all, a circle of a 0.08 radius corresponds to a tolerance range larger than the just noticeable chromaticity difference. This can be illustrated by plotting such a circle together with the 3-step MacAdam ellipse on the CIE 1931 chromaticity diagram, see Fig.1.[3] The 3-step MacAdam ellipse is often regarded as the chromaticity discrimination threshold. The 0.008 unit radius circle on the CIE 1976 UCS diagram also shows as an ellipse on the CIE 1931 chromaticity diagram (the dotted trace). Clearly, a 0.008 radius circle transforms into an ellipse which is much larger than the 3-step MacAdam ellipse. Therefore, D50 sources fall into this tolerance may appear different in chromaticity from source to source. In response to this concern, ISO/DIS 3664:1998 adopts a 0.05 radius circle on the 1976 UCS diagram. This circle is drawn on the CIE 1931 diagram and shown as the solid trace, which is much closer to the 3-step MacAdam ellipse. Therefore, it is hoped that D50 sources fall into this tolerance will appear closer in color.

Naturally, such a reduction in chromaticity tolerance requires two conditions to be met before it can be enforced. First, the D50 illumination sources in concern can be controlled within that tolerance in chromaticity in current industrial practices; second, the current instruments can provide the necessary precision and accuracy.

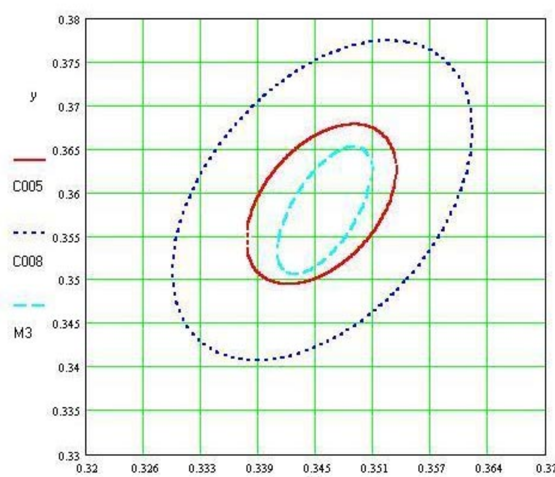

Fig.1 Chromaticity tolerances on D50 illumination in ISO 3664 (1975 version, dot trace, "C005"; 1998 DIS version, solid trace, "C008") on the CIE 1931 chromaticity diagram as compared to the just noticeable color difference, represented by the 3-step MacAdam ellipse (dash trace, "M3").

D50 Fluorescent lamps

Another task of revising the standard was to respond to the suggestion of defining CIE F8 as the standard illuminant. Although the joint group came in favor of maintaining CIE D50 as the standard illuminant, it cannot be denied that CIE F8 has been the *de facto* standard because the vast majority of D50 sources in the graphic art industry are fluorescent lamps. CIE F8 is a fluorescent lamp that probably represents the best D50 simulator by conventional fluorescent lamp technology without resorting to extreme techniques such as multi-layer phosphor coating and narrow-band spectral filtering techniques. Given the four mercury spectral lines in the visible range, conventional fluorescent lamps are never the best daylight simulators. The situation is especially problematic for D50 simulation because the strong spectral emission line at 436nm does not allow much continuous energy at the shorter wavelength or blue spectral region to be added by phosphor fluorescing. Nonetheless, daylight fluorescent lamps are efficient, safe, inexpensive and durable, making them favorable sources for industrial applications.

The spectral output of daylight fluorescent lamps depends on many operating and environmental factors. In essence, any factor that may possibly impact on the physical status of mercury atoms within the bulb will affect the spectral output of the lamp. Such physical status changes of the mercury atoms can redistribute the relative energy among all the mercury spectral lines, causing drastic spectral changes, resulting into visible changes in chromaticity. To illustrate the problem, two published graphs are adapted and shown here.[4] Fig. 2 is a plot of the light output of a typical fluorescent lamp as a function of lamp bulb temperature. Apparently, the fluctuation of the light output with regular room temperature changes (e.g. 15-25°C) can be as high as 50%.

