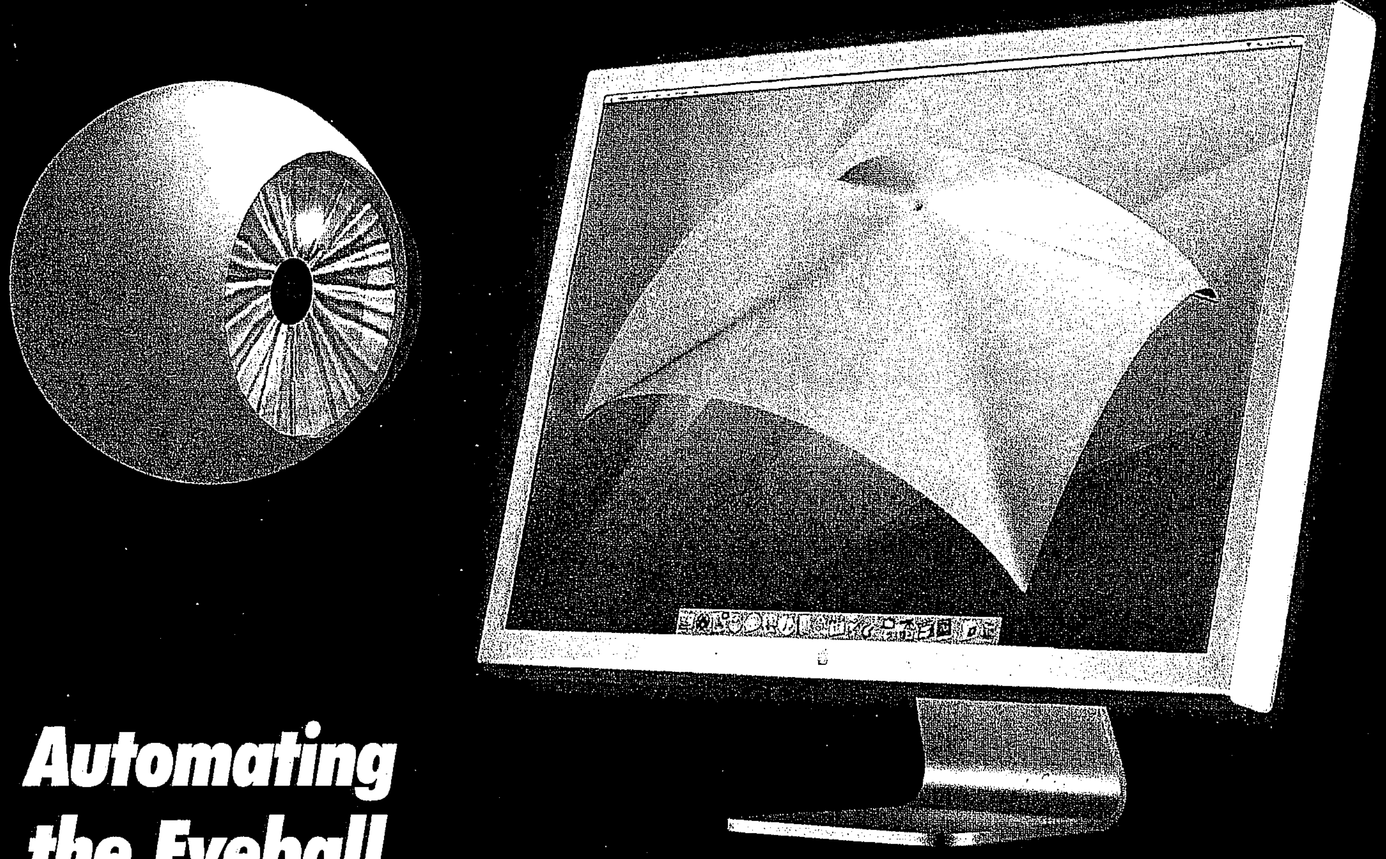
DISPLAY-METROLOGY ISSUE

Information DISPLAY

January 2007
Vol. 23, No. 1

SID

Official Monthly Publication of the Society for Information Display



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Reflections on Sunlight – or Daylight – Readability

