Evaluating the Optical Characteristics of Stereoscopic Immersive Display Systems

John Penczek*
University of Colorado
Boulder
and
Engineering Laboratory
National Institute of Standards and Technology[1]
325 Broadway, MS 686.01
Boulder, CO 80305

Steven G. Satterfield
Information Technology Laboratory
National Institute of Standards and Technology
Gaithersburg

Edward F. Kelley
KELTEK

Timothy Scheitlin
Computational and Information Systems Laboratory
National Center for Atmospheric Research

Judith E. Terrill
Information Technology Laboratory
National Institute of Standards and Technology
Gaithersburg

Paul A. Boynton
Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg

Presence, *Vol. 24, No. 4, Fall 2015*, 279–297
doi:10.1162/PRES_a_00235

Abstract

As large immersive displays have evolved over the years, the measurement methods used to characterize them must also advance to keep up with the changing technologies and topologies. We propose a general suite of optical measurements that can be used to determine the basic visual performance characteristics for a variety of immersive display systems. These methods utilize current display industry best practices and new research that anticipates the measurement challenges posed by the new technologies. We discuss the need for higher resolution detectors for the new generation of laser and LED (light-emitting diode) projector systems. The introduction of multi-primary displays is addressed by the implementation of new test patterns that better simulate the display performance of typical images. Methods to evaluate the unique attributes of stereoscopic displays, such as cross-talk and left eye/right eye differences, are described and interpreted. In addition, it is shown that the ambient lighting environment or display topology can have a detrimental impact on the display image quality. The application of these measurement methodologies is demonstrated by the evaluation of three display systems: two rear-projection and one front-projection display. We highlight how these measurements can identify potential display performance limitations, and offer advice on how to address some of these limitations.

1 Introduction

Immersive displays are under considerable scrutiny as a means to enhance the user experience and assist in our understanding of complex problems. They are not only gaining popularity in the entertainment industry, but are also prevalent in a variety of fields as researchers try to obtain greater insight in analyzing complicated datasets or models. Commercial and research applications range from drug discovery, energy research, geospatial analysis, to virtual reality training scenarios. These applications often use the immersive display to leverage the huge processing power of the human visual system to analyze the image. Display manufacturers have tried to further exploit our visual sense of spatial immersion (to enhance a viewer's perception of being physically present in the scene) through improvements in the image field of view, resolution, and the addition of stereoscopic images. It is generally considered that an image field of

*Correspondence to jpenczek@nist.gov.
1. 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.

view greater than 60° is necessary in order to induce a strong sense of spatial immersion, or presence (Hale & Stanney, 2015). Some designs pursue the immersive experience through head-mounted displays, where each user can have a distinct view; however, this article will focus on designs where several users can be positioned in front of large displays and collectively share the same physical space and visual information.

Initial efforts to improve the immersive experience pursued larger screen sizes, which enveloped a larger field of view. Subsequent evolutions of immersive displays have further expanded the field of view such that the user could be completely contained within the visual scene. The development of the cave automatic virtual environment (CAVE) surrounded the viewer with three to six large screens in a room-sized cube (Cruz-Neira, Sandin, DeFanti, Kenyon, & Hart, 1992; Cruz-Neira, Sandin, & DeFanti, 1993). Stereoscopic imagery and head-tracking could also be added to enhance the visual experience by giving the user greater perspective and viewer position feedback. As these new immersive display technologies are introduced, they have an impact on the visual quality of the content that is being presented. It is critical that the visual performance of the immersive display system be evaluated in order to understand how to maximize the visual experience.

We propose a suite of optical measurements that characterize how well a display system renders the intended image content to the viewer. These measurements determine some of the basic performance characteristics of the displays, but do not capture the intangible immersive experience that one might feel in a CAVE environment. Even so, a knowledge of these properties can guide the display manufacturer toward better display designs, and advise the display system operator on more effective ways to present their content. We first highlight some of the critical visual characteristics of a display system, then present current best practice measuring methods to determine these characteristics, and finally demonstrate the implementation of these measurement methods on three different immersive display systems. Initially, we employ the characterization methods on single-screen front- and rear-projection systems in order to determine the intrinsic capabilities of the display system. We then extend the measuring methods to include the impact of the adjacent screens on the main screen, using a CAVE system.

2 Essential Display Visual Performance Characteristics

The display industry has developed objective visual performance characteristics that can be used to evaluate the image rendering capability of a display. These characteristics are generally expressed in terms of photometric and colorimetric values, which take into account the visual response of the human eye (Berns, 2000). The eye mainly perceives the spatial and temporal changes in brightness and color of the observed images. We will focus on the static characteristics of images as rendered by immersive displays. Temporal characteristics can also be important, but are addressed in standards published by the International Committee for Display Metrology (ICDM) and the International Electrotechnical Commission (IEC) (e.g., ICDM, 2012; IEC 62341-6-3, 2012). We will briefly review some of the critical display attributes, and discuss their impact on the viewing experience.

2.1 Optical Detectors

Calibrated optical detectors are used to acquire the raw radiometric data, and convert it to absolute photometric and colorimetric data. For photometric data, the visible spectrum is weighted by the photopic response of the eye and expressed in terms of luminance or illuminance. The illuminance has units of lux, and describes the amount of photopically weighted light incidence on a surface (like a projection screen). The luminance has units of candela per meter squared (cd/m^2), and roughly corresponds to the relative brightness of an object. The Commission Internationale de l'Eclaige (CIE) has standardized the human perception of color by weighting the visible spectrum with the color-matching functions of the CIE 1931 standard colorimetric observer (ISO 11664-1, 2007). The resulting tristimulus values represent a 3D color space, which is commonly transformed into a 2D color mapping in the form of the CIE 1931 chromaticity diagram, or the more perceptually uniform color spacing of the CIE 1976 uniform chromaticity scale (UCS) (CIE, 2004). This 2D mapping allows any perceived color to be represented by CIE 1931 (x,y) or CIE 1976 (u′,v′) chromaticity coordinates.

The accuracy of the luminance and color data that the optical detector reports is largely dependent on the design of the instrument. The less expensive detectors use filters to simulate the true photopic response (for photometers) or color-matching functions (for colorimeters). In practice, it is difficult to create a filter and detector combination that accurately matches the ideal profiles. Higher accuracy can be achieved by measuring the actual visible spectrum with a spectrometer, then calculating the photometric and colorimetric values using the tabulated values of the photopic and color-matching functions (Berns, 2000). For displays that have red, green, and blue primaries with relatively broad spectra, the accuracy of the filtered detectors can be comparable to the more expensive spectrometers. However, as new displays start introducing LED and laser light sources, the performance difference between the filtered detectors and spectrometers becomes more noticeable. Our unpublished work has shown that the performance of typical filtered detectors degrades substantially as the bandwidth of the light source decreases, and becomes unacceptable for the laser sources. For narrower spectral bandwidth light sources, it is usually necessary to use spectrometers or spectroradiometers. Our results indicated that a detector bandwidth of ≤ 5 nm was needed for luminance and color measurements of laser sources. In addition, the light produced by the display can have other characteristics, such as varying polarization, laser speckle, spatial nonuniformity, and temporal modulation. For example, liquid crystal display (LCD) and polarization-based stereoscopic displays produce polarized light. This can be problematic for spectrometers, which often use polarization-dependent spectrally dispersive elements. However, if spectral measurements are necessary, some spectroradiometers can be purchased that are relatively polarization insensitive. Therefore, when deciding which detector to use for the display measurements, one should carefully consider the properties of the display to be measured.

