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2.1: *Invited Paper:* Daylight and Sunlight Display Readability Measurement Methods

Edward F. Kelley,*
National Institute of Standards and Technology, Boulder, Colorado, USA; kelley@nist.gov
Max Lindfors, and
Nokia, Helsinki, Finland; Max.Lindfors@nokia.com
John Penczek
DuPont Displays, Santa Barbara, California, USA; John.Penczek@usa.dupont.com

Abstract: *We propose a composite measurement method to characterize display performance and readability under both daylight and sunlight illumination. The measurements are performed separately in a laboratory, then combined and scaled to daylight and sunlight levels. Measurements of the low-resolution bidirectional reflectance distribution function can be included to simulate hand-held-display utilization.*

Key Words: contrast, daylight readability; display measurements; display readability; display reflection measurements; dynamic range, low-resolution BRDF measurements; maximum readability; sunlight readability

Introduction

High demand exists for sunlight-readable displays. At present the term "sunlight-readable" is ill-defined. Often the display is placed outdoors in bright sunlight to see if it can be read easily. This is not objectionable, but it is not reproducibly quantifiable. However, to simply point a sun-level light source at a display where the source is placed at a substantial angle from the normal is not representative of daylight conditions. Such an arrangement neglects the contribution from a diffuse surround. We propose a general method to characterize the dynamic range, contrast, and readability of a display under daylight conditions. This paper is a preliminary attempt to document measurement standards for daylight testing of displays. As such, these methods may not be applicable to all displays and may be regarded as areas for further research.

The techniques discussed in this paper are to be performed in the laboratory. Both uniform diffuse illumination and directed illumination from a discrete source are made separately and then combined and scaled mathematically to approximate the response to daylight levels.

Sources for Daylight

As used in this paper, daylight is a combination of blue skylight and direct sunlight. For skylight, we will scale the measurement results for a uniform diffuse illumination with an illuminance level of $E_a = 10^4$ lx. For direct sunlight we will scale the measurement results for directed illumination at an illuminance level of $E_{sun} = 10^5$ lx. However, please note that different levels of illuminance and luminance may be appropriate for different applications. We propose that if no illuminance or luminance levels are quoted with the results then the above levels shall be assumed. If other levels of illuminance or luminance are used, then they must be included with the reported measurement result.

Source Spectra: The spectra and color temperatures of the light sources used are important *only* if there is significant color to the display or if the display exhibits fluorescence. For these occasions where an accurate spectrum is required, we propose the use of a skylight spectrum corresponding to a color temperature of 17 000 K and a sunlight spectrum corresponding to a color temperature of 5500 K. [1] Laboratory tungsten-halogen sources can often be converted to these color temperatures by means of colored filters (e.g., photographic color-conversion filters 80A, 80B, 80C, 80D, or light-balancing filters 82, 82A, 82B 82C). Such filtration maintains the broadband nature of the daylight sources. If there is fluorescence in the display components, then the correct broadband illumination spectrum must be used. If there is no fluorescence, then the filtration can be placed in front of the luminance meter; this avoids the possibility of heating the filter material and thereby changing its spectral transmission when placement of the filter near a hot lamp is attempted.

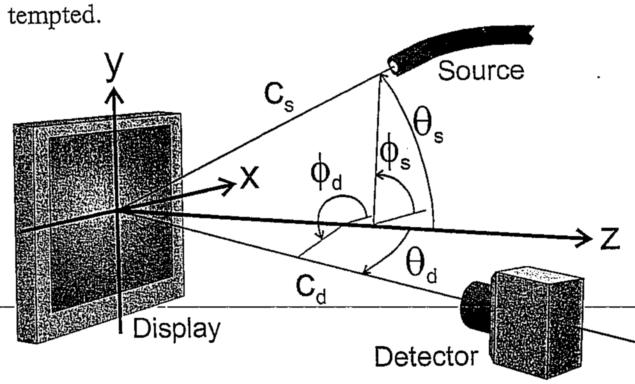

Figure 1. Coordinate system with a small discrete source at angles (θ_s, ϕ_s) and detector at (θ_d, ϕ_d).

Determination of Reflection Parameters

The Cartesian coordinate system relative to the center of the screen is shown in Fig. 1 with spherical-polar coordinates locating the source (θ_s, ϕ_s) and detector (θ_d, ϕ_d). The distance to the center of the source is c_s and to the center of the detector is c_d. The reflection parameters are determined in several steps:

First, for emissive displays, a darkroom measurement is made of the full-screen white luminance L_W and the full-

* Optoelectronics Division, Electronics and Electrical Engineering Laboratory, Technology Administration, U.S. Department of Commerce. This is a contribution of the National Institute of Standards and Technology and is not subject to copyright.

screen black luminance L_K at center screen. (These luminances are zero for purely reflective displays.)