Although most in the display industry refer to sunlight readability as a major metric for the quality of a display, it is, in fact, "daylight" readability – factoring in not just the sun but also the ambient light, but clouds, the beach, the paint on the walls, etc. – which is more vital to the performance of modern displays.

by Edward F. Kelley

THERE IS MUCH INTEREST in the sunlight readability of displays. We often see demonstrations at exhibitions where a bright sun-level source is pointed at a display from a substantial angle from the normal to show how easily the display can be read. The conclusion we are expected to take away from such a demonstration is that the display is sunlight-readable. And, in a sense, it is. But the "sunlight" readability of interest is more correctly called daylight readability. Not only is the direct sunlight a factor, but also the diffuse illumination from the surround – blue sky, clouds, the ground, *etc.* So, to demonstrate or measure "sunlight" readability without including the diffuse component may prove to be inadequate in qualifying a display for daylight use. For example, perhaps we are able to tilt our transflective cell-phone display so that we can read it successfully in direct sunlight, but on a bright but cloudy day, the display may become unreadable because only a quasi-uniform diffuse illumination remains – an illumination condition under which the display may not exhibit much contrast.

Keep in mind that the readability of a display does not depend only upon contrast – or the character contrast if it is different from the full-screen contrast. The background luminance in the vicinity of the display, the character size, the average luminance of the display, and the age of the viewer also affect how readable the display is.[1] A display can have a high contrast but have such a low average luminance compared to the surround that it is unreadable. However, whatever vision model is applied to determine readability, the basis for that determination starts with a measurement of the ambient contrast – the ratio of the white luminance to the black luminance under ambient illumination. We often measure the ambient contrast for full-screen white and black (*i.e.,* sequential contrast), hoping that the character-stroke contrast is approximately the same as the full-screen contrast. (Character-stroke contrast under ambient illumination is an important measurement that is still an active area of research.) The industry needs clear and applicable measurement standards to

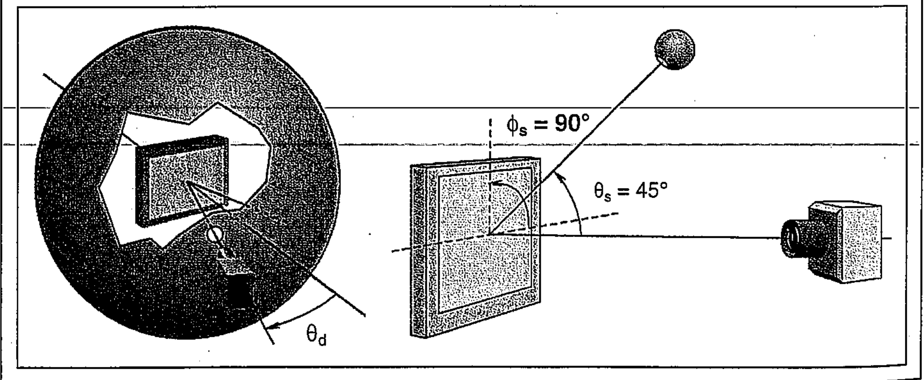

Fig. 1: Daylight contrast measurements performed using an integrating sphere to simulate a uniform diffuse skylight and a separate apparatus to simulate the direct sunlight (here shown at 45° above the normal).

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adequately quantify ambient performance of displays for daylight use. Scaling laboratory measurements to daylight levels rather than insisting on daylight sources makes such measurement standards accessible to more people and renders their implementation straightforward. Additionally, such measurements allow us to scale the measurement results to other ambient conditions besides daylight.