2.2 Display Photometric Characteristics

The display luminance, color, and their uniformity are the most basic characteristics of a display. Luminance is a prime attribute of the visual information. Its magnitude often dictates how striking and readable the information appears, especially relative to the background lighting. The contrast ratio between the maximum white luminance to the black luminance is a common ergonomic metric that is closely related to the readability of the display. It is an important metric that conveys how easily the observer can detect small intensity differences between image features. Because the contrast ratio of large immersive displays is often limited by the background lighting that can wash out the black level, these display systems continue to pursue higher white luminance technologies. However, the drive to higher luminance levels is complicated by the need to maintain uniform luminance over the entire screen. A uniform screen appearance is more than an aesthetics issue; it helps preserve the contrast ratio over the whole image.

2.3 Spectral and Colorimetric Characteristics

In many cases, color provides valuable information. Expanding the range of possible colors that the display can render (its color gamut) enables more information to be encoded into the greater color range. Often the image content is encoded with a certain standard color space, such as sRGB or the International Telecommunication Union BT.709 (IEC 61966-2-1, 1999; ITU-R BT.709-5, 2008). This content then presumes that the display is calibrated to accurately render that color space. An indication of a display's color range and how well the display reproduces the standard color space can be obtained by measuring the chromaticity coordinates of the primary colors (usually red, green, and blue). These chromaticity coordinates can be plotted as a triangle on a CIE 1931 or 1976 chromaticity diagram relative to the triangle formed by the standard colors. Any mismatch between the two triangles would indicate the degree to which the image content could not be accurately rendered. A comparison between the measured white color and the standard chromaticity coordinate is another reference point for characterizing the color mismatch. It should also be noted that human vision is particularly sensitive to inaccurate color rendering of natural scenes, where viewers have expectations for certain color in landscapes and flesh tones.

Plotting the color gamut triangle in the chromaticity diagram is a simple visual representation of the display's color capability. A more quantitative measure is to calculate the color gamut area within the triangle in the CIE 1976 chromaticity diagram (ICDM, 2012). An even better characterization of a display's range of perceptible colors is given by the three-dimensional CIE 1976 (L*a*b*) color space, which is typically called the CIELAB color space (ISO 11664-4, 2008). An appropriate sampling of rendered colors can serve to define the outer boundary of the three-dimensional color space for a given display. A subsequent calculation of the color gamut volume within that boundary provides a valuable metric for the perceptually visible span of colors that the display is capable of producing.

Although the use of chromaticity coordinates is a convenient shorthand formalism for describing a color, in some cases measuring the actual spectral distribution of the light is desirable. This is particularly useful when measuring the reflection behavior of a projection screen or the transmission characteristics of 3D glasses.

2.4 Display Uniformity and Viewing Dependence

The basic luminance and color measurements are usually measured perpendicular to the display center. However, these properties are not generally the same over the entire display, and the luminance and color difference from the center tends to increase for larger screens. This is particularly the case for traditional projection systems. If the luminance and color nonuniformity are large, then the image quality will depend on the screen position. This undesirable situation can result in distorted or hidden information.

The luminance and color differences can be quantified by measuring the display at several standard screen positions. For small displays, the detector is typically translated to each screen position and performs the measurements perpendicular to the screen. However, for large immersive displays, the viewer is relatively close to the screen, so the viewer would normally pivot his/her foveal view such that it is centered on the new position. This viewing condition can be experimentally simulated by the vantage-point measuring method, where the detector's optical axis goes through the same eye location in space as it is tilted to measure each of the screen locations (ICDM, 2012). However, the vantage-point method does have the disadvantage of coupling in any viewing angle dependence with the screen position nonuniformity.

The viewing angle dependence of a display can be separately characterized by measuring the changes in luminance and color with varying inclination angles at the same screen location. The variation with viewing angle would quantify how the image characteristics at a specific screen location would change for an observer moving around, or how the characteristics would differ for two observers looking at the same content.

2.5 Display Performance with Ambient Illumination

The display's intrinsic performance is characterized under dark room conditions. However, in normal operation, each display system may actually be viewed with some ambient illumination. For emissive displays, including projector systems, any ambient illumination will have a detrimental effect on the image quality. The ambient light washes out colors and degrades the black level, thereby reducing the color range and impairing readability via glare and lower contrast. The relative impact of the ambient light is dependent on the lighting configuration and the technology of the display system. Therefore, the change in the display performance with ambient illumination needs to be uniquely evaluated for each immersive display system. These changes are typically characterized by the relative decrease in parameters such as contrast ratio and color gamut.

2.6 Stereoscopic Display Performance

The use of stereoscopic displays helps to enhance the immersive viewing experience. However, it also

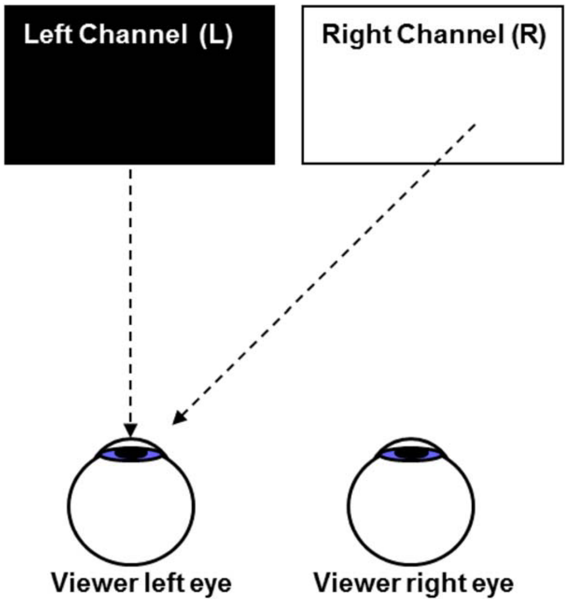

Figure 1. *Illustration of 3D crosstalk for the left eye where light from the right eye image channel leaks into the left eye image.*

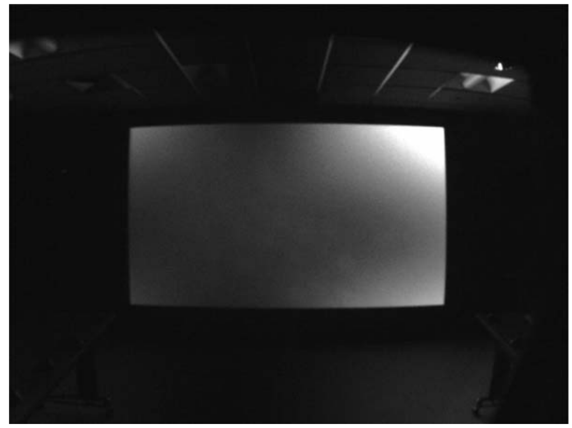

Figure 2. *Example of 3D crosstalk from display #3 as viewed through the left eye glass lens.*

introduces more design and measurement challenges. Whereas conventional displays render the same image to the left and right eyes, stereoscopic displays introduce parallax between the left and right eye images. Aside from the difference in perspective between the two images, the rest of the content should be the same. Significant differences in characteristics (such as luminance, color, alignment, and magnification) between the left and right eye images can induce visual fatigue and discomfort (Kooi & Toet, 2004; Pöllön et al., 2012). Therefore, stereoscopic displays with glasses need to be characterized by similar (monocular) photometric and colorimetric measurements taken on conventional displays, then a comparison of the differences between the left and right eye data.

In addition to the monocular characteristics, one key characteristic of stereoscopic displays is how well they can optically isolate the left and right eye images as they are rendered to the viewer. If an image that is intended for one of the eyes leaks to the other eye, it can cause an offset "ghost" image in the unintended eye. The light leakage is called 3D crosstalk, and is defined as the percent of light that is leaking from the unintended image to the intended image. Figure 1 illustrates the situation where the left eye 3D crosstalk occurs when light from the right eye image leaks into the left image. In this example of a stereoscopic display with glasses, the 3D time-sequential rendering system opens the left eye shutter glass when the black image is rendered for the left eye, and closes the left eye shutter glass when the white image is rendered for the right eye. Any light that leaks through the closed shutter glass of the left eye will lead to left eye 3D crosstalk. An example of this situation is given in Figure 2, as obtained by a photopically weighted camera viewing display #3 through the left eye lens. The figure shows that for these 3D glasses, the light leakage is most severe in the diagonals, corresponding to the display corners. All of the 3D systems in this study exhibited similar behavior. The ability of the liquid crystal active shutter glasses to block the light from the unintended image is angle dependent, and a function of the eye glass design.