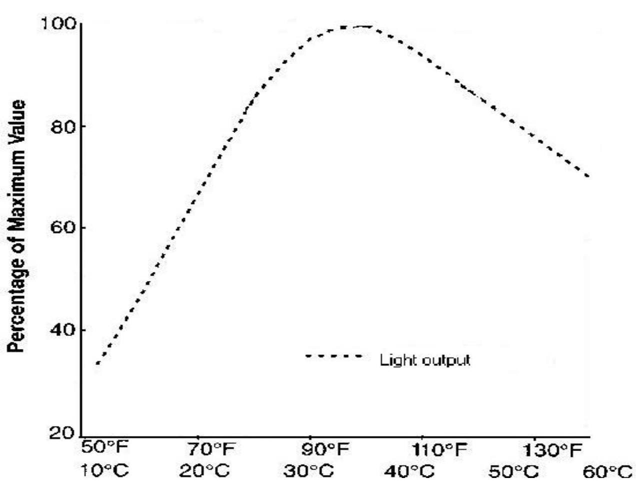

Fig.2. Light output of a typical fluorescent lamp as a function of lamp bulb wall temperature.

Fig.3 shows the chromaticity changes of typical daylight fluorescent lamps as a function of lamp bulb wall temperature on the CIE 1931 chromaticity diagram. Each dot represents a 20°C change starting from -20 °C. For comparison, Fig.3 also includes the color change of a typical cool white fluorescent lamp. A 3-step MacAdam ellipse is also drawn to illustrate the amount change in the perceptual space. Fig. 3 seems to suggest that a temperature change of about 20°C can cause a chromaticity change as defined by a 0.05 radius circle on the CIE 1976 UCS diagram, which is the required newer tolerance. It is necessary to point out that the lamp bulb wall temperature will not be ambient temperature although they are directly related. In most cases, the type of fixture that will be used may contribute more to the lamp bulb wall temperature. However, that is assuming the illumination system is sufficiently warmed up. When the lamps are first turned on, the bulb wall temperature will be the same as that of ambient temperature. In practice, do users actually warm the system up sufficiently? The answer will probably be inconsistent.

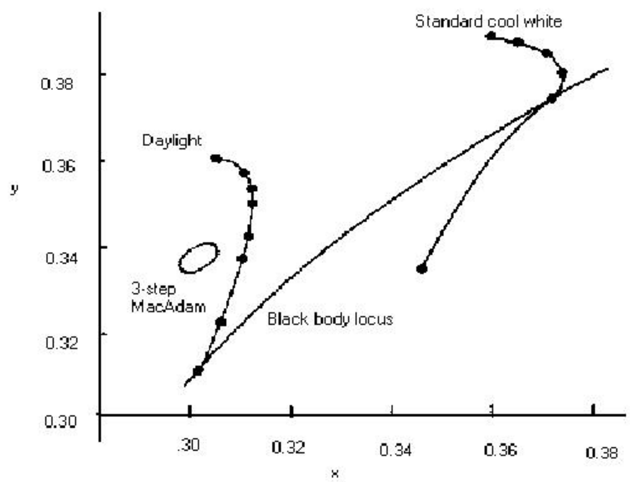

Fig.3. Chromaticity changes of daylight fluorescent lamps and typical cool white fluorescent lamps as a function of lamp bulb wall temperature.

Measuring the chromaticity of D50 illumination

ISO 3664 is prudent to use only a spectral power distribution on the sample-viewing plane to specify illumination. It seems that if we can measure the spectral power distribution of the illumination incident on the sample-viewing plane, we can avoid getting into possible problems related to a specific source or source system. Of course, that is only true if the instrument used is capable of providing the necessary precision and accuracy. As it is known that the precision of a spectroradiometric system is the property of a specific instrument, and the accuracy of an instrument depends largely on its calibration. Because even CIE D50 is only a numerical standard, strictly speaking, no system can be said to have been calibrated to such a standard. Current Tungsten-halogen standard does not provide enough energy in the blue light region, and as a consequence, there are often large disagreements between different instruments in lamp chromaticity measurements.

