

High Dynamic Range Displays and Low Vision

James A. Ferwerda, Munsell Color Science Laboratory, Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, Rochester, NY, USA

Abstract

The variations in light energy we experience are huge. For example, the average luminance outdoors can be 100 million times greater during the day than at night. The luminance dynamic range at any moment can also be large, with contrasts on the order of 10,000:1 from highlights to shadows. Luminance levels can also change dramatically over time and from place to place. Vision functions over these variations through a variety of adaptation mechanisms, however vision is not equally good under all conditions. In particular, people with low vision (often the elderly and those with visual disorders), can be profoundly impaired by low intensity, high dynamic range, and rapidly changing luminance levels. Unfortunately, existing clinical vision tests are typically done at moderate, near-optimal levels and contrasts, and may therefore underestimate a person's impairments. The need to develop more comprehensive and meaningful tests of vision and visual impairment under realistic illumination conditions has recently been articulated by both the National Eye Institute and the National Research Council, however, the limited output characteristics of standard display devices has been a significant impediment to progress. The emergence of high dynamic range (HDR) displays presents unique opportunities to develop new tools for vision research and testing and to advance our understanding of the effects of illumination on vision and visual impairment. This paper outlines some of these opportunities and describes some initial work to evaluate the use of HDR displays in this area.

Introduction

We experience huge variations in light energy in real-world environments. For example, the average luminance in sunlit scene can be 100 million times greater than the same scene lit by starlight. The instantaneous luminance dynamic range we experience at any moment can also be large, with ratios on the order of 10,000:1 from highlights to shadows, and even greater if light sources are visible. Luminance levels can also change over time and from place to place such as when the sun is obscured by clouds or we enter or leave a tunnel [IES93].

Human vision functions over these changes in illumination conditions through a variety of adaptation mechanisms that include the pupil, the duplex retina of rods and cones, photopigment bleaching, and neural gain controls [Shapley84]. Through the coordinated action of these mechanisms, vision functions over a luminance range of almost 14 log units. Figure 1 shows the range of light we encounter in natural scenes and summarizes some of the visual parameters associated with the different ranges.

However, visual performance is not equally good under all luminance conditions. At high average (daylight/photopic) luminance levels visual functions such as acuity, contrast sensitivity, color discrimination, depth perception, and motion

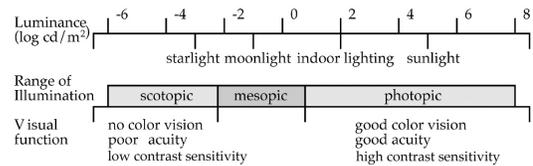


Figure 1. Range of illumination in the environment and associated visual parameters. Adapted from [Hood86]

perception are near optimal. However under low luminance (mesopic/scotopic) conditions in twilight or at night, performance is substantially reduced [Hood86].

The instantaneous dynamic range of luminance in a scene can also have a significant impact on vision. For example, a bright light source in the visual field can cause light scattering in the eye, that can produce discomfort and veiling glare that can significantly reduce visual sensitivity and performance [Vos84]. Similarly, rapid temporal changes in the levels of illumination can also have a negative impact on vision. Nearly everyone has experienced the temporary blindness that occurs when entering a dark room from bright daylight or vice versa.

Low Vision

While these situations are minor annoyances for younger people with normal vision, the elderly and people with diseases of the visual system are often profoundly impaired by the variations in illumination they encounter in the world [Faye76, Mainster03]. A range of studies have shown that low luminance, high dynamic range, and rapidly changing illumination conditions can dramatically reduce visual performance in older people [Pitts82, Kline85] and in people with glaucoma [Glovinsky92], macular degeneration [Owsley01], retinitis pigmentosa [Jacobsen86], optic neuritis [Schneck93], diabetic retinopathy [Wolfe91], and other visual disorders. These losses in performance often translate into severe functional impairments in important tasks of daily living such as reading, mobility and driving, face recognition and social interaction, and the ability to use tools and appliances [NRC02].