For the left eye 3D crosstalk calculation, the viewpoint luminance through the left eye lens is first measured with a full white screen for the left eye channel and a full black screen for the right eye channel ($L_{\mathcal{L}\mathrm{WK}}$). Then the luminance $L_{\mathcal{L}\mathrm{KW}}$ is measured with a black screen rendered to the left eye channel and white screen to the right eye channel. And finally, the luminance $L_{\mathcal{L}\mathrm{KK}}$ is measured with a black screen for both eyes channels. The left eye 3D crosstalk is calculated by (Woods, 2012):

$$X_{\mathcal{L}} = (L_{\mathcal{L}\mathrm{KW}} - L_{\mathcal{L}\mathrm{KK}})/(L_{\mathcal{L}\mathrm{WK}} - L_{\mathcal{L}\mathrm{KK}}). \quad (1)$$

A similar process was used for determining the right eye 3D crosstalk. The test patterns used for this measurement, and all other measurements discussed in this study, are available at the National Institute of Standards and Technology website (NIST, 2015).

Other factors such as accommodation–vergence mismatch may also induce visual discomfort. This can occur when the 3D image stereo pairs induce an eye convergence point that is far away from the focused image at the display screen. (This mismatch is not addressed in this study.) They are largely effected by the 3D content. Therefore, the content providers should be aware of exceeding recommending guidelines when creating or displaying 3D imagery (Ukai & Howarth, 2008; Urvoy, Barkowsky, & Le Callet, 2013).

3 Optical Measuring Methods

A variety of optical measuring methods are utilized to extract the critical visual characteristics of immersive displays. The photometers, colorimeters, and spectroradiometers used to measure the photometric and colorimetric values are usually the same for both immersive and non-immersive displays. However, which instruments should be employed, how they should be used, and the necessary metrics to evaluate these display systems can vary, depending on the specifics of the technology. Regardless, the core visual parameters (such as luminance, color, and contrast ratio) tend to be important across display technologies. In the following section, we advise the reader on the appropriate measuring methods for determining the essential photometric and colorimetric characteristics as part of a rigorous evaluation of a large immersive display system. We introduce a suite of measurements that can be used to determine the fundamental visual characteristics of most large immersive display systems. A variety of immersive displays are used to demonstrate the general applicability of these methods. The photometric and colorimetric measurements from these displays are presented, highlighting the salient characteristics. Some guidance is given in interpreting the results, and recommendations are offered when the performance is lacking.

3.1 Description of Display System Test Cases

The utility and flexibility of the proposed optical measuring methods is demonstrated by conducting measurements on two rear-projection systems, and a front-projection system. All of these display systems used 3D active shutter glasses for stereoscopic vision. A description of the three display systems is summarized in Table 1. Figure 3 illustrates the typical detector setup conditions used for each display system. The detector was aligned to simulate the eye position of a typical viewer. For the first and second display systems, the user is generally standing in front of the screen, with or without head-tracking devices. We used a 170 cm (5′7″) tall viewer to simulate the eye height, standing about half the screen height away from the front screen, and centered horizontally on the screen. The third display system was set up in front of a U-shaped conference table. The detector was aligned to the height at the center of the screen, which roughly corresponded to the seated eye height of a typical viewer, and set back to the middle of the conference table. Although this third display system may be perceived as immersive (with $> 60^{\circ}$) only for a viewer near the very front of the display, this system was included in our study in order to highlight some of the unique aspects of front-projector systems.

The typical viewing conditions define the nominal viewpoint location on the front screen. Most of the measurements were performed with the room lights off. However, some measurements were conducted with partial room lighting. In the case of the 4-wall CAVE system, the estimated impact of the light from the side screens and floor was also evaluated.

3.2 Basic Display Optical Performance Characteristics

These fundamental luminance and color characteristics are usually measured in the center of the screen and under dark room conditions. In the case of the large

Table 1. *General Characteristics of the 3D Immersive Display Systems Measured in This Study*

Characteristic	Display System #1	Display System #2	Display System #3
Install year	2004	2013	2009
Screen size	2.67 m × 2.07 m	4-wall CAVE (3.04 m × 3.04 m per wall)	3.78 m × 2.13 m
Screen resolution	1280 × 1024	1920 × 1924 (2 overlapping projectors per screen)	1920 × 1080
Projector	3-chip DLP ®* lamp projector	3-chip DLP ®* lamp projector	3-chip DLP ®* lamp projector
Display type	Rear-projection	Rear-projection	Front-projection
Nominal measurement position	1.65 m high, 1.22 m from front	1.65 m high, 1.52 m from front	1.46 m high, 5.4 m from front

*DLP ® is a registered trademark of Texas Instruments.

Figure 3. *The typical detector configuration is shown for each display system measured in this study. In the case of display #2, the figure shows the adjacent screens turned off in order to measure the intrinsic characteristics of the front screen, which is not the normal operational scenario for a CAVE.*

immersive display tested in this study, these values are measured at the viewer's eye height and the horizontal center of the front screen (the viewpoint location). The luminance and color measurements are usually made over a range of colors, typically including black, peak white, and the red, green, and blue (RGB) primary colors. Several performance metrics can be determined from these basic measurements, such as contrast ratio, color gamut, and color gamut area. The inclusion of additional colors, such as the cyan, magenta, and yellow secondary colors (CMY), often helps to better describe the color gamut capability of the display through a color gamut volume evaluation.

Industry best practice recommends that measurement of colors should be input-referred. For example, when a peak red primary is to be displayed, a maximum electrical signal is provided at the red channel video input. The display technology, color calibration, and color management eventually dictate the final luminance and color rendered to the viewer. The sRGB or BT.709 color space is often used to render images for desktop or high definition TV applications (IEC 61966-2-1, 1999;

ITU-R BT.709-5, 2008). The ambient room lighting, and unintended light from adjacent screens in CAVE displays, can also alter the observed luminance and color. But these extrinsic effects will be discussed in a later section.

Since the spectra of the RGB primaries for all the immersive displays under test were relatively broad, a filter-based detector would have been appropriate for the basic measurements. However, some of our more extensive measurements required the actual spectral data. Therefore, a precision spectroradiometer (Photo Research PR-740)[2] with a 1° aperture and 4 nm bandwidth was used for the discrete photometric and colorimetric display measurements. In addition, the availability of area detectors with absolute luminance and accurate color calibrations enables high resolution mapping and analysis of the visual information. Some examples of the utility of area detectors will also be presented, using an SBIG ST-2000XMIUV camera with a relative photopic filter.

All of the display characteristics are measured using simple test patterns, where luminance and color measurements are obtained from a fully illuminated screen, or small rectangular box, of a given display color. Since the displays evaluated in this study use front- or rear-projection systems, our measurement procedures have their roots in past projection standards (IEC 61947-1, 2002; ISO 21118, 2012). However, advances in display technologies have necessitated improvements in the measuring methods (ICDM, 2012). We demonstrate some of the new methodologies in this study and highlight the value of their use.