Given the uncertainty level of a spectroradiometric measurement, the corresponding chromaticity uncertainty can be derived. One method is to derive the 95% confidence chromaticity ellipse or the error ellipse, based on spectroradiometric measurement uncertainty.[5] Spectroradiometric errors are usually systematically estimated for a specific instrument or measurement. For example, a National Institute of Standardization and Technology (NIST) spectroradiometric calibration may specify an uncertainty of 4%. The 95% confidence chromaticity for a 10% uncertainty in absolute spectroradiometric measurements (which is probably typical of current industrial practice) is derived for D50 and shown in Fig. 4 (the dot trace). The 3-step MacAdam ellipse (the dash trace) and the newer ISO tolerance (the solid trace) are again shown for comparison. Such an error can cause problem if the "true" chromaticity of illumination happens to fall in between the ISO/DIS 3664:1998 tolerance ellipse and the 3-step MacAdam ellipse. Unfortunately, this region covers about half the chromaticity tolerance ellipse as defined by the newer ISO standard. The enforceability of such a tolerance should therefore be concerned. For D50 source vendors, measurement errors occurred during the lamp manufacturing process, system component (reflector, diffuser and etc.) supplying/manufacturing process, and the final system assembling process may add up together to give an accumulated error range potentially larger than the tolerance defined by ISO/DIS 3664:1998.

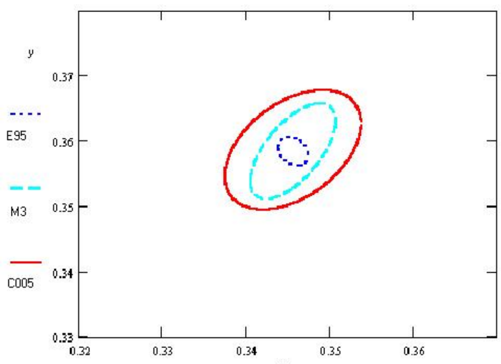

Fig.4. The 95% confidence ellipse (E95, dot trace) of the chromaticity coordinates for a spectroradiometric uncertainty of 10%, as compared to the 3-step MacAdam ellipse (M3, dash trace) and the newer tolerance (C005, solid trace) required by ISO/DIS 3664:1998 on the CIE 1931 chromaticity diagram.

The CIE Color Rendering Index

The CIE Color Rendering Index has been used to grade the color rendering property of general lighting for about two and a half centuries. Although the method has been subject to much criticism,[6] it has been widely accepted and used. It can be proven that as few as four narrow bands properly chosen in the visible spectral region can achieve a general CRI better than 90.[7] The CIE CRI method was intended to grade energy efficient lamps for general lighting purposes. The mid point of the index (50) is set for warm white fluorescent lamp. When the index approaches its full scale, it will lose its expected sensitivity for critical lighting evaluations. The usefulness of the color-rendering index can also be discounted if only the general CRI is used. Both versions of ISO 3664 require the CIE CRI evaluation: a general index no lower than 90; each individual index from sample 1 to 8 to be no lower than 80. Is the CRI method good enough for the graphic art industry? It would be helpful if we can examine how much rendering error we can encounter by using various D50 illumination sources.

Color rendering properties of general D50 fluorescent lamps

In addition to illuminant D50, CIE Publication 15.2 also includes the CIE F8, representing a broadband 5000K fluorescent lamp, and the CIE F10, representing a 5000K narrow-band fluorescent lamp.[8] F10 is probably the most deficient D50 lamp that one can encounter in the real world. Because the general rule for commercial lamps is that the lower the CRI, the higher the efficiency of the lamp, it is highly possible that F10-like lamps are involved somewhere in the color reproduction chain. In most cases, arbitrary D50 fluorescent lamps intended for color evaluation will fall in between the CIE F8 and the CIE F10. For comparison, a commercially available filtered tungsten-halogen D50 simulator is also included to compare the color rendering properties of other types of CIE D50 simulators.

