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Standards for illumination of digital prints and photographs

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Abstract. Standards for illuminating digital prints and photographs have a number of quite different applications. In the graphic arts industry, the main applications are defined as appraisal and critical comparison, for which 500lux and 2000lux are specified in ISO 3664. In the museum world much lower levels of illumination are imposed when artefacts are considered to be prone to damage from such exposure. For display and storage of photographic prints, BS 5454:2000 is applicable and specifies maximum levels of 50 lux and 200 lux respectively. While these standards provide recommendations for exposure to radiant energy with the goal of limiting damage to materials and maximising visual discrimination, there is a need for more data on the radiative damage spectrum for the materials used in digital prints and photographs and other artefacts, and on the viewing conditions which can maximise visual performance for specific tasks. It is recommended that radiative exposure is measured in watts per square metre instead of lux to give a better indication of the propensity for radiative damage of a given illumination source.

1. Introduction
Viewing conditions for the display of reflective artefacts such as digital prints and photographs have three independent and potentially conflicting goals: first, to display the prints which is maximally satisfying for the viewer and which enables the artistic intent of the creator to be conveyed; secondly, to minimise the radiative damage which might arise in the viewing environment; and thirdly to achieve the most sustainable display possible by minimising the energy required in the display.

2. Performance on visual discrimination tasks
User satisfaction is difficult to quantify directly, and therefore it is preferable to measure performance on visual discrimination tasks under different lighting conditions. The ability to perform a visual discrimination task is of course dependent on characteristics of the human visual system, such as spectral sensitivity, luminance-level adaptation, and contrast sensitivity. It is also possible to evaluate lighting conditions by measuring observer preferences for reproductions under the different conditions, although this approach introduces additional elements of subjectivity.

From the literature on psychophysics (including the Weber-Fechner Law and Steven's Law [1]) it can be deduced that the perceived difference between two reflective stimuli increases as the incident illumination increases. However, relatively little work has been done to test this assumption systematically under real viewing conditions. It has recently been reported [2] that observer performance in detecting a 3 CIELAB $\Delta E^*_{ab}$ threshold difference actually fell as illuminance increased, and the optimum illuminance for this threshold detection task was approximately 600 lux. It is not clear why performance fell at high illuminance levels in this case, but it is possible that glare on
the prints influenced visual perception despite the notional geometry of the viewing booth being
designed to minimise this possibility.

The quality of a lighting source for visual discrimination is usually measured by the CIE Colour
Rendering Index [3] (CRI), which for a set of standard reflectances compares the visual response
under a reference and test illumination spectral power distribution. A CRI of 100 indicates a perfect
match, while a CRI > 90 indicates a good match. The CRI does not indicate the absolute ability of a
human observer to discriminate between two stimuli, but the predicted closeness of the match under
two different viewing conditions; so for example a tungsten source may have a CRI close to 100
relative to the reference CIE Illuminant A, but observers may perceive threshold colour differences
better under an illumination source with a higher correlated colour temperature.

The visual discrimination performance required in different display applications varies
considerably, from basic recognition of high-contrast shapes, through perception of tonal differences
in monochrome photographs and documents, recognition of basic colour categories, colour preference
judgements, through to fine discrimination of small tone and colour differences. This suggests a finer
granularity in the specification of viewing illuminances, and further research to support such
specifications. For certain tasks (such as viewing historic documents) it may not even be necessary to
have illumination at the photopic level, which suggests adapting luminances below 10 candelas per
square metre (cd m⁻²) may be feasible.

3. Light sources, efficacy and visual performance

Current drivers of new developments in lighting technology today include the environmental
imperative for greater efficacy, and the potential for improved colour rendering quality. For the
purpose of viewing photographs and prints we can now add commercially-available LED light sources
to the traditional incandescent and fluorescent lamps.

Although fluorescent lamps have a spectral emission characterised by narrow-band spikes, by
adjusting the phosphors used to coat the tube manufacturers are able to produce fluorescent lamps with
a high CRI relative to CIE daylight illuminants. Currently lamps with a CRI of 98 and above relative
to CIE D50 are commercially available [4]. Fluorescent lamps have efficacies of up to 50 lumens per
watt (lW⁻¹), compared with around 15 lW⁻¹ for incandescent.