All of the systems in this study were stereoscopic displays that utilized 3D glasses. Although the fusion of images from both eyes creates part of the immersive effect, the monocular display characteristics are still an important component of the display quality. The assessment of the display's monocular optical characteristics was demonstrated by measuring the display as observed through the left lens of the active glasses. The lens of the active glasses was placed directly in front of the lens of the spectroradiometer and modulated the transmitted light at its native refresh rate. The spectroradiometer was allowed to automatically select its optimum integration time depending on the signal level, which was typically several seconds. A summary of the basic optical characteristics of each display is given in Table 2. All of these measurements were taken with the room lights off. In addition, in the case of display system #2, only the front screen was turned on in order to measure the performance of the screen with the least light contamination from the adjacent floor and side screens. Although this setup does not represent the usual operational scheme of the CAVE, it does characterize the intrinsic screen properties absent the immersive environment contribution. The effect of the light contamination from the adjacent screens will be discussed later.

Display system #2 produced the largest luminance to the viewer at the reference viewpoint. This was likely due to the fact that it had the newest projector technology and that it used two projectors to illuminate a single screen. The large luminance also helped this system to obtain the best contrast ratio. This provided the viewer with a greater dynamic range in which to see small differences in shades where subtle features may lie. However, the luminance and contrast ratio were not uniform for any of the displays. The luminance was sampled at nine screen positions (center and 10% of the screen dimension from the corners and edges), by using the vantage-point method. By this method, the sampled luminance nonuniformity was found to be roughly 50% for the front screens of all the displays. Although this level of nonuniformity would clearly be noticeable on a typical desktop monitor, it is actually difficult to notice by a user in front of these screens because of the large angular subtense of the visual field. A higher resolution representation of the screen luminance nonuniformity can be obtained by using a photopically corrected area detector (camera). Figure 4 shows an example of the relative luminance map of the screen from display system #3. Figure 5 gives the horizontal and vertical luminance profile taken through the center of the relative luminance

2. Certain commercial equipment, instruments, materials, systems, and trade names are identified in this article in order to specify or identify technologies adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the systems or products identified are necessarily the best available for the purpose.

Table 2. *Dark Room Monocular Optical Characteristics of the Display Systems Measured in This Study Measured Through the Left Lens of the Active 3D Glasses*

Monocular Characteristics	Display System #1 (1 screen, rear-projection)	Display System #2 (4 screens, rear-projection)	Display System #3 (1 screen, front-projection)
Luminance (cd/m^2)	6.5	22	19
Contrast ratio (L_{white}/L_{black})	254	1660	1255
Luminance nonuniformity $= 100\% \times (1-L_{min}/L_{max})$	45	54	46
White color (CIE 1931 chromaticity and CCT)	(0.3015, 0.3348) 7062 K	(0.2953, 0.3425) 7305 K	(0.3304, 0.3658) 5585 K
Color gamut area (CIE 1976 diagram)	33%	28%	36%
Color gamut volume (CIELAB volume)	1,026,100	824,720	1,066,500
White color nonuniformity (maximum $\Delta u'v'$)	0.0063 3.6× for blue	0.0062 3× for blue	0.0039 2× for blue
White luminance change with viewing direction	−22% (at 45°)	−27% (at 45°)	−19% (at 30°)
White color chromaticity shift $\Delta u'v'$ at 45°	0.0018 (0.0059 for blue)	0.0015 (0.0045 for blue)	0.0011 at 30° (0.0013 for green)
Transmission of glasses (photopically weighted)	27%	32%	30%
Percent color area loss (due to eye glasses)	7.6%	10%	4.7%

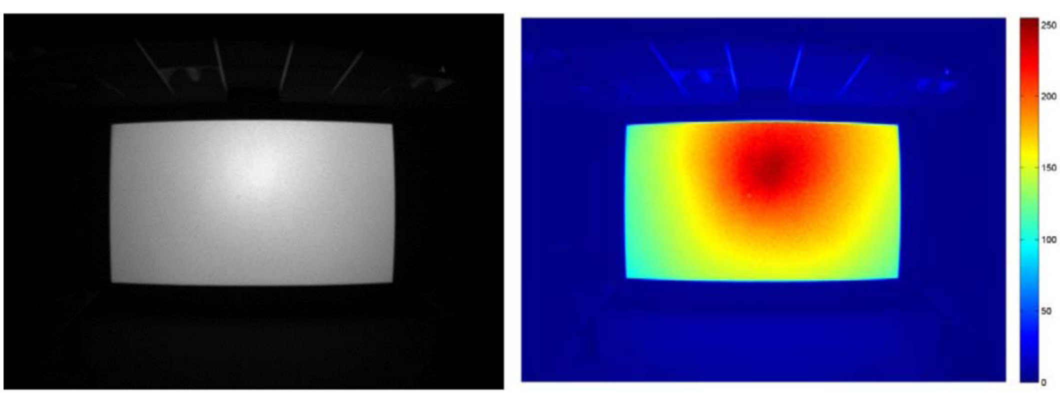

Figure 4. *Relative luminance distribution across display system #3 screen. The right image is a false color representation of the original greyscale image on the left.*

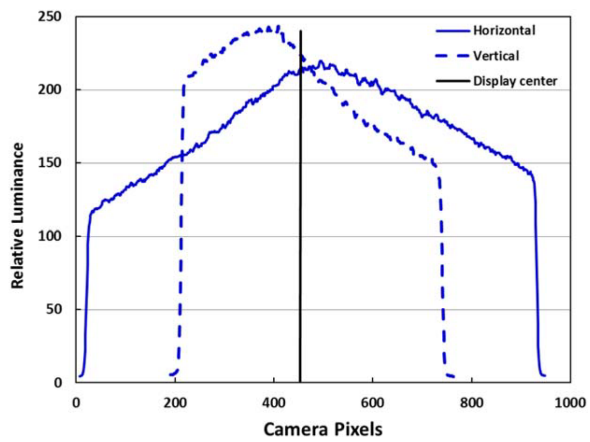

Figure 5. *Relative horizontal and vertical luminance profile through screen center of display #3. The vertical profile is from top to bottom of the screen with increasing pixel number.*

map. The luminance maps provide a useful visual representation of the display nonuniformity. All three of the projection systems tested tended to have a luminance (and contrast ratio) peak near the center of the screen, and dropped off toward the screen edge. As a consequence of this nonuniformity, the critical features will be most discernable near the screen center and start fading away near the edges. The luminance maps may also be a useful tool to better align the optical axis of the projector and help minimize the luminance nonuniformity.

Broadband white light sources are often described by their correlated color temperatures (CCT), which describes the white color based on a blackbody at the same temperature (Berns, 2000). A measurement of the white point chromaticity and CCT is a valuable indicator for determining the color calibration of the display system. The white color CCTs (see Table 2) for displays #1 and #2 were measured to be a bit bluish relative to the standard sRGB or BT.709 white point of 6504 K (IEC 61966-2-1, 1999; ITU-R BT.709-5, 2008), while display #3 was too yellow. This suggests that the coded input color signals will not be rendered correctly for sRGB-encoded image content. The color rendering range (or gamut) was characterized by measuring the colors produced by the display for pure red, green, and blue signal inputs. The results are presented in Figure 6 on a CIE 1976 UCS diagram. The range of colors that the display can render can be visualized by the area within the RGB triangle in the CIE 1976 chromaticity diagram. The relative magnitude of this color gamut area is usually expressed as a percentage of the total area contained within the spectrum locus of all visible colors (ICDM, 2012). Although display #1 has the same 33% color gamut area as the sRGB standard, Figure 6 confirms that the RGB triangle of display #1 does not completely overlap the sRGB triangle. In this case, display #1 is not capable of producing deep blue colors that may be encoded in the intended signal. In fact, all three projection systems were not able to cover the deep blue colors required for sRGB or BT.709 color encoding.

The CIELAB color gamut volume values given in Table 2 were estimated by measuring the maximum white, red, green, blue, cyan, magenta, yellow, and black rendered colors for each display system and calculating the volume within those boundary points (IEC 62341-6-2, 2012; Braun & Spaulding, 2002; CIE 168, 2005). The color gamut volumes for displays #1 and #3 are substantially larger than the sRGB value (8.2×10^5), but these values should be tempered by how much of those volumes overlap the sRGB color space.