Clinical Low Vision Testing

Given the important effects that illumination conditions have on visual abilities and impairments, it is curious that standard clinical tests of vision are typically done under near ideal, photopic, glare-free conditions [NRC94]. There is converging evidence that these tests may not provide a sufficient picture of visual performance in the real world, often severely underestimating the impairments that people experience [Higgins00]. However, for a variety of reasons, advances in clinical vision testing have been slow in coming.

Low luminance levels

In the low luminance domain, testing is difficult in part because of the problem of producing calibrated and repeatable luminance levels. Although there is a large psychophysical literature on visual performance under scotopic and mesopic conditions [Hess90], most laboratory work has not typically included observers with low vision, and the instruments and tests have been custom-built. One researcher with a low vision focus modified a Humphrey automated perimeter to allow scotopic range contrast sensitivity testing of observers with macular degeneration [Owsley01], but this device is not commercially available. A low-tech approach for clinical low luminance testing is the SKILL acuity card [Haegerstrom-Portnoy97] that approximates low luminance, low contrast conditions at normal illumination levels with black letters on a gray background, however it has not been verified that performance under these conditions is the same as under actual low luminance conditions. Outside the laboratory, low luminance testing has largely been limited to measures of acuity and contrast sensitivity, so tests of other basic functions such as color discrimination, depth and motion perception, and visual search, and direct tests of performance on real-world visual tasks would be valuable.

High contrast and glare

Visual assessment under high dynamic range conditions typically falls under the rubric of glare testing [Elliot93]. A variety of instruments have been developed for testing basic visual functions such as high and low contrast visual acuity and contrast sensitivity in the presence of a glare source. These include the Miller-Nadler Glare Tester, the Brightness Acuity Tester (BAT), and the Berkeley Glare Test. A number of commercial devices have also been developed including the Vistech MCT8000, the Humphrey Model 570, the EyeCon 5, and the Opthimus glare test. Unfortunately the geometries and luminance levels of the glare sources and targets differ from device to device, and in all, the glare source is located a different visual field location than the test target, which has made it difficult to develop a coherent picture of the effects that high dynamic range conditions have on visual performance.

Changing luminance conditions

Since aging and disorders of vision often affect the ability to adapt to changing luminance levels, dark adaptation is a standard clinical tool. The traditional instrument is the Goldmann-Weekers dark adaptometer, though recently an LED-based device, the LKC Technologies Scotopic Sensitivity Tester became available. Low vision researchers have also modified a Humphrey automated perimeter to measure dark adaptation in patients with age-related macular degeneration [Owsley01] but the device is not commercially available. Typically the time course of recovery of contrast sensitivity is tested either with spot or grating targets. With respect to light adaptation one clinical testing protocol is known as “glare recovery” and involves the macular photostress test described by [Severin67] where a penlight is held close to the eye for several seconds and the time taken before pre-test acuity returns is used as a measure of adaptive function. Another line of testing involves calculation of the “transient adaptation factor” by measuring contrast sensitivity across the time course of early light

adaptation (<1 sec) after the onset of a glare source [Higgins99]. As with testing in the low luminance and high dynamic range domains, testing protocols are variable, the range of functions tested is limited, and testing has largely been limited to observers with normal vision.

HDR Displays and Low Vision Testing

The need to develop more comprehensive and meaningful tests of vision and visual impairment under realistic illumination conditions has recently been articulated by both the National Eye Institute [NEI99] and the National Research Council [NRC02]. Modern electronic display systems and advanced computer graphics methods should in principle, allow the development of powerful new tools. However, the limited output levels and dynamic ranges of existing displays devices have been an impediment to progress. The emergence of HDR displays [Seetzen03,04] provides a unique opportunity to develop new tools for understanding the effects of varying luminance conditions on human visual performance and visual impairment. We are currently working on three related projects:

First, we have constructed HDR displays and are evaluating their properties as visual stimulators [Ferwerda09, Zhang10]. On the basis of this work we are developing HDR display based tests that allow efficient, automatic assessment of the effects of absolute luminance level and dynamic range on standard measures of visual performance such as acuity, contrast sensitivity, color discrimination, light and dark adaptation, glare disability and recovery, visual fields, motion perception, and visual search.