LEDs tend to have more broadband emissions, and white LED sources are manufactured from a
combination of two or more LEDs to give complete coverage of the visual spectrum. In some systems
the output of three or more LEDs can be independently controlled to modulate the overall spectral
power distribution, although it is still difficult to match to reference illuminants and CRIs are below
90. Although LEDs have a greater apparent efficacy (achieving over 50 lumens per watt in
commercially-available packages and reportedly over 200 lW⁻¹ in the lab [5]), they produce a more
directional emission which requires diffusion for illumination of photographic displays, and a
consequent loss of efficiency. Commercially available LEDs also suffer from a loss of efficacy as
current increases.

As yet LED lamps have made little impact in the photograph display and conservation fields. For
both fluorescent and LED sources, the spectral power distribution differs very considerably from
traditional incandescent sources, and the lux measure used to quantify illuminance does not adequately
convey the propensity for radiative damage in such cases, as is shown below.

Fluorescent lamps have several sharp peaks in their relative spectral power distribution. Most such
lamps exhibit strong peaks at approximately 405 and 437nm, arising from the emission of the mercury
vapour of the lamp. ‘White’ LEDs used as illumination sources are commonly InGaN blue LEDs with
a strong peak at approximately 465nm, combined with a phosphor coating to generate emission in the
green and red regions.

It is possible that the presence of these strong peaks in the short-wavelength region of the visual
spectrum in LED and fluorescent lamps may accelerate radiative damage of certain materials.
4. Standards for viewing photographic prints

For viewing photographs and prints, applicable ISO standards that are published or in development are:

- ISO 3664:2009 Graphic technology and photography — Viewing conditions [6]
- BS 5454:2000 Recommendations for the storage and exhibition of archival documents [7]
- ISO 18937:2010 (WD) Imaging materials — Photographic reflection prints — Methods for measuring indoor light stability [8]

4.1. ISO 3664:2009

ISO TC 42, working jointly with ISO TC 130, has recently revised the graphic arts viewing standard ISO 3664, which defines viewing conditions for practical appraisal and critical comparison of prints and other media. This new revision provides a clearer definition of the reference illuminant and the procedures to be used to evaluate simulators of that illuminant. Such a definition is of great importance in graphic arts, since the determination as to whether a reproduction is a good visual match to a proof or original requires a precisely standardised viewing condition to avoid the possibility of false matches or false rejections.

The reference illuminant is defined to be the CIE D50 daylight illuminant, whose spectral power distribution is given over the range 300-780nm. Illumination levels for critical comparison (P1) and practical appraisal (P2) conditions are defined as 2000 lux and 500 lux respectively, with tolerances of 500 and 125 lux.

As ISO 3664:2009 is concerned with optimising the appearance of hard copy prints and photographs, it specifies that the viewing illumination should have the same effective UV content as that of the D50 reference illuminant, in order to achieve the higher brightness and whiteness levels intended by the manufacturers of the substrates used.

In addition to illuminance and uniformity specifications, ISO 3664:2009 defines the performance of viewing illumination in terms of three indicators: the CIE Colour Rendering Index, the CIE Metamerism Index for the visible spectrum (MI_{VIS}), and the CIE UV Metamerism Index (MI_{UV}). The MI values are based on the predicted colour difference between two standard reflectances which match under certain SPDs, when illuminated by a test and reference illumination SPD. The MI_{UV} value provides an indirect measure of the relative UV content of the source, which is important in many print viewing applications where fluorescent media are used and the total reflectance has a significant fluorescent component.

To ensure consistency in the computation of CRI, MI_{VIS} and MI_{UV} values, ISO 13644:2009 provides a detailed computational procedure. As with the CRI, MI_{VIS} and MI_{UV} values are relative to the reference illuminant CIE D50.

The 2000-lux illuminance specified in ISO 3664:2009 P1 viewing condition corresponds to an adopted white luminance of 637 cd m^{-2}, which compares with a typical display luminance of 80-120 cd m^{-2} and an adopted white luminance in a more typical 300-500 lux viewing environment of 95-160 cd m^{-2}. The higher level needs additional evidence to justify it given the propensity for radiative damage and the greater energy consumption associated with it.