How would we quantify ambient contrast for daylight conditions? We would want to create a laboratory apparatus that permits us to measure the display properties – for example, contrast – to simulate daylight without having to take the display outdoors, where the lighting conditions are uncontrolled. We can imagine having an integrating sphere to supply a uniform diffuse illumination (uniform hemispherical, uniform over 2π sr) and place the display inside the sphere. Then we can imagine a separate measurement with a directed source to simulate the sun as shown in Fig. 1.[1] What we obtain from these measurements is not the ambient contrast, but the reflection parameters for the black and the white screens so that we can calculate what the performance would be for the desired ambient daylight illumination conditions. Some prefer to create simulated daylight illumination in the laboratory so they can see with their eyes how the display appears under artificial daylight conditions. These more-realistic configurations offer advantages particularly when the ambient environment is complicated as in a cockpit or automobile or when there is a requirement to simulate realistic bright daylight conditions. However, such a process can be very costly because of the brightness of the illumination that is required. If we make good measurements of the reflection parameters that characterize the display's performance under suitable laboratory illumination, we can then scale the results up to daylight levels without having to invest in the bright sources. Of course, we do not see the ambient contrast with our eyes when we make these scaling measurements; we simply calculate the ambient contrast from the reflection parameters. Scaling such measurement results is an acceptable solution because we are not dealing with light intensities that require nonlinear considerations.

Here is an outline of the process: We determine the diffuse reflectances for black and white screens using the integrating sphere. Separately, we determine the reflectance factors for the directed source for black and white screens. We then select the illuminance level we want for skylight and use the diffuse reflectance values to calculate what the diffuse contribution would be to the reflected luminance. Then we select the illuminance level for directed sunlight and use the reflectance-factor values to calculate what the directed-source contribution would be to the reflected luminance. Finally, we add these reflected luminance levels to the darkroom measurements of the white and black screens to obtain the resulting luminances that would be observed under the selected daylight conditions. Obviously, purely reflective displays have no darkroom luminances.