The screen color nonuniformity of each display was sampled at the same nine locations used in the vantage-point luminance nonuniformity measurement. The color nonuniformity was evaluated by determining the white chromaticity difference between any two locations (i and j) on the front screen using the following CIE 1976 chromaticity difference equation:

$$\Delta u'v' = \sqrt{\left(u'_i - u'_j\right)^2 + \left(v'_i - v'_j\right)^2} \qquad (2)$$

where (u'_i,v'_i) and (u'_j,v'_j) represent the CIE 1976 chromaticity coordinates at any combination of two screen locations, with i and $j = 1$ to 9, and $i \neq j$. The amount of color nonuniformity can be characterized by the maximum $\Delta u'v'$ value on the screen. For the three display systems in our study, the maximum $\Delta u'v'$ value for a white screen was relatively small, ranging from 0.004 to 0.006. However, the color nonuniformity results in Table 2 also highlight that the blue screen was found to be more than a factor of two worse. This suggests that the color rendering will be different across the screen, and is starting

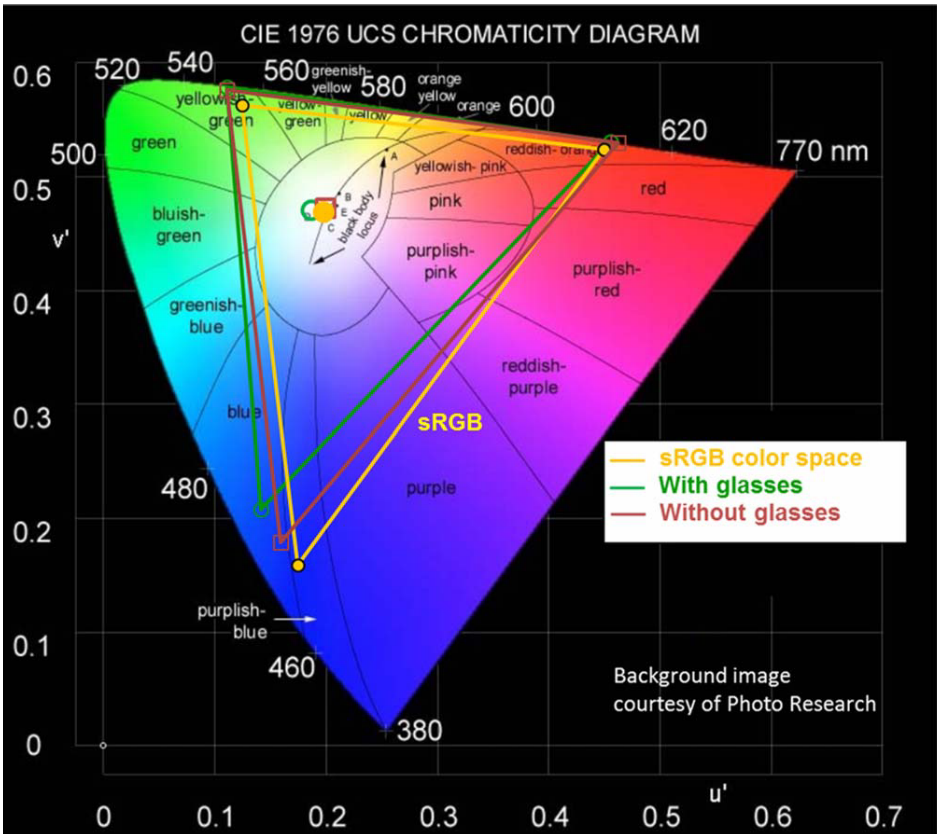

Figure 6. *White and RGB primary colors rendered by display #1 illustrated on the CIE 1976 UCS chromaticity diagram. The colors were measured with and without the 3D glasses and compared to the standard sRGB color gamut.*

to approach the $\Delta u'v' = 0.04$ value that is considered noticeable for nonadjacent colors (ICDM, 2012).

The viewing angle dependence of the display characteristics were determined by changing the inclination angle of the detector's optical axis while maintaining the same viewpoint position at the screen center. For displays #1 and #2, the detector could swing out to a 45° viewing direction. Display #3 could be measured out to only 30°. Projection systems generally have a non-Lambertian light scattering distribution transmitted or reflected off the projection screen, where the luminance typically drops off with viewing direction. This was observed in the displays measured in this study, with up to a 27% reduction in white luminance at the 45° viewing direction (see Table 2) relative to viewing at normal incidence. However, no significant degradations in the contrast ratios with viewing direction were measured. Display color was found to shift with viewing direction. The rear-projection displays tended to exhibit the largest white color shifts. A measure of the primary colors suggested that the blue primary was the dominant factor, with the blue primary shifting up to $\Delta u'v' = 0.0059$ at the 45° viewing direction. However, these color shifts are not especially large. Therefore, an observation of an image over the measured angular range would not likely perceive a noticeable difference.

The color performance of these stereoscopic displays can be affected by the quality of the active shutter glasses. The spectral transmission properties of the 3D glasses used by all three displays was obtained (see Figure 7) by measuring the spectral radiance of a white screen with and without the glasses. All of the displays

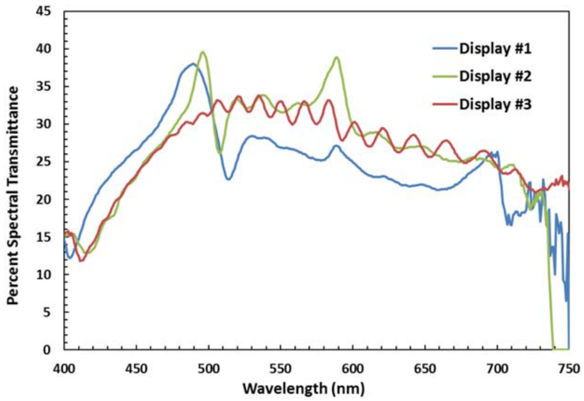

Figure 7. *Percent spectral transmittance of left lens of active glasses used by the three display systems in this study.*

tested had 3D glasses with a significant drop-off in the blue. Figure 6 demonstrates that this drop-off reduces the color gamut of the display in the blue region, resulting in a 5% to 10% loss in color gamut area. In addition, by measuring the luminance of the screen with and without glasses, the eye glass transmission data in Table 2 show that about 70% of the luminance signal is lost passing through the glasses. Although about 50% of the luminance loss is due to the time-sequential blanking of the eye glasses needed to produce the stereoscopic effect. These results demonstrate that the eye glasses can play an important part in the image quality of the display. Since the eye glasses are by far the least expensive element of the display system, there is an opportunity for significant gains in display performance by using better eye glasses or stereoscopic technology.

All of the optical measurements presented thus far used a full screen image of a single color. However, for some newer projector technologies, especially those that have more than the standard three RGB primaries, it has been observed that display performance can change depending on the test pattern (Kelley, Lang, Silverstein, & Brill, 2009). A color-signal white methodology has been developed to gauge the test pattern dependence and estimate the display performance for more realistic imagery (Kelley, Lang, Silverstein, & Brill, 2009; ICDM, 2012).

Figure 8 illustrates the sequence of test patterns used for these measurements. The luminance (rear-projector) or illuminance (front-projector) measurements are typically measured at the center of the nine RGB box locations. For display technologies that do not inherently exhibit luminance loading behavior, the sum of the RGB luminance or illuminance values should add up to the full screen white value (ICDM, 2012). However, if the display technology does exhibit luminance loading (e.g., Organic Light Emitting Diode (OLED) displays or LCDs with local dimming), then the measurement must take into account the signal level and size of the test patterns. For color displays in which the input signals conform to a standard set of RGB digital values, any difference between the measured full screen white luminance (or illuminance) and the sum of the RGB measurements indicates a lack of color additivity of the color signal primaries between the test patterns. This would suggest that the display's color management system renders the images differently in each case. In that case, the use of single full screen color test patterns is not recommended, since these test patterns would not provide an accurate representation of the display performance for typical imagery. For the displays measured in this study, the white luminous flux of the front-projector and the white luminance of the rear-projectors were found to be the same for the full white screen and color-signal white method. This check confirms that the traditional single color full screen measurements could be used to characterize these displays.