The CIE D50, F8 and F10 will appear the same in color to the eye. However, when a color patch is viewed under one of these sources, the color appearances of the color samples will be different depending on the spectral reflectance of the color samples. The differences can be calculated given the spectral reflectance of the color sample and the spectral power distribution of the source. In this paper, the ubiquitous ColorChecker™ is used to calculate the color rendering properties of these sources. The spectral reflectance data of the ColorChecker™ were the production means measured over a period of seven years with a GretagMacbeth™ ColorEye™-545 spectrophotomer (45/0 measurement geometry). The data are from 360nm to 750nm at a 10nm interval. The instrument has a bandwidth of approximately 5nm. The colors rendered by different sources were calculated using the CIE 10° observer color matching functions and plotted on the CIE 1976 a*b* diagram for each color patch on the ColorChecker™ and shown in Fig.5.

It is not surprising that the higher the saturation of the color, the higher the deviations rendered by a D50 source from that by the CIE D50 illuminant. It is necessary to point out that the magnitudes of some of the deviations have to be discounted if the non-uniformity of the CIE a*b* diagram, especially the exaggeration of the calculated differences for some highly saturated colors, is considered.[9]

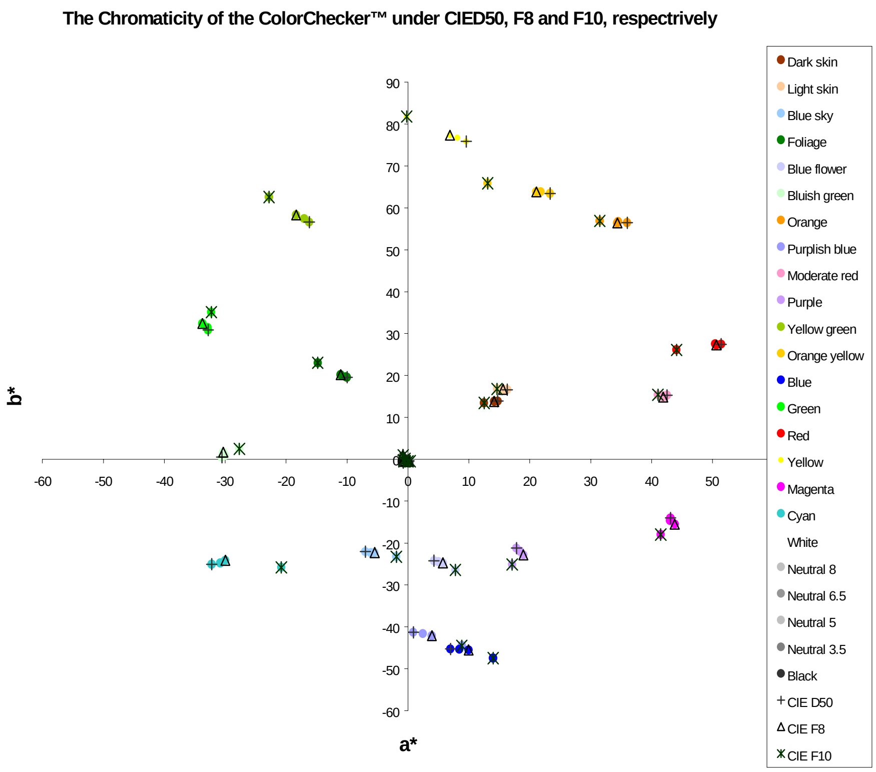

*Fig.5. Chromaticity of the ColorChecker™ on the CIE 1976 a*b* diagram viewed under the CIE D50, F8, F10 and a commercial tungsten-halogen CIE D50 daylight simulator, respectively. The symbol " + ", " Δ" and " * " represents the color coordinates under CIE D50, F8 and F10, respectively; For each cluster of dots, the unmarked dot represents the Tungsten-halogen D50 simulator.*