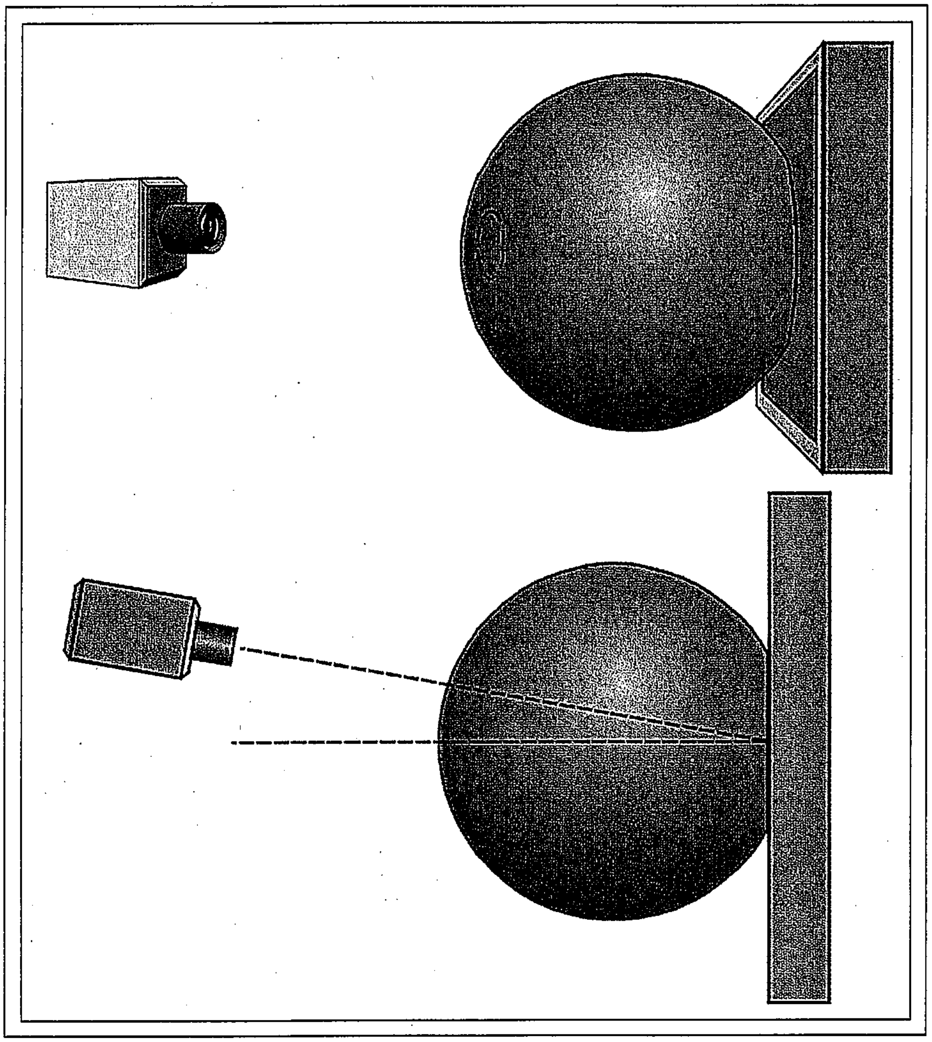

Fig. 2: Sampling sphere; side view at top, top view at bottom.

Figure 1 shows one possibility where the directed source simulating the sun is placed at 45° from the normal. Other configurations may well be useful for display evaluation depending upon the type of display and its intended application. However, the use of an integrating sphere to supply the uniform diffuse illumination represents the worst-case diffuse illumination that might be obtained on a beach (or on snow) under an overcast sky or in a living room with light walls, ceiling, furniture, and carpeting. The diffuse-reflectance measurement is also one of the most robust reflection measurements we can perform on displays – it easily provides reproducible results. Certainly, other diffuse ambient conditions might be appropriate for different purposes and applications, but it must be remembered that whenever the haze component of reflection is non-trivial, the measured reflection characteristics can be very sensitive to the

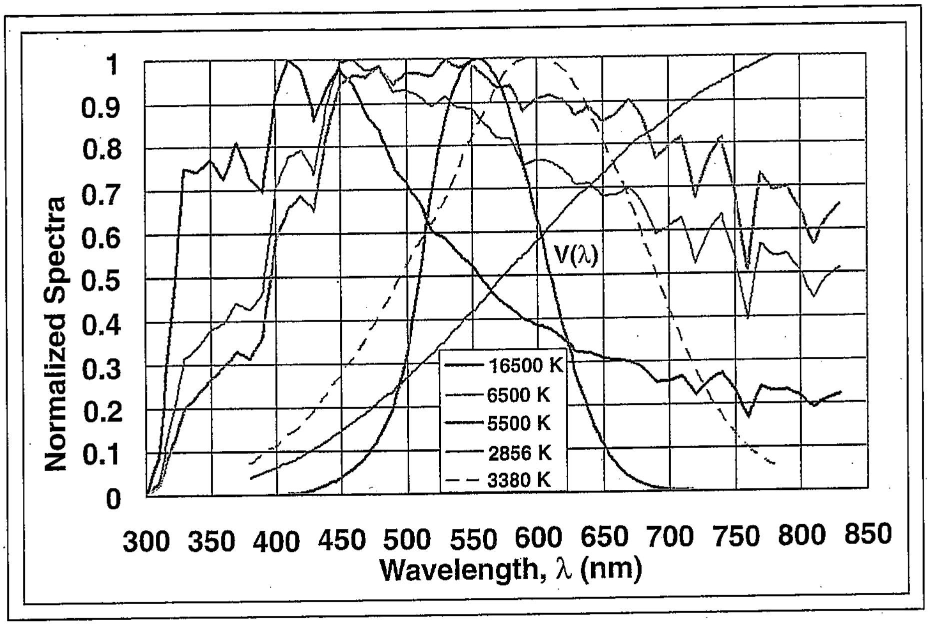

Fig. 3: Various spectra for daylight and laboratory sources compared to the spectral luminous efficiency for the human eye for photopic vision, V(λ).

apparatus geometry if the illumination is not uniform as it would be from an integrating sphere – this is particularly true in the vicinity of the specular configuration direction. The point here is that a directed-source measurement by itself is insufficient. The diffuse reflectance measurement is also needed.

Attempting to obtain an integrating sphere that is sufficiently large to adequately contain the larger displays can be difficult, bulky, and very expensive. The requirement that the illumination be uniformly distributed in the hemisphere at the region of measurement can be obtained using several types of apparatus. One of the best devices to accomplish such a measurement is a properly constructed sampling sphere.[2] Figure 2 shows a sampling sphere being used to measure the diffuse reflectance of a display. The advantage of the sampling sphere other than being less costly and easier to use is that the level of uniform-diffuse illumination can be quite high, making the measurement of the diffuse reflectance more robust and accurate.