The open configuration of the front-projector system (display #3) enabled the properties of the projector and screen to be characterized separately. This allowed for a better understanding of how each of the major components of the system contributed to the net performance of the display system. For example, by measuring the average white illuminance at the standard nine screen locations, and multiplying by the screen area (in square meters), we obtained an average projector luminous flux of 1440 lumens. This value could then be compared to the manufacturers' stated value for the projector. How much of the projector light is then reflected by the screen to the viewer is dependent on the scattering profile of the screen. The scatter profile can be engineered to preferentially scatter more light into the direction perpendicular to the screen plane, which is characterized by

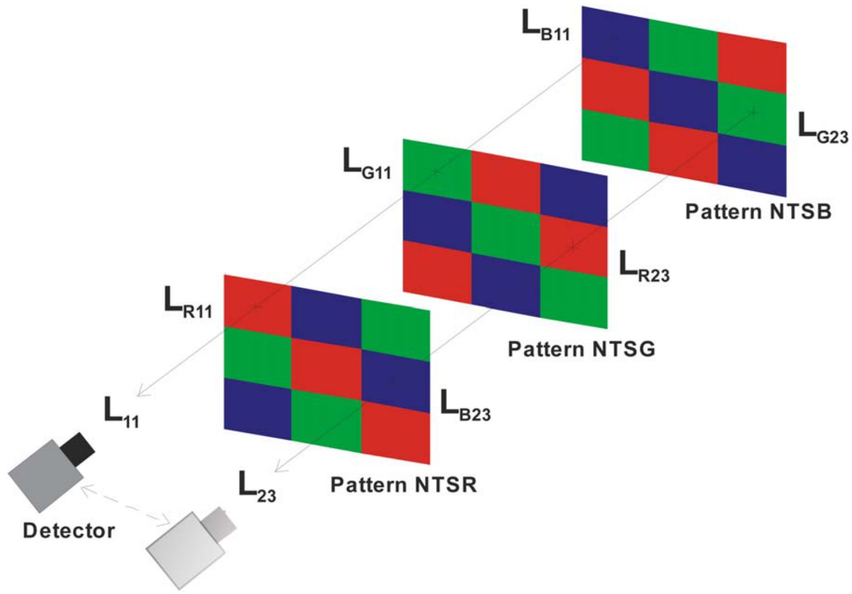

Figure 8. *The nonatile trisequence patterns used by the color-signal white method.*

the screen gain. The screen gain is determined by measuring the luminance reflected by the screen relative to the luminance that would be reflected by a perfectly reflecting diffuser (ICDM, 2012). For display #3, the screen gain was found to be 0.92. Since most of the viewers are within $\pm$ 30° of the display normal, an engineered screen with higher gain could have used to improve the system's photometric performance. The current screen was also found to produce minimal color shifts.

3.3 Evaluating the Influence of Ambient Illumination

As with all displays, the display characteristics can be affected by external/unintended lighting. The external lighting may come from luminaires in the room. In the case of a CAVE configuration, unintended lighting may also come from screens adjacent to the one being viewed. Most often, the ambient illumination is unavoidable or necessary. However, a better understanding of how the ambient lighting impacts the display performance can guide the display owner or content provider in minimizing the negative aspects of the light contamination. Each of the display systems in this study had its own unique ambient light issues. For display #1, the user would generally view the single screen in a dark room. However, the room itself had a light-colored carpet and white walls. Therefore, the light from the screen could be scattered off these surrounding surfaces and wash out the image on the screen. The 4-sided CAVE (display #2) represents an extreme example of a concave display geometry, where light created from adjacent areas of the display system can unintentionally illuminate the viewing area of interest. The conference room format of display #3 illustrates a use case were the users may need overhead lighting in order to write, but where the lighting design can lead to light contamination on the screen. Each display system was measured under its unique ambient illumination environment, and its impact on display performance was determined.

In the case of display #1, the screen faces a white wall 3.8 m away. It was observed that light emitted from the rear-projection screen backscattered off the surrounding surfaces and created light contamination on the screen. This backscatter was investigated by covering the majority of the facing white wall with a black curtain. This produced a 5% reduction in the display luminance (due to

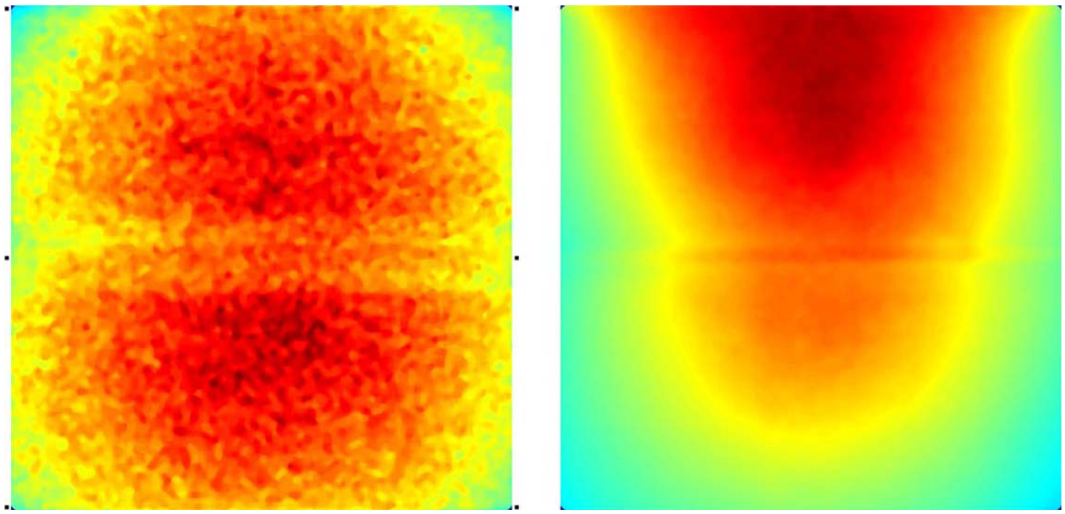

Figure 9. *Relative contrast ratio false color map of display #2, with the floor and side screens turned off (left image) and turned on (right image). Red indicates a high contrast ratio.*

the backscatter), a 1% increase in the contrast ratio (due to a darker black level), and a 1% increase in the color gamut area. Therefore, the backscatter from the surrounding surfaces had a minimal impact on the display performance. This was likely due to the low display luminance and relatively large room size.

The 4-wall CAVE of display #2 represents a situation where the scattering surfaces are in close proximity to the front screen, in addition to emitting their own light. In order to quantify the worst case impact of the light contamination from the adjacent screens, the front screen image properties were measured with the floor and side screens emitting at their maximum white luminance. Although this is not a typical scenario for a CAVE system, it does help to bound the impact of the light contamination relative to the absence of that light. This situation resulted in a front screen luminance increase of 18%, the contrast ratio collapsed to 7.3, the color gamut area dropped to 9.7%, and the color gamut volume was reduced to 25% of its original value. Typical imagery would not likely produce these dramatic effects. Since the ambient illumination was measured separately from the front screen emission, it could be scaled to more typical luminance values for the floor and side screens, and then used to predict the front screen characteristics. For example, if the floor and side screens emit at only 30% of their maximum white luminance, the front screen luminance would increase by 5%, the contrast ratio would decrease to 21, the color gamut area drops to 19%, and there would be a 47% loss in the color gamut volume compared to the case with no ambient illumination. These are center of front screen values, and will vary over the screen.