Second, we have been taking advantage of HDR displays’ unique capability to present photometrically accurate images of real scenes under different lighting conditions to develop a new class of methods for assessing functional vision on important real world tasks such as face recognition and social interaction, sign and display reading, walking and driving, and commercial transactions. In complementary work we have been developing methods for producing images that simulate how HDR scenes appear to low vision observers [Irawan05]

Finally we are beginning to explore the possibility of using HDR displays to develop simple, effective screening tests for the early detection of eye diseases such as cataracts, macular degeneration, glaucoma, diabetic retinopathy, and retinitis pigmentosa.

Phototoxicity and HDR displays

One of the virtues of HDR displays for low vision testing is that they can be very bright, with maximum luminance on the order of daylight (3000-10,000 cd/m²). However the high intensities produced by HDR displays may also pose a hazard to observers in the form of phototoxic effects and this may be especially true to observers whose eyes are already compromised by disease. Therefore before using HDR displays for low vision testing it is necessary to evaluate their potential phototoxicity.

Ocular phototoxicity

Ocular phototoxicity can take photomechanical, photothermal, or photochemical forms depending on the intensity and duration of the light exposure [see Glickman02 for a review]. Figure 2 provides an overview of the relevant ranges and

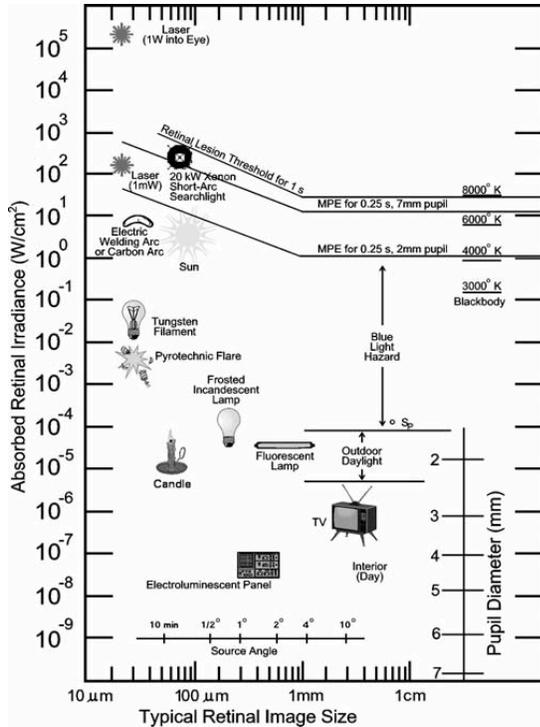


Figure 2. Ocular phototoxicity. Types, causes and parameters. From [Slincy02].

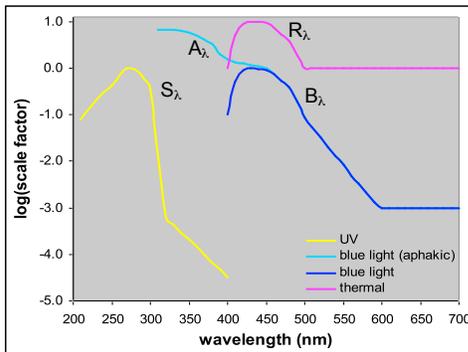


Figure 3. ICNIRP phototoxicity hazard functions.

parameters. While photomechanical and photothermal effects are only caused by viewing high intensity light sources like lasers, welder's arcs, and the sun, photochemical damage can be produced at much lower intensities, and there is evidence that the effects may be cumulative. For example, the photochemical effects of moderate, long-term UV exposure on the eye's optics and its role in the development of cataracts are well known. Of more recent concern is the so-called "blue light hazard" produced by short-wavelength visible light, and its potentially damaging effects on people with retinal disease [Simons93, Cideciyan05]. While there is still a degree of controversy about magnitude of the blue light hazard, there is sufficient concern that the International Committee on Non-Ionizing Radiation Protection (ICNIRP) recently revised its recommendations for blue light exposure limits [Slincy05a].