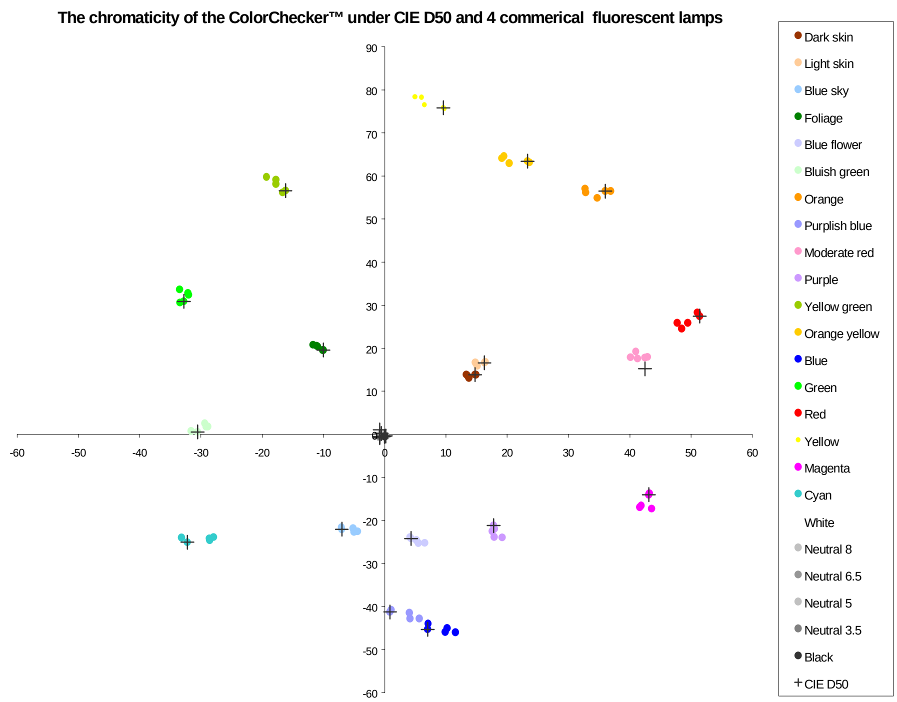

*Fig.6. Colors of the ColorChecker™ on the CIE 1976 a*b* diagram viewed under CIE D50 and 4 commercial D50 fluorescent lamps. For each cluster of color dots, the one that is marked by a "+" represents CIE D50; the other dots represent the four fluorescent lamps.*

In the case of F10, the chromaticity deviation can be as high as 10 units (CIELAB, CIELAB color difference scale will be used through this paper except specified otherwise), which will be extremely undesirable when the deviation is predominantly in hue. The filtered tungsten-halogen CIE D50 simulator shows the least rendering deviation. Colors that are affected in this manner include the Yellow, Orange, Purplish Blue and Cyan color patches. In comparison, F8 is much better source than F10. However, there still can be a hue deviation of 2-3 units for these same colors.

Color rendering properties of commercial D50 fluorescent lamps conforming to ISO/DIS 3664:1998

It will be desirable to examine how current popular D50 fluorescent lamps being supplied to the graphic art industry perform in terms of color rendering for the ColorChecker™. To demonstrate the effect, spectral data on available D50 fluorescent sources used by the joint group were used to calculate the rendered colors of the ColorChecker™. Only four of these sources that fully conform to the newer requirement according to the CIE MI assessment method (informative Annex C of ISO/DIS 3664:1998) will be used. The results were again plotted on the CIE 1976 a*b* diagram as shown in Fig.6. It can be seen that the chromaticity coordinates of some of the saturated colors rendered by these lamps have a significant spread. The chromaticity deviation can be as large as 5 units in the blue region. Most of these lamps deviate away from the CIE D50 illuminant.

Is the CIE CRI reliable?