Display designers and content providers of these CAVE systems should recognize that the quality of the viewing experience at a given screen location can be impacted by the image content on the adjacent screens. This is illustrated by the contrast ratio maps in Figure 9. The maps were captured by digital camera images of the front screen rendering its minimum black color state and its maximum white state. The grayscale camera employed a photopic filter to simulate the eye's response. The 2D contrast ratio map was determined by performing a camera pixel-by-pixel ratio of the white field image to the black field image. The contrast ratio map in the left image, with the adjacent screens turned off, resembles the luminance profile produced by the two overlapping rear-projectors. However, the right image (with the adjacent screens turned on) is dominated by the light contamination from the side screens and floor. This image demonstrates that the contrast ratio is the lowest adjacent to the left and right screen, and the floor, due to the light contamination from those planes.

For projection displays, the amount of light contamination on the front screen is dependent on the scattering profile of the side screens and floor. The amount of side scatter can be reduced by using engineered screens with higher screen gain. Alternatively, direct view displays, such as narrower viewing range LCDs or OLED displays, can be used instead of projection displays to limit the amount of light contamination on the adjacent screens. But the benefits of enhancing the forward light scattering/emission would need to be balanced against any significant reduction in the viewing angle performance and the enhanced light contamination incident on the opposing screen (for concave geometries). Another approach to limiting light contamination from the adjacent screens is to use darker backgrounds in the image content when possible.

In the conference room environment of display #3, the overhead fluorescent lights were the dominant source of light contamination on the screen. Although the room designers were careful to use dark materials for the reflective surfaces, some of the fluorescent lighting was directly illuminating the presentation screen. The light contamination from the fluorescent lights produced a 63% increase in the screen luminance, the contrast ratio dropped to 2.7, the color gamut area dropped to 3.3%, and the color gamut volume was reduced to 8% of its original value. Therefore, the ambient lighting severely impacted the viewability of the imagery. This could be mostly mitigated by baffling the overhead lighting, and using directional or local lighting at the conference table.

3.4 Stereoscopic Display Measurements

Several stereoscopic measuring methods have been standardized for direct view displays (IEC 62629-12-1, 2014; ICDM, 2012), but they have yet to be developed into projection display standards. This study adapts the direct view stereoscopic display measuring methods. These methods focus on 3D crosstalk, and the luminance or color differences observed between the left and right eyes. The left–right eye differences were also evaluated as a function of viewing direction and head tilt. The 3D crosstalk was measured at the nominal viewpoint location and the standard equally spaced nine screen locations using the spectroradiometer. It was also measured in high resolution over the entire screen using a photopically weighted camera. These measurements provide an indication of the display's 3D static image performance. The evaluation of a 3D display's dynamic characteristics (such as flicker and motion artifacts) are still under development.

A full white test pattern was presented on the screen for the left and right eye signal channels. The luminance of the screen was measured through the left lens of the 3D glasses, then through the right lens. The luminance difference between the left and right eye for all three displays was found to be only 1% or less (see Table 3). A similar process was followed when measuring the monocular contrast ratio difference between the eyes, and yielded differences of less than 3%. The color differences between the left and right eyes at the user's nominal viewpoint were also found to be relatively small, with the blue primary exhibiting the largest differences. Although the human visual system is most sensitive to color changes in the blue region, the observed chromaticity differences measured for the display under test were too small to be a concern. The luminance and color differences were also measured on the standard nine locations over the screen. The worst case values are tabulated in Table 3. These values were higher than the nominal viewpoint values, but still found to be at acceptable levels.

The luminance and color difference dependence on viewing direction followed a similar procedure as the monocular measurements, but now for both eyes. Table 3 summarizes the viewing dependence results by listing the worst case values. For the most part, only small left–right eye chromaticity differences were observed. However, the chromaticity difference of the blue primary for display #2 was approaching the $\Delta u'v' = 0.004$ threshold where adjoining colors are considered discernable. This chromaticity difference was persistently high for all viewing conditions, which suggested an issue with the 3D

Table 3. *Left and Right Eye Differences of the Stereoscopic Optical Characteristics for the Display Systems in This Study Measured Through the Active 3D Glasses in a Dark Room*

3D Characteristics	Display System #1 (1 screen, rear-projection)	Display System #2 (4 screens, rear-projection)	Display System #3 (1 screen, front-projection)
Viewpoint white luminance difference	0.8%	1.0%	1.0%
Max white luminance difference (from 9 locations)	1.9%	1.2%	1.5%
Viewpoint white chromaticity difference ($\Delta u'v'$)	0.0006 (0.0027 for blue)	0.0013 (0.0034 for blue)	0.0008 (0.0020 for blue)
Max white chromaticity difference (from 9 locations) ($\Delta u'v'$)	0.0010	0.0022	0.0009
Max luminance difference with viewing direction	1.5%	3.2%	1.1%
Max white chromaticity difference with viewing direction ($\Delta u'v'$)	0.0006 (0.0006 for blue)	0.0016 (0.0034 for blue)	0.0011 (0.0018 for blue)
Left eye viewpoint 3D crosstalk	0.3%	0.4%	0.4%
Left eye 3D crosstalk vantage point non-uniformity (Std. deviation of 9 points)	± 0.08%	± 0.03%	± 0.01%
Camera average left eye 3D crosstalk (camera distance from screen)	1.4 ± 1.3% (3.3 m)	1.0 ± 0.8% (4.5 m)	1.4 ± 1.3% (5.4 m)

glasses. If that was the case, it could be readily remedied by a different choice of 3D glasses.

The 3D crosstalk performance of the displays was measured at the nominal viewpoint on the front screen, in a dark room, with any side screens turned off. This viewpoint location was the foveal vision area of the observer, and corresponded to the sweetspot of the 3D crosstalk pattern, which tended to give the lowest crosstalk values. The simulation of foveal vision is realized by the 1° measurement field angle of the detector. The viewpoint 3D crosstalk values of the three display systems in our study are given for the left eye in Table 3. The right eye 3D crosstalk measurements yielded similar low values. The 3D crosstalk nonuniformity of the three display systems is expressed in Table 3 as the standard deviation of the crosstalk at the nine standard locations on the screen using the vantage point method. As indicated by the 3D crosstalk nonuniformity data, the crosstalk levels remained relatively low over the entire screen. The low crosstalk values are partly a consequence of the vantage point method for measuring screen uniformity, which tends to align the sweetspot of the 3D crosstalk pattern to the center of the measurement area. This is reasonable for large immersive displays, where head and eye glass movements are necessary in order to observe the different areas of the display. Negligible levels of 3D crosstalk were also measured for viewing directions up to 45°, and tilting the eye glasses/head sideways up to 20°.

Additional information may be obtained via camera images of the 3D crosstalk (as demonstrated in Figure 2), which offers a wider viewing field. The camera images can be used to create 2D crosstalk maps of the entire display (Penczek, Boynton, & Kelley, 2013). This can provide information on how the 3D crosstalk changes from our central foveal vision toward our peripheral vision. These crosstalk maps can be evaluated in a variety of ways depending on the application. For example, Table 3 gives the camera average 3D crosstalk and standard deviation over the entire screen for each the three display screens in this study.

4 Summary

We have proposed a suite of optical measuring methods that can be used to evaluate a wide variety of immersive display systems. These methods were applied to front- and rear-projection displays, in single screen and multi-screen CAVE environments. It was demonstrated how the methods can determine the dark room monocular display characteristics, the influence of ambient lighting and light from adjacent screens, and some stereoscopic properties of the displays. The measurements reveal some of the intrinsic capabilities of a display, and give the user a greater understanding of how the display is rendering the intended image content. This information can be used by display designers to develop better displays, and to guide display owners in operating their displays more effectively.