Some worry about the levels of the illumination needed. Direct sunlight might be 10^6 lx and blue skylight might be 10^4 lx. It can be difficult to arrange for sources with exactly these levels of illumination. Because of scaling, we can make the measurements using laboratory sources and then scale them to exactly the daylight levels we need to use. The only intensity requirement is that the reflected luminance be sufficiently bright enough to be measured over the luminance from the emissive displays. This can be a challenge for some displays; illuminating those at large angles from the normal such as 45° will require a very bright light to obtain a sufficiently measurable reflected luminance. If we are not using an emissive display, but a reflective one, then the level of the illumination is much less important.

What about the correlated color temperature (CCT) of the sources? Direct sunlight might be 5500 K, and skylight might be 16500 K on the average. We show several different spectra in Fig. 3. How important is the correct source color temperature? If we are simply measuring black and white screens of gray displays (*i.e.*, where the reflection properties are spectrally flat), then, in general, the color temperature may only influence our measurements of luminance by 5–10% from a yellowish tungsten-halogen source to our blue skylight. Why? Because a luminance measurement is most sensitive to greenish light content and is less affected by the red and blue portions of the spectrum. Notice the normalized products of all the spectra in Fig. 4 with the spectral luminous efficiency of the human eye, V(λ); this shows how the luminance meter responds when measuring those very different spectra in Fig. 3. If we are measuring reflective color displays that do not have a spectrally flat response, then we would have to pay closer attention to the color temperature and spectral content of the illumi-

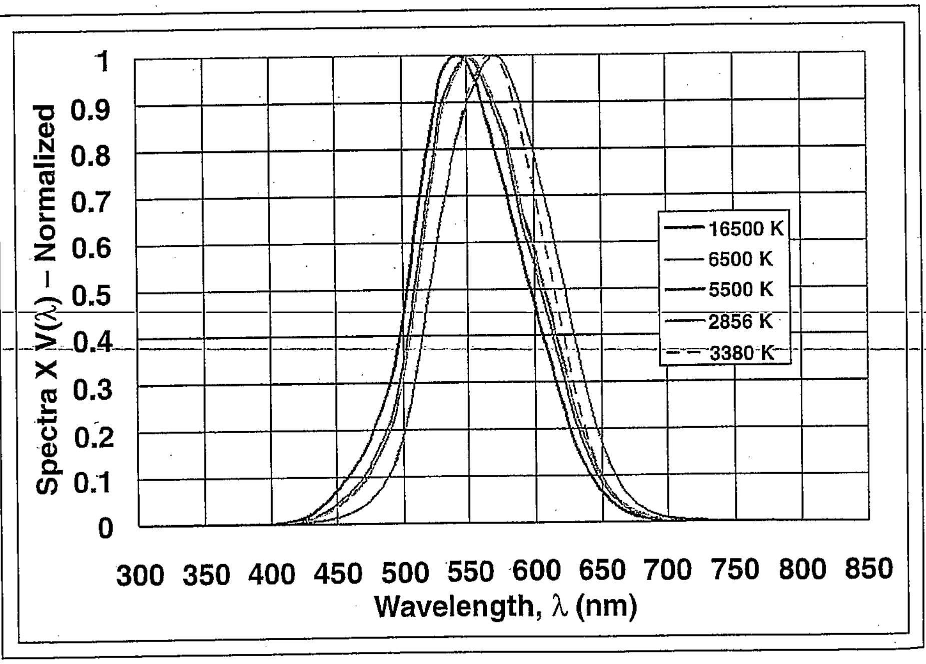

Fig. 4: Products of V(λ) times the spectra in Fig. 3.