Next, to make the diffuse-reflectance measurement we place the display inside an integrating sphere (or equivalent, such as a properly illuminated hemisphere), where the luminance of the center of the display is measured from 6° to 10° from the normal; typically we use 8°—see Fig. (2). We configure the screen to show full-screen white. At (or near) the center screen we measure the illuminance E_h and the luminance L_h with reflections. The diffuse reflectance ρ_W for the white screen is

$$\rho_W = \pi(L_h - L_W)/E_h \, ; \qquad (1)$$

similarly for the black full screen,

$$\rho_K = \pi(L_u - L_K)/E_u \, , \qquad (2)$$

where L_u is the reflected luminance including the screen luminance and E_u is the illuminance at (or near) screen center. The quantities in parentheses are the net reflected luminances. With the uniform diffuse source, the illuminance measurement can be made by use of either a white reflectance standard ($E_{std} = \pi L_{std}/\rho_{std}$, where $\rho_{std} \approx 0.99$) or an illuminance meter. Caution is in order to be sure that neither the white standard nor the illuminance meter is so near the center of the screen that it interferes with the illuminance hitting the screen. Additionally, the white standard or illuminance meter must be in place when the screen luminance is measured, so that both the luminance and illuminance are measured at the same time without changing the internal configuration within the enclosure or integrating sphere.

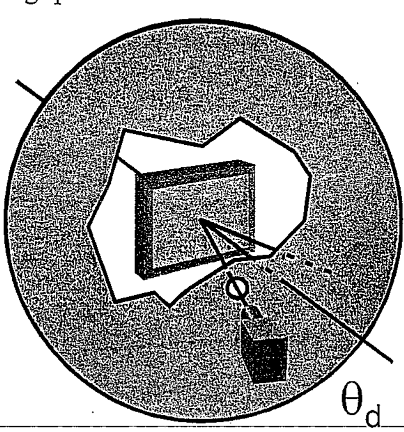

Figure 2. Diffuse-reflectance measurement with detector at angle θ_d from the normal (from 6° to 10°); configuration shown is for ϕ_d = 180°.

Note that in practice, when the uniform diffuse measurement is made on displays that emit polarized light, the (unpolarized) illuminance from the uniform diffuse source should be much greater than the back-reflected illuminance arising from the display. If not, it is possible that the display-emitted polarized light reflecting off the walls of the enclosure and back onto the display may create some nontrivial errors.

Next, the display is removed from the uniform diffuse source, and a discrete source is used to simulate the sun illumination. This measurement is performed in a darkroom, with the illuminances measured in the plane of the screen, and not by positioning the illuminance meter so that it faces toward the source (if using a source-directed illuminance measurement, we must multiply the result by $\cos\theta_s$ to get the proper illuminance hitting the screen from angle θ_s). For a source not in the specular direction, the luminance factor for a white full screen is

$$\beta_W = \pi(L_b - L_W)/E_b \, , \qquad (3)$$

where L_b is the luminance including reflections and E_b is the illuminance at center screen. Similarly for the black full screen,

$$\beta_K = \pi(L_n - L_K)/E_n \, , \qquad (4)$$

where L_n is the luminance of the black screen including reflections and E_n is the illuminance at screen center.

Note that if there are not differences in the reflection properties of the on-state vs. the off-state of the display, then the display need not be measured in its on-state, and the reflection parameters can be measured with the display off. A CRT (cathode-ray-tube) display is such an example. For such cases $\rho = \rho_W = \rho_K$ and $\beta = \beta_W = \beta_K$.

Regarding illuminance measurements for the discrete source: The illuminance must be measured at the same location at which the luminance is measured. Often this requires the display to be moved and an illuminance meter put at the former position of the screen center. Alternatively, the illuminance normal to the source (at a large distance c_s) can be measured separately and corrected to the illuminance on the display by multiplying by $\cos\theta_s$. In any case, the illuminance should not be measured by the use of a white diffuse standard unless a specific geometric calibration has been performed for that geometry. Their reflectance values near 0.99 are based upon using a uniform diffuse source, not a directed one. We suggest using an illuminance meter with good cosine correction.