To aid in calculating safe light levels the ICNIRP has developed the spectral phototoxicity hazard functions illustrated in

Figure 3. These functions provide scale factors by which retinal irradiance functions are multiplied to determine exposures. The R_λ and S_λ curves are for estimating thermal and UV effects, the B_λ and A_λ curves are for estimating "blue light" exposure. Curve B_λ is the standard, but the A_λ curve has a near UV extension for "aphakic" eyes that lack the protection provided by a natural lens.

Estimating the Phototoxic Potential of an HDR Display

HDR display radiometry

Since commercial HDR displays are still scarce and data on their radiant emissions is more so, we based our calculations on data gleaned from publicly available documents describing the original Brightside DR37P prototype HDR display [Brightside07]. While the specific components of newer displays may vary, the general designs are similar and so we believe that our analysis and findings will remain relevant.

The DR37P consisted of a 70x40 array of 1 Watt white LEDs (Philips Luxeon LXHL-PW01) that transilluminated a Philips color LCD panel. Multiplying the LED's normalized emittance spectrum by the transmissivities of the LCD's filter curves produces the "red", "green" and "blue" and summed "display white" radiance functions shown in Figure 4. These functions can be scaled to appropriate physical values using the relation,

$$L_v = 683 \int_{\lambda} L_{e,\lambda} V(\lambda) d\lambda \quad (1)$$

where (L_v) is the display's maximum luminance, $(L_{e,\lambda})$ is the display's relative spectral radiance, $V(\lambda)$ is the CIE photopic luminous efficiency function, and k is a scaling constant that takes into account all the transmission losses in the LCD panel including filters, polarizers, the liquid crystal, and other components. Taking the display's maximum luminance as 3000 cd/m², and solving for k yields the physical radiance values (W/cm²sr⁻¹) shown on the y-axis in Figure 4. The physically scaled "display white" curve in Figure 4 represents the maximum energy spectrum emitted by the HDR display. At maximum output levels, the total display radiance is 8.9x10⁻⁴ W/cm²sr⁻¹.

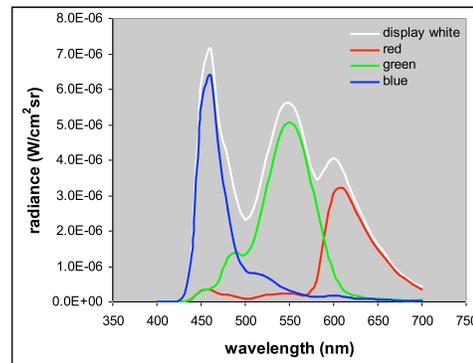


Figure 4. Spectral radiance functions. Brightside DR37P HDR display at maximum luminance (3000 cd/m²).

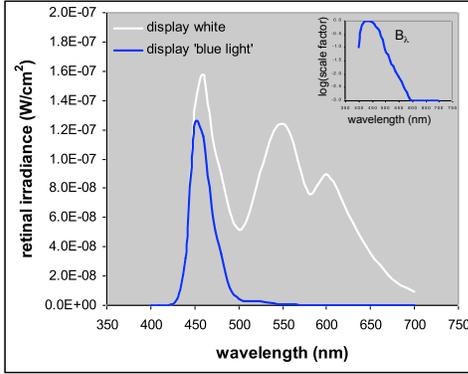


Figure 5. Retinal irradiance, HDR display "white" and display "blue light".

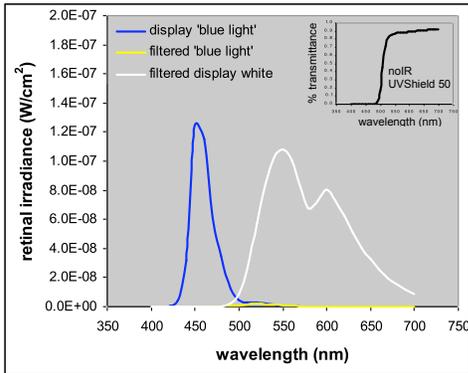


Figure 6. Further reduction in retinal "blue light" through the use of short wavelength filter glasses.