4.2. BS 5454:2000

BS 5454:2000 is primarily concerned with media of long-term significance. It recommends a maximum of 200 lux for display of materials with lower light sensitivity such as carbon black inks, and a lower 50 lux level for light-sensitive materials. It recommends a total exposure of 18,000 lux (18Klux) hours, and states that illumination should have a maximum of 10 watts of UV radiation per lumen of visible light. For viewing while in storage (for example for conservation purposes) an illuminance of 100-300 lux is recommended. Exposure to UV is limited to a maximum of 10 watts in the UV region per lumen of visible light.
In setting 18Klux total exposure complete reciprocity is assumed, as it is stated that "exposure of a document to 50lux for 10hrs is likely to cause the same deterioration as exposure to 500lux for one hour". However, reciprocity failure in radiative damage has been shown to exist [9-12].

4.3. ISO 18937
ISO 18937 is still under development. Its scope is to specify methods and procedures for measuring the indoor light stability of colour photographs. It specifies a range of test illumination conditions, sources, and associated longpass filters to control UV content of the illumination.

The viewing conditions, and associated illumination intensities, currently included are:

- indoor daylight (30-80klux)
- direct sunlight in-window (50-100klux)
- cool white fluorescent (30-80klux)
- other sources i.e. compact fluorescent, tungsten, LED, OLED, metal halide and others (20-80klux)

It is noted in ISO 18937 that reciprocity failures may occur in high-intensity light fading tests, and that "the closer accelerated test conditions are to actual use conditions, the more meaningful the test results become".

ISO 18937 also specifies humidity and temperature control for accelerated exposure tests, which are important as it has been shown that their effects can be significant [13].

5. Radiative damage to reflective media
Optical radiation induces a colour change in printed inks and papers. Such changes are usually in the direction of reduced contrast and colourfulness, and are therefore almost always undesirable. Some degree of change, such as a slight yellowing of the paper, is inevitable as documents age, but the goal of the conservator is to minimise such damage and preserve the appearance of the object with as much fidelity to the original as possible.

Oxidative changes to inks, quenching of fluorescent whitening agents and other changes are distinctly more likely with UV radiation than visible light, and since shorter wavelengths are more energetic it is often assumed that the degree of damage is a continuous function of wavelength. This assumption is broadly supported by experimental results [14, 15], but there is insufficient data on the damage-activation spectra of dyes, pigments and other materials to rely on the assumption and there remains the possibility that some materials may be selectively affected by wavelength.

Radiation intensity levels for viewing of photographs and prints is normally measured and specified in terms of photopic illuminance, whereby the irradiance is weighted by the CIE photopic luminous efficiency function over the range 360-830nm. The units of illuminance are lux. A measure in lux therefore correlates with the amount of light energy available to the human visual system, but not to the total radiative energy, since photopic luminous efficiency has a Gaussian-like shape that peaks at 555nm and asymptotes to zero at the red and blue ends of the visible spectrum.

6. Spectral power, correlated colour temperature and propensity for radiative damage
Figure 1 shows the spectral power distribution (SPD) of the radiant exitance of black body (or Planckian) radiators at four selected correlated colour temperatures, from 3000 to 6000 K. At 3000 K the SPD is very similar to that of unfiltered tungsten, while at higher CCTs the SPDs approximate that of natural daylight.
According to ISO 3664:2009, 'The human visual system is excellent at adapting to the colour temperature of illumination sources which approximate a Planckian radiator between 3000K and 6000K.' However, at low power such adaptation may not be complete and for example a source with a correlated colour temperature (CCT) of 3000K may appear yellowish, while a CCT of 6000K may appear bluish [16]. Daylight simulators with CCTs of 5000-6500K are in widespread use and are standardised in many industries such as paint, textile and papermaking. The CIE Colour Rendering Index defines the agreement between the spectral power distribution of a source and a reference illuminant of a similar CCT, but the illuminant used as reference can be any published illuminant; for example a low-power tungsten lamp will have a high CRI against a reference Illuminant A, but may lead to relatively poor visual discrimination of blue and green colours.

In a black body radiator, at higher correlated colour temperatures (CCT) the relative power at short wavelengths increases, as does the luminous efficacy. Hence the balance is between greater visual performance and energy efficiency against the likelihood that a higher proportion of more damaging short-wavelength radiation will be present.