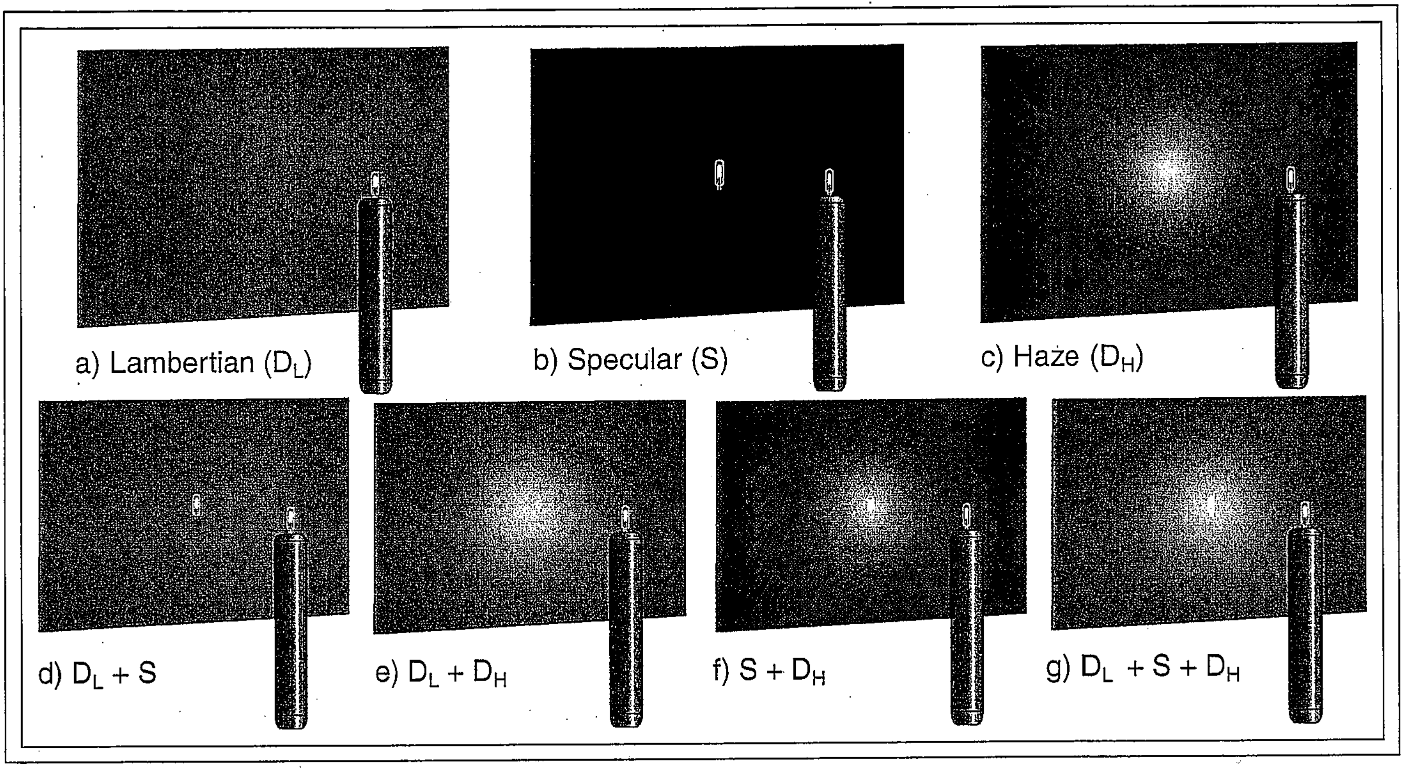

Fig. 5: Very different types of reflection characteristics may be observed in displays. We show here three components of reflection. Lambertian-like reflection resembles dark matte wall paint behind the display front surfaces. Specular resembles mirror-like reflection (distinct virtual image of the source) from the front surface (and sometimes interior surfaces). Haze diffuses light out of the specular direction but retains the directionality of the specular component. Haze and Lambertian are both types of diffuse reflection (scattering out of the geometrical specular direction). Both haze and Lambertian components are proportional to the illuminance from a source, but the specular component is proportional to the luminance of the source.

nation and a spectrally resolved measurement may be needed. Depending upon the reflection properties of the display being measured, we may not get away with using an arbitrary light source. The safest thing to do is to resort to spectrally resolved measurements and then calculate the resulting luminance based upon the spectral content of the various sources from the desired ambient conditions. This will assure that we have a luminance uncertainty of less than 5%. This yields the ability to invest more money in the detector – a spectroradiometer – and less money in the sources to obtain the required CCT. For such measurements, we obtain the spectral diffuse reflectance and the spectral reflectance factor for the isolated directed source. The resulting ambient contrast can then be calculated for any type of source that might be employed – with any spectral content desired; *i.e.*, the results of the spectrally resolved measurements permit us to use different spectra for the diffuse illumination and the directed source illumination.