Calculating retinal irradiance

The potential phototoxicity of a light source is a function of the radiant exposure H received by the retina. Radiant exposure can be calculated as $H = E_r t$, where E_r is the retinal irradiance produced by the source in W/cm^2 , and t is the exposure duration. The retinal irradiance can be calculated as,

$$E_r = \pi L_e \tau d^2 / 4f^2 \quad (2)$$

where L_e is the total source radiance, τ the transmittance of the ocular media, d the pupil diameter, and f the eye's focal length [Sloney05b].

Photomechanical and photothermal effects

Using recommended values for the constants ($\tau = 0.9$, $d = 3\text{mm}$, $f = 17\text{mm}$) [Sloney02], yields the spectral retinal irradiance function indicated by white line in Figure 5. Integrating the function yields that the total retinal irradiance produced by the HDR display is $19 \times 10^{-6} W/cm^2$. This is well below recommended photomechanical and photothermal toxicity limits for extended exposure durations recommended by ICNIRP, and is on the same order as the irradiance produced by typical sunlit environments (10×10^{-6} to $100 \times 10^{-6} W/cm^2$) [Sloney05b].

Photochemical effects ("the blue-light hazard")

To evaluate the potential for photochemical effects, it is necessary to examine the spectral composition of the display's output. While the display's UV radiance ($<400\text{nm}$) is negligible, radiance in the short-wavelength visible range is relatively substantial. B_λ , the "blue-light hazard function" to allow calculation of the photochemical toxicity hazard posed by a visible light source. This function is shown in the inset in Figure 5. The white curve in Figure 5 represents the radiant output of the "full white" HDR display and the blue curve represents the product of this spectrum with the blue-light hazard function. Using Equation 2 above, the corresponding retinal irradiance produced by the display's blue light output is $4 \times 10^{-6} W/cm^2$. This is an order of magnitude lower than the already conservative blue-light limit of $220 \times 10^{-6} W/cm^2$ recommended by the ICNIRP for extended exposures [Sloney05a]. Therefore, based on the available data and current standards it appears that the Brightside HDR display and similar designs would pose no known hazards to normal or low vision observers.

Further mitigation of the blue light hazard

While the blue-light exposure limits recommended by the ICNIRP are conservative and were specifically designed to minimize phototoxic effects for people with retinal disease, future research may reveal that even lower limits are prudent. Therefore the yellow curve in Figure 6 shows that by having the observers wear commonly prescribed short-wavelength filter glasses (NoIR UVShield 50 [NOIR]) it is possible to cut blue light exposure to negligible levels ($1.02 \times 10^{-7} W/cm^2$) while only reducing maximum display luminance by 23% to 2310cd/m^2 .

How bright would an HDR display have to be to be dangerous?

While current HDR display designs appear to pose no hazard to viewers, LEDs are getting more powerful all the time so there the potential to someday create very bright HDR displays. This raises the question of how bright a display would have to be to be dangerous in terms of ocular phototoxicity. Using the HDR display design described above and ICNIRP's $220 \times 10^{-6} W/cm^2$ blue light exposure limit as a guideline, yields a display with a maximum luminance of approximately $165,000\text{cd/m}^2$. This corresponds approximately to the luminance of white paper in bright sunlight (on the beach at the equator to be exact). It seems unlikely that commercial displays with this characteristic will be manufactured anytime soon.

Conclusion

The emergence of HDR display technology has the potential to revolutionize current approaches to vision testing in both clinical and research settings. The goal of the work described in this paper is to leverage the power of this new technology to greatly improve the scope and relevance of testing methods, and to increase the potential availability comprehensive and meaningful tools for assessing vision and visual impairment. The hope is that this work will serve as a foundation for significant advances in the detection, diagnosis, remediation, and prevention of low vision.

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