Scientific applications of immersive displays often use visualization to present complex datasets or scenes to a researcher. In doing so, it is important for the content provider to understand the limitations of the display. The content provider could expend significant effort on image content that the display may not be capable of rendering. If there are subtle shades or patterns that contain important information, then the display must have the intrinsic contrast ratio in order for the viewer to perceive it. For the displays in this study, the projector light source nonuniformity resulted in the best contrast ratios lying near the center of the screen under dark room conditions. We also demonstrated that the contrast ratio can be dramatically degraded, and its profile across the screen modified, with the introduction of ambient lighting. For example, Figure 9 shows that the ambient light contamination shifts the position of the best contrast ratio to the central top of the screen. Light contamination can be especially problematic for multi-wall CAVE systems, where the images from the adjacent screen can reduce the viewability at the region of interest. For single screen displays, the ambient lighting can be somewhat mitigated by a more careful configuration of the light sources. However, the concave geometry of many CAVE systems is prone to self-contamination issues. Therefore, the image content needs more careful consideration, such as minimizing the luminance levels around critical features in images. The 3D crosstalk from stereoscopic displays can also lead to reductions in the effective contrast ratio of the system, especially for higher spatial frequencies features (Penczek, Boynton, & Kelley, 2013). The quality of the active shutter glasses can play a large role in this case.

In addition to the image information encoded via intensity variations or shading, the information can also be color encoded. This utilizes the human visual system's ability to discern color differences. Content providers can exploit our sensitivity to color by enhancing certain image features, such as using false color maps. However, our ability to fully utilize color information is usually limited by the display. We have demonstrated that all of the displays in this study have a limited range of colors, yet the number of possible colors approaches or exceeds that of common color spaces, such as sRGB. We also showed how the color range can be significantly reduced by light contamination, or the 3D glasses, although both of these detractors can be dealt with if we are aware of them. A more difficult problem occurs when the intrinsic display color gamuts do not completely overlap the standard sRGB color space. In this case, the encoded colors in the image would be rendered differently on each display. The lack of accurate color gamut mapping to sRGB may not be so apparent for artificial scenes or synthetic images, but may be noticeable for natural scenes and flesh tones, where users have specific expectations of the proper color. This issue can be minimized by a color calibration to the sRGB color space, but should eventually be resolved through the development of higher gamut displays.

As new technologies are introduced into immersive displays, the viewer is likely to benefit from an improved visual experience. However, these advances will require a thoughtful consideration of how these new systems should be measured. When LED and laser sources are used, the spectral resolution of the measurement detector needs to increase. Narrow bandwidth light sources may also put further demands on the instrumentation in regard to dynamic range, intensity saturation, polarization dependence, and frame synchronization. Further, as the display's image rendering gets more complex, the measurement methods also need to adapt. For example, display technologies that exhibit luminance loading, or utilize features like local dimming, are sensitive to the images being tested. Similarly, the introduction of multi-primary, or RGB and white primary displays, has led to a plethora of color management solutions. Displays have already developed to the point where they can change their color management depending on the content in the individual frames. The measurement community continues to develop strategies, such as the color-signal white measuring method, to address the growing display complexity, yet further refinements will be needed in order to keep pace with the evolving display innovations. This study highlights the current best practices for determining the basic characteristics of today's displays. Although these measurements provide important and necessary metrics for display performance, they are still inadequate to quantifying the "wow" factor of a quality immersive display.

References

Berns, R. S. (2000). *Billmeyer and Saltzman's principles of color technology* (3rd ed.). New York: John Wiley & Sons.

Braun, G., & Spaulding, K. (2002). Method for evaluating the color gamut and quantization characteristics of the output-referred extended-gamut color encodings. *Proceedings of the IS&T/SID Tenth Color and Imaging Conference,* 317–324.

CIE 15. (2004). *Colorimetry.* Vienna: International Commission on Illumination.

CIE 168. (2005). *Criteria for the evaluation of extended-gamut colour encodings.* Vienna: International Commission on Illumination.

Cruz-Neira, C., Sandin, D. J., DeFanti, T. A., Kenyon, R. V., & Hart, J. C. (1992). The CAVE: Audio visual experience automatic virtual environment. *Communications of the ACM, 35*(6), 65–72.

Cruz-Neira, C., Sandin, D. J., & DeFanti, T. A. (1993). Surround-screen projection-based virtual reality: The design and implementation of the CAVE. *Computer Graphics (Proceedings of SIGGRAPH '93), ACM SIGGRAPH,* 135–142.

Hale, K. S., & Stanney, K. M. (2015). *Handbook of virtual environments: Design, implementation, and applications* (2nd ed.). Boca Raton: CRC Press.

ICDM. (2012). *Information display measurement standard, V1.03.* Campbell, California: Society for Information Display.

IEC 61966-2-1. (1999). *Multimedia systems and equipment—Colour measurement and management—Part 2-1: Colour management—Default RGB colour space—sRGB.* Geneva: International Electrotechnical Commission.

IEC 61947-1. (2002). *Electronic projection—Measurement and documentation of key performance criteria—Part 1: Fixed resolution projectors.* Geneva: International Electrotechnical Commission.

IEC 62341-6-2. (2012). *Organic light emitting diode displays—Part 6-2: Measuring methods of visual quality and ambient performance.* (See Annex B.) Geneva: International Electrotechnical Commission.

IEC 62341-6-3. (2012). *Organic light emitting diode displays—Part 6-3: Measuring methods of image quality.* Geneva: International Electrotechnical Commission.

IEC 62629-12-1. (2014). *3D Display devices—Part 12-1: Measuring methods for stereoscopic displays using glasses—Optical.* Geneva: International Electrotechnical Commission.

ISO 11664-1. (2007). *Colorimetry—Part 1: CIE standard colorimetric observers.* Geneva: International Organization for Standardization.

ISO 11664-4. (2008). *Colorimetry—Part 4: 1976 L*a*b* colour space.* Geneva: International Organization for Standardization.

ISO 21118. (2012). *Information technology—Office equipment—Information to be included in specification sheets—Data projectors.* Geneva: International Organization for Standardization.

ITU-R BT.709-5. (2008). *Parameter values for the HDTV standards for production and international programme exchange.* Geneva: International Telecommunication Union.

Kelley, E. F., Lang, K., Silverstein, L. D., & Brill, M. H. (2009). A rational methodology for estimating the luminous flus based upon color primaries from digital projection displays. *National Institute of Standards and Technology Internal Report 6657.* Gaithersburg, MD.

Kooi, F., & Toet, A. (2004). Visual comfort of binocular and 3D displays. *Displays, 25*(2–3), 99–108.

NIST. (2015) Information Technology Laboratory. *Immersive display test patterns.* Retrieved from http://www.nist.gov/itl/math/hpcvg/idisplays.cfm

Penczek, J., Boynton, P. A., & Kelley, E. F. (2013). Measuring 3D crosstalk uniformity and its influence on contrast ratio. *Journal of the Society for Information Display, 21*(6), 225–230.

Pöllön, M., Hakala, J., Bilcu, R., Järvenpää, T., Häkkinen, J., & Salmimaa, M. (2012). Color asymmetry in 3D imaging: Influence on the viewing experience. *3D Research, 3*(3). doi: 10.1007/3DRes.02(2012)5

Ukai, K., & Howarth, P. A. (2008). Visual fatigue caused by viewing stereoscopic motion images: Background, theories, and observations. *Displays, 29*(2), 106–116.

Urvoy, M., Barkowsky, M., & Le Callet, P. (2013). How visual fatigue and discomfort impact 3D-TV quality of experience: A comprehensive review of technological, psychophysical, and psychological factors. *Annals of Telecommunications, 68*(11–12), 641–655.

Woods, A. J. (2012). Crosstalk in stereoscopic displays: A review. *Journal of Electronic Imaging, 21*(4). doi: 10.1117/1.JEI.21.4.040902