Finally, these results are scaled to daylight levels by use of the diffuse reflectances and the luminance factors to obtain the luminance of full-screen white, K_W, and black, K_K, under the specified daylight conditions with the sun at angle θ_s from the normal:

$$K_W = L_W + \rho_W E_a/\pi + \beta_W E_{sun} \cos\theta_s/\pi \, , \qquad (5)$$

and

$$K_K = L_K + \rho_K E_a/\pi + \beta_K E_{sun} \cos\theta_s/\pi \, . \qquad (6)$$

In all conditions the luminance meter lens is focused on the surface of the display because no specular configuration is specified for the measurements in this paper. (Specular measurements with small sources are problematic and difficult to make reproducible and robust. [2]) Note that the luminance factors β can change depending upon the discrete-source configuration whereas the diffuse reflectances ρ are fixed for each display

Reflected Luminance Levels: In general, for emissive displays, the source of illumination should be sufficiently bright so that the reflected luminance L is much greater than the darkroom white luminance L_W; that is, $L >> L_W$.

If this is not the case, and if the luminances are measured with different luminance meters, there can be significant errors introduced when subtracting similar luminances to determine the net reflected luminances that provide the reflection coefficients. However, if the *same* luminance meter is used, and the linearity of the luminance meter is very good over the ranges of luminances measured with sufficient resolution, then the requirement placed on the source luminance can be relaxed somewhat because the luminances are no longer independent. For some displays when a discrete source is far away from the normal ($\theta_s \geq 25°$) the required luminance of the source can be extraordinary in order to get reproducible results. In any case, better results can always be achieved with brighter sources.

Dynamic Range and Contrast: At this point it would be tempting to define an ambient dynamic range or full-screen contrast ratio under specified ambient conditions [3],

$$D = K_W / K_K \,. \qquad (7)$$

Related to such a dynamic range or full-screen contrast ratio is the contrast,

$$C \equiv (L_{max} - L_{min})/L_{max} = (K_W - K_K)/K_W = (D-1)/D. \quad (8)$$

However, readability is not dependent only upon contrast; more is needed.

Readability Issues

Readability depends, in a complex way, on the contrast, the luminance, the character height, and the age of the reader. For the purposes of this paper, we will define a simplified, approximate, step-by-step procedure suitable for use with daylight measurement methods.

We employ the contrast definition that is used in the CIE 145 Visual Performance Model [4]:

$$C = |L_{ave} - L| / L_{ave} \,.$$

There are two cases to consider, positive polarity, with black letters on a white background (the default case), and negative polarity, with white letters on a black background. For the default case with black letters and a white background (positive polarity), $L = K_K$ is the luminance of black with reflections included, and L_{ave} is the local average luminance of the black text with a white background with reflections included [5]:

$$L_{ave} = 0.75 K_W + 0.25 K_K \,; \qquad (9)$$

and the contrast becomes

$$C = \frac{|0.75K_W - 0.75K_K|}{0.75K_W + 0.25K_K} = \frac{|K_W - K_K|}{K_W + (K_K/3)} \,. \qquad (10)$$

In order to include the effects of luminance, character height and viewer age, we use the relative visual performance (RVP) model described in CIE 145. [4] The RVP value P is between zero and one, $0 \leq P \leq 1$, where $P = 1$ is normalized to the performance level of a young adult reading critical detail sizes of 4.5' (minutes of arc) with an average luminance of 1000 cd/m^2. $P = 1$, or 100 %, means that reading is 100 % accurate.

For our simplified case, we fix the critical detail size to 1.5' of arc, which represents the size of stroke widths, diacritics, and punctuation of small font sizes common on many electronic displays (for a 400 mm viewing distance, a 1.5' mark would be 0.17 mm high and a typical character height might be 1.7 mm to 2.3 mm [15' to 20']). Using this critical detail size and the information in CIE 145, we can generate a family of curves for each age group. In Fig. 3 we show the curves for 25-year-old adults. The RVP P-value is the ordinate, the curves are labeled according to the appropriate contrast, and the abscissa is the average luminance level.

Readability in positive polarity (black text on white): First calculate the average luminance and contrast according to Eqs. (9) and (10). Then find the RVP value from the appropriate diagram for the luminance and the contrast for the appropriate age group.

This procedure provides a simplified step-by-step way of calculating the readability in daylight ambient conditions. Readers needing more detailed predictions of the readability are advised to use the formulas published in CIE 145. These formulas enable predictions for a wide range of luminance levels, character sizes, and user ages.

For example, suppose our daylight luminances are $K_W = 800$ cd/m^2 and $K_K = 250$ cd/m^2; then the average luminance is $L_{ave} = 623$ cd/m^2, and the contrast is $C = 0.62$. For a 25-year old adult (discerning 1.5' detail), the RVP or readability is $P = 0.95$, or 95 %. To do the same thing using the graph (not shown) for a 75-year old would result in a readability of $P = 0.48$, or 48 %.