In Fig.7, the average color deviations calculated above for CIE D50, F8, F10 and the four commercial D50 fluorescent lamps are plotted against the general CRIs of these sources. The correlation coefficient between the ColorChecker™ color deviations rendered by different D50 sources and the general CRIs of these sources is as high as 0.98. It would be interesting to test the correlation of the color deviations with the average of special CRI from 8 to 14, as provided by the CIE CRI method. The relationship is therefore also plotted in Fig.7 (dot trace). The corresponding correlation coefficient is 0.95, which is slightly lower than that for the general CRI (1 to 8). It seems that the general CRI is a good overall indicator of a D50 source's average color rendering capability.

However, in most cases, an average index may not be enough. ISO 3664 therefore requires each individual CRI from sample 1 to 8 to be no lower than 80, corresponding to a color difference of about 4 units (CIE 1964 U*V*W*). However, the special color rendering from sample 8 to 14 can be more important because they are more saturated and more easily affected by illumination. To examine the problem, the color deviations calculated from the minimum individual CRIs (1 to 8 and 1 to 14, respectively) for each D50 source are plotted in Fig. 8. Sources 1 to 4 are the commercial fluorescent sources mentioned earlier. Source 5 to 7 is the CIE F8, CIE F10 and the filtered tungsten-halogen D50 simulator, respectively. It is clear that large color deviations may exist for samples 1 to 8, as represented by the solid bars. If the smallest index is to be selected from sample 1 to 14, the deviations are more than twice as much, which should cause concerns.

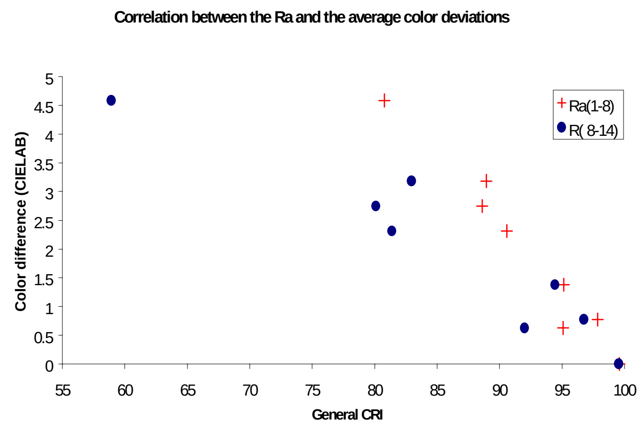

Fig.7. Correlation of the ColorChecker™ color deviations under various D50 sources versus the general CRI ("+") and the averages of special CRI (dot) from 8 to 14 of these sources, respectively.

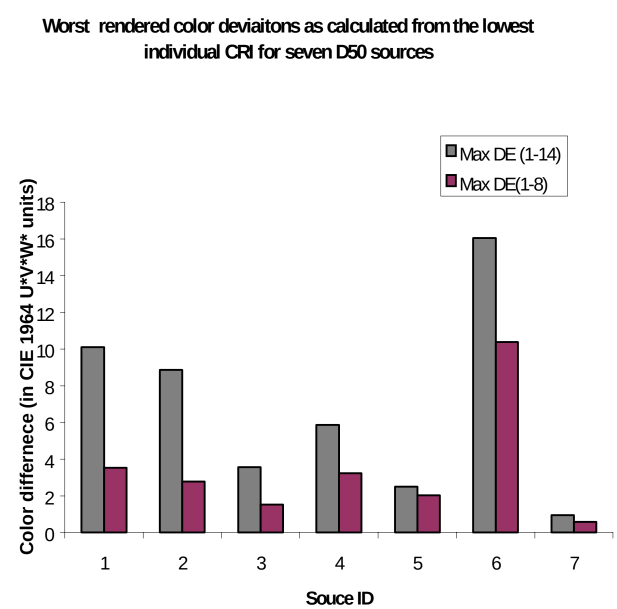

Fig.8. Maximum color deviations calculated from the CRIs of seven D50 sources. The solid bars represent the case that the lowest individual CRI was chosen from 1 to 8; the shadowed bars are for that from 1 to 14.