While ISO 3664:2009 is primarily concerned with graphic arts viewing, Informative Annex C suggests that a CCT as low as 2800K and an illuminance as low as 375 lux are acceptable for exhibiting photographic prints.

Table 1 gives the illuminance (in lux), radiant exitance (in watts per square metre) and photon count (x 10^{18}) for the four black body radiators in Figure 1, in three wavelength ranges: the visible, the UV-A region and a short-wavelength region of the visible spectrum.
Table 1. Properties of black body radiators (normalised to 1.0 watt m\(^{-2}\) at 560nm)

| CCT (Kelvins) | 3000 | 4000 | 5000 | 6000 |
|---------------|------|------|------|------|
| Photopic illuminance of black body radiator (lux) | 7315 | 7185 | 7192 | 7231 |
| Radiant exitance of black body radiator over visible spectrum 380-700nm (watts m\(^{-2}\)) | 29.93 | 28.85 | 30.00 | 31.72 |
| Radiant exitance of black body radiator over short-wavelength region of visible spectrum 380-450nm (watts m\(^{-2}\)) | 1.86 | 3.80 | 5.87 | 7.86 |
| Radiant exitance of black body radiator over UV-A region 310-400nm (watts m\(^{-2}\)) | 0.81 | 2.47 | 4.97 | 7.80 |
| Photons sec\(^{-1}\) over visible spectrum (x 10\(^{18}\)) | 89.84 | 82.61 | 82.90 | 85.36 |
| Photons sec\(^{-1}\) over short-wavelength visible (x 10\(^{18}\)) | 3.97 | 8.02 | 12.34 | 16.46 |
| Photons per second over visible + UV-A (x 10\(^{18}\)) | 90.49 | 84.98 | 88.15 | 94.33 |

It can be seen that the black body radiators are normalised in such a way that the illuminance, radiant exitance and photon count values are very similar for all four CCTs. However, it can be seen from Figure 1 that the four radiators have very different relative power levels in the short-wavelength (blue) end of the visible spectrum. Clearly the black body radiators with higher CCTs have significantly more power in the shorter wavelengths.

Unless there is a wavelength-selective damage spectrum, it is likely that radiative damage correlates with the number of photons incident on the surface. The photon count in Table 1 was determined for the SPDs shown in Figure 1 from Planck's equation \(E = hv\) or \(E = hc/\lambda\), where \(c\) is the speed of light, \(\lambda\) is its wavelength and \(h\) is Planck's constant.

Although the propensity for damage continues to increase at shorter wavelengths than UV-A, this can be discounted for photographic display since oxygen in the atmosphere efficiently blocks the lower wavelengths, and glass used in windows and the envelopes around light sources is also normally opaque to the shorter wavelengths.

Table 1 suggests that the lux measure is likely to be a good predictor of the propensity for radiative damage for those sources which are similar to black body radiators and are filtered to remove wavelengths below 380nm. However, other sources, especially those with a higher proportion of short-wavelength energy, are likely to have a different and possibly higher propensity to cause radiative damage. For example, fluorescent lamps have a sharp peak in the relative spectral power distribution at 437nm and 'white' LEDs emit strongly in the blue region, at a peak wavelength which depends on the type of LED used.

7. Conclusions

Existing standards for the illumination of digital prints and photographs have focused on either the maximising visual performance or on limiting radiative damage, and for most applications there is a need to achieve a balance between these.

Recent work on the standardisation of conditions for the display of photographs and prints improve the definition of illumination sources for the goals of maximising visual performance and minimising radiative damage. However, certain assumptions are made in these specifications which require further evaluation. In particular, further work is needed to understand:

- the radiative damage spectrum for the materials used in digital prints
- the illumination levels and spectral power distribution which lead to optimum visual performance

Greater specificity is needed in the available data so that it is possible to select optimum illumination levels and spectral power distributions for particular applications. The requirement to maximise the
energy efficiency of illumination also imposes a requirement to understand the minimum illumination intensities required for a given visual task.

Given that a simulator of daylight illumination is likely to give better performance on visual discrimination tasks, light source quality should in the absence of further data be defined in terms of the CRI and MI values relative to a reference D50 illuminant.

The propensity for radiative damage varies over the electromagnetic spectrum and for many sources the conventional lux measure may not adequately express this. Hence the use of watts m⁻² is recommended in preference.

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