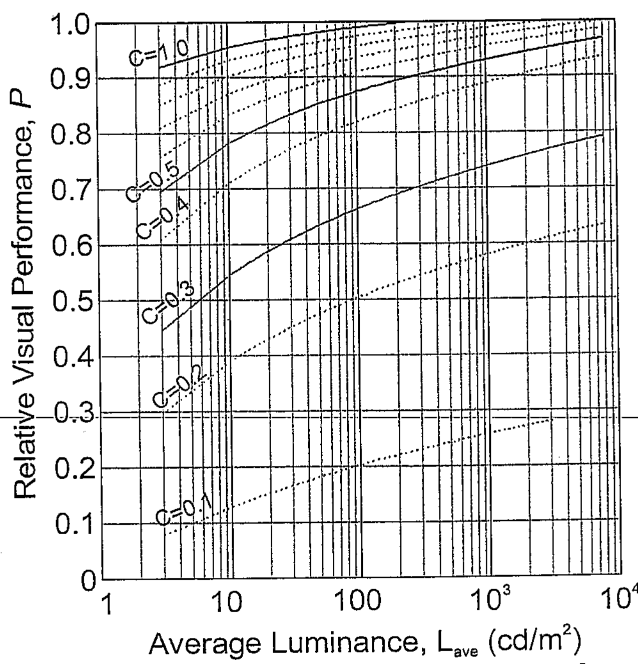

Figure 3. CIE RVP for 25-year-old adults as a function of contrast and average luminance.

The perception of images is even more complex and beyond the scope of this paper. Models exist that can be applied for analysis of image quality in ambient lighting. [6, 7]

Readability in negative polarity (white text on black): To roughly estimate the readability in negative polarity, multiply the RVP for the positive polarity with 0.9. This degradation value of 0.9 is an experience-based coefficient that is in line with published research. [8, 9]

Daylight-Sunlight Measurement Methods

Many methods can be described, but two methods in particular seem to represent typical situations that could be encountered under sunlight conditions.

45°-Sun Measurement Method: The 45°-sun measurement method consists of making a measurement of the white and black screens under two illumination conditions. A uniform diffuse ambient measurement obtains ρ_W and ρ_K to simulate a skylight surround. The second measurement is of the luminance-factors β_W and β_K assuming that the center of a discrete source is $\theta_s = 45°$ overhead above the display normal where $\phi_s = 90°$. These measurement results are combined to provide the luminances of black and white under daylight illumination K_W and K_K, as described above. The 45°-sun full-screen contrast ratio or dynamic range is given by

$$D_{45°} = \frac{K_W}{K_K} = \frac{\pi L_W + \rho_W E_a + \beta_W E_s \cos\theta_s}{\pi L_K + \rho_K E_a + \beta_K E_s \cos\theta_s}, \quad (11)$$

and the readability is tested using the above method.

In practice, this is a difficult measurement to make because of the placement of the $\theta_s = 45°$ source. The angular diameter of the sun is 0.5°, and obtaining laboratory light sources of sufficient luminance at such a small subtense can be difficult. Essentially all apparatus geometric parameters affect the accuracy, and detailing the requisite accuracies will be relegated to a future paper.

Maximum Sunlight Readability Measurement Method: Diffuse reflectance measurements of the white and black screens are made, as above, to obtain ρ_W and ρ_K. Next, measurements of the luminance factors β'_W and β'_K are obtained use of a source with a subtense of 0.5° or less, allowing the luminance meter to observe the center of the screen and be moved any place within a cone, say $\theta_d \le 15°$, centered about the normal. The source (facing the screen center) is moved about in the hemisphere in front of the screen. The entirety of the source must remain in the hemispherical region. The source and detector can be moved manually to estimate the angles for which the readability is maximized; those angles can be refined in the laboratory to establish the maximum readability.

These reflection parameters are combined and scaled to give the luminances of black and white, K_W and K_K, under the highest readability conditions. The angular arrangement that provides the greatest readability with the readability analysis above represents the maximum readability of the display.

It is not necessarily the case that the maximum contrast will provide the greatest readability. In the event that such is the case, the maximum full-screen contrast ratio or dynamic range is

$$D_{max} = \frac{K_W}{K_K} = \frac{\pi L_W + \rho_W E_a + \beta'_W E_s \cos\theta_s}{\pi L_K + \rho_K E_a + \beta'_K E_s \cos\theta_s}. \quad (12)$$

For some displays, the maximum will occur when the source is nearest 90° from the normal of the screen. For other displays, particularly reflective displays, the maximum may occur when the source is much nearer the normal. Certain types of displays deliberately use light from certain directions (especially overhead directions) to enhance the readability of the display, often for handheld devices.

This maximum readability measurement method amounts to a low-resolution bidirectional reflectance distribution function measurement where the specular configuration is avoided. Detailing the requisite apparatus geometric-parameter accuracies is complicated and will be left for a future paper.

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