Many who have used existing standard measurements for characterizing displays are accustomed to placing a discrete illumination source at a certain angle from the normal and measuring the reflections from the position of the normal to obtain what they refer to as a diffuse reflectance. They often then make a specular-configuration measurement on that same source to obtain a specular reflectance, where the source is on one side of the normal and the detector is on the other side of the normal at the same angle. Many years ago, displays exhibited simple reflection properties, for example, monochrome cathode-ray tubes (CRTs). They had only a specular component from a front polished glass and a Lambertian component (like dark-gray matte wall paint) from the phosphor surface. For these types of displays with fairly simple reflection properties, we could measure specular and diffuse reflectance in this way and be adequately correct. Because of the simple specular nature of the glass, the specular reflectance measurement contained mostly the specular component, and because of the Lambertian nature of the phosphor screen, the diffuse reflectance measurement was very robust and did not depend greatly upon the exact configuration of the apparatus. Times have changed.

Today, we have displays that can have much more complicated reflection properties. Unfortunately, the terms "specular reflectance" and "diffuse reflectance" have been retained by the display industry and improperly applied to more complicated reflection situations without regard to the fact that these terms have precise definitions according to the CIE.[3] Because the front surface of some displays can be located very near the pixel surface, it is possible to use a diffusing front glass that will eliminate the distinct virtual

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artifact, in units of JND. A comparison of the human and SSO estimates is shown in Fig. 6. Not only is the correlation between the two estimates quite good (r = 0.934), but the absolute magnitude of the predictions is close to the actual values in JND. This absolute agreement might be even closer if the extended observation interval (several seconds) for the human observers was taken into account.

Conclusion

The Spatial Standard Observer offers a new tool for design, specification, and inspection of visual displays. The ability to automatically measure mura in flat-panel displays will improve the efficiency and thus lower the cost of automated manufacture of large flat-panel displays. A perceptually based measure of motion blur will allow rational design and selection of displays and display technologies, as well as rational specification of displays for the consumer. A perceptually based measure of screen grain will allow optimized design of projection screens. We have described three specific applications of the SSO, but there are many others. Just as the measurement of luminance is fundamental to the engineering of displays, so too should be the measurement of visible spatial contrast, through a device such as the SSO.

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sunlight readability

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image that would be observed from a purely specular surface. The reflection property that arises from the diffusing microstructure on the front surface of some displays is an intermediate state between specular and Lambertian that has been called haze. Haze is observable as a fuzzy ball that follows the specular direction of a small source, but is proportional to the illuminance from that source – see Fig. 5. Whenever a nontrivial haze component is present, the measurement result becomes sensitive to the geometry of the apparatus, particularly for angles in the vicinity of the specular configuration.[4] Thus, for any given modern display, we can no longer haphazardly place a light source at some angle from the normal and call it a diffuse reflectance measurement; we need to employ a uniform-diffuse illumination to properly evaluate all types of displays equally and robustly.

Because of the very different reflection properties that displays can exhibit, we need more robust measurement methods than have been used in the past in order to measure reflection under ambient conditions. Combining the diffuse reflectance measurement with the directed-source measurement – at a significant angle from the normal – provides us with flexible and reproducible measurement results that can characterize the ambient performance of displays for daylight readability.

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motion blur

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perceived edge blur during motion is very well simulated by our model and, thus, that this method is a good alternative to the smooth-pursuit camera system. Lastly, a perceptual metric that predicts the perceived sharpness of a moving edge from the combination of BEW and luminance contrast was established.

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