CIE Metameric Index Assessment Method

Because it has been known that the CRI is not a good parameter to gauge the performance of a CIE daylight simulator for color matching purposes, the CIE metameric index method for assessing the quality of daylight simulators is adopted in ISO/DIS 3664:1998. The CIE method involves the computation of color mismatches of five pairs of virtual metamers in the visible region and three pairs of virtual metamers in the UV region, for a corresponding CIE illuminant (CIE D50, in this case), when viewed under a daylight simulator.[2] The mismatch can be expressed in the CIELAB or CIELUV color differences to grade the simulator under test. A corresponding category scale from "A" to "E" is also recommended both for the visible index and the UV index. Because the method is for the assessment of daylight simulators that are intended for critical color matching purposes, a very fine scale is used (A: 0-0.25, B: 0.25-0.50, C: 0.50-1.00, D: 1.00-2.0, E: 2.0 or larger, in CIELAB). If converted onto the CRI scale, assuming CIELAB and CIE 1964 U*V*W* color difference formula are similar in scaling, a grading from A to C corresponds to the CRI range from 100 to 91. Therefore for D50 sources with the CRI over 90 (using the CIE D50 as the reference for CRI calculation), the MI will be more sensitive to distinguish which source is a better D50 simulator in spectral content.

In essence, both the CRI and MI are used to test the closeness of the spectrum of the simulator to that of the corresponding CIE illuminant. The CRI is intended to test the deviation of the final rendered color from that by the reference source. If there is a difference in spectrum between the CIE illuminant and the simulator, a color sample may appear different in color under the two illuminations, which can be quantified by CRI using the selected set of color samples. The MI is to test the degree of mismatch of a pair of metamers that match under the CIE illuminant. Therefore, the simulator may render the color of the metamer and the standard differently as compared to the CIE illuminant, but the simulator can still be a good simulator as long as the metamer color matches the standard color. From this perspective, the MI seems less stringent than CRI in terms of identifying the spectral difference. However, the CRI is historically set on a cruder scale while the MI is scaled according to the color discrimination threshold of the human visual system.

The correlation between the CRI and the MI_{vis}

The visible metameric indices of the seven sources discussed above are calculated using the metamers given in ISO/DIS 3664:1998. They are plotted against the general CRIs of these sources as shown in Fig. 9. It seems that there is a good correlation between the two indices (the correlation coefficient is about 0.91). However, for two out of the four D50 fluorescent lamps, the MI is better than 1 or "C", their general CRIs are lower than 90.

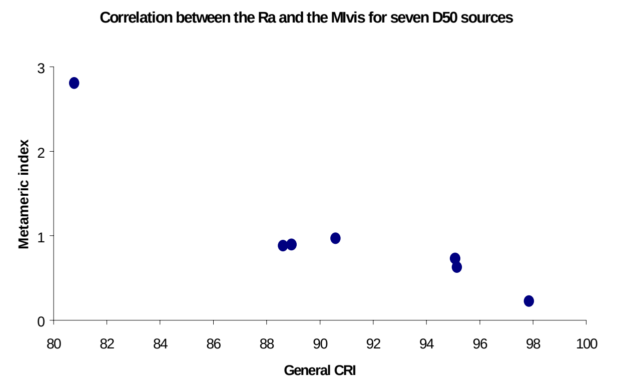

Fig.9. Correlation between the general CRI and the MI for the seven D50 sources.

"Individual" MI_{vis}

Similar to the general CRI, the MI_{vis} is also an average of five individual color differences. However, each pair of metamers was chosen to test the spectral deviation between the CIE illuminant and the source under test with colorimetric weighting across the visible spectrum, which is different from the CRI. Each sample in the CRI evaluation tests the spectral content of the source for a specific spectral range. Still, it will be interesting to compare the maximum color difference of the five metamer pairs with that of the average. The largest color differences (mismatch for the metamers) among the five pairs of metamers for each D50 sources are selected and plotted in Fig.10 together with the averages (the CIE MI_{vis}). It can be concluded that the maximum color difference among the five metamer pairs is consistent with the CIE MI_{vis}.

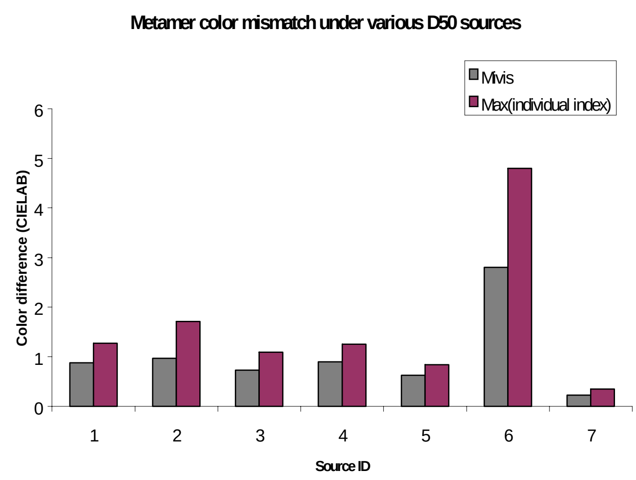

Fig.10. Color differences for the five pairs of the CIE D50 metamers under various D50 sources. The solid bars represent the maximum color difference out of the five metamer pairs; the shadowed bars represent the average color differences of the five pairs of metamers or the CIE MI_{vis}.

The tolerance on UV performance

Because of the use of fluorescent agents in paper and colorants, daylight simulation should also include the simulation of the ultraviolet region. The UV index is also the average of three individual indices. Each individual index is more sensitive to one of the three spectral bands divided from 300nm to 400nm. ISO/DIS 3664:1998 also adopts the UV MI but only requires the index to be lower than 4. If we set the CIE D50 spectral data to 0 from 300nm to 400nm, the UV index can be calculated to be 3.3. That is to say, the limit of an index value of 4 is meaningless. That is equivalent to say that ISO/DIS 3664:1998 does not impose a limit on the UV content of D50 illuminations.

It is known that the majority of commercial D50 fluorescent lamps do not simulate the UV component of the CIE illuminant. Therefore, for samples with significant amount of fluorescent agents involved, sources meeting ISO/DIS 3664:1998 may not be the proper source at all. Under these cases, a tighter UV index limit should be used.

Summary

Illumination standardization is not an easy task. It is hoped that this paper will prepare the readers for a clearer understanding of what the newer standard assures in term of D50 illumination and the potential difficulties in its implementation.

Chromaticity

Given the nature of fluorescent lighting and the current capability in spectroradiometric measurement, the newer tolerance on chromaticity in ISO/DIS 3664:1998 is probably too tight if we are to conduct traceable chromaticity measurement. The human eye can indeed easily challenge the spectroradiometric measurement in terms of precision, when it comes to direct comparison. However, for those who concern about the loose tolerance on chromaticity of D50 illumination probably can be satisfied as long as all D50 sources or lamps presented in their immediate viewing vicinity meet a tight chromaticity tolerance. Their chromaticity coordinates need not necessarily to be within the 0.005 unit chromaticity circle on the 1976 UCS diagram when measured by traceable measurement.

Color Rendering Index

The general CRI can be useful to represent potential color rendering errors of D50 sources. It must be remembered that D50 sources conforming to ISO/DIS 3664:1998 can produce large color rendering errors for some saturated colors. The problem can cause concern in some situations such as that when a print or a transparency is compared to its softcopy on a CRT monitor. It seems like for critical color rendering, a refined (on a finer scale) CRI evaluation method is need for daylight sources.

Metameric Index

The MI_{vis} will serve as a useful index to assess a D50 source for color matching purpose. Because the index is intended for the evaluation of daylight simulators for critical color matching purpose, most fluorescent lamps D50 sources will score around 1. How important is the difference between a value of 0.8 and 1.2 in CIELAB? It can be reasonably speculated that a set of metamers for CIE F8 may be more pertinent for the graphic art industry, although the joint working group has enough reasons to disfavor it for the moment. As for the UV index, a MI_{uv} value of 4 imposes no meaningful restriction on the UV component of D50 sources at all.

Acknowledgements

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