Characterization of crosstalk in stereoscopic display devices

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Abstract — Many different types of stereoscopic display devices are used for commercial and research applications. Stereoscopic displays offer the potential to improve performance in detection tasks for medical imaging diagnostic systems. Due to the variety of stereoscopic display technologies, it remains unclear how these compare with each other for detection and estimation tasks. Different stereo devices have different performance trade-offs due to their display characteristics. Among them, crosstalk is known to affect observer perception of 3D content and might affect detection performance. We measured and report the detailed luminance output and crosstalk characteristics for three different types of stereoscopic display devices. We recorded the effect of other issues on recorded luminance profiles such as viewing angle, use of different eye wear, and screen location. Our results show that the crosstalk signature for viewing 3D content can vary considerably when using different types of 3D glasses for active stereo displays. We also show that significant differences are present in crosstalk signatures when varying the viewing angle from 0 degrees to 20 degrees for a stereo mirror 3D display device. Our detailed characterization can help emulate the effect of crosstalk in conducting computational observer image quality assessment evaluations that minimize costly and time-consuming human reader studies.

Keywords — stereoscopic displays, medical imaging, crosstalk.

1   Introduction

Stereoscopic display devices have many advantages compared with 2D displays. They can augment our understanding of complex structures, increase detection of abnormalities, and improve the detection rate in breast imaging.[1] These displays seem to benefit depth-related tasks performed in close proximity[2] and offer improved visualizations of volumetric data for detection, diagnosis, and treatment of disease as well as training and preparation of medical professionals.[3]

The technology delivers two images, one to each eye individually. These images when viewed simultaneously generate a sensation of depth within the scene for the observer. Stereoscopic display devices have the potential to advance medical imaging applications. The added depth cues when viewing complex volumetric anatomy structures can allow for improved diagnostics.[2] In mammography applications, due to the superposition of normal breast tissue, subtle lesions may be masked or missed by the reviewer and false positives can appear because of an overlap of normal structures. Alternatively, identified legions can be verified through a different view before they are confirmed.[4]

The evolution of these displays has led to many different types of technological implementations in the market. At present, 3D stereoscopic displays are available to consumers, showcasing multiple approaches to delivering stereo image pairs. Examples of such displays include liquid crystal displays (LCD) with a 120 Hz refresh rate using active shutter glasses, LCDs using passive polarized 3D glasses, and autostereoscopic displays using lenticular sheets or parallax barrier with multiview or single view configurations. Comparing the performance on different types of 3D display devices poses a challenging problem. A single volumetric data set can be viewed using different stereoscopic display technologies, which can have different characteristics (active vs. passive).

In this work, we measure and compare high quality luminance measurements collected from three different stereo technologies, which include a 3D display with a passive stereo mirror, a passive interlaced 3D display, and an active 120 Hz 3D display device. These measurements will help assess signal detection task performance on the devices using a computational model.

Many studies have been conducted on crosstalk measurements of stereo display devices. Some focus on the displays, including the 3D glasses used with the particular technology while others on the human observer viewing 3D content and answering questions related to their experience.[5–8] For instance, Ref. 8 investigates questions related to technology comparisons including effects of shuttered displays versus polarized displays. They concluded through human observer experiments that observers experienced greater brightness when they watched 3D still images on a polarized display

compared with a shuttered display, while readability was better on shuttered displays compared to polarized devices. We intend to investigate these questions in the context of medical imaging tasks using a measurement and modeling framework.[9,10] Most of these human observer studies use video game and movie content for their test subjects. Medical images used in diagnosis of tumors, microcalcification, and lumps where signal detection and estimation tasks are performed tend to differ in nature from 3D content used for entertainment. Thus, linking these studies to gray scale X-ray radiography or computed tomography images is often difficult.

Detailed luminance characteristics of different 3D display technologies can highlight how devices behave at certain gray levels when displaying a content. Our goal is to have multiple highly detailed measurements from 3D display devices in certain experimental conditions and incorporate them into a stereoscopic model observer [9,10] in order to simulate perception tasks and assess observer performance for clinically relevant images. We present the measurement methodology and results obtained for three different stereoscopic display devices. We also varied conditions such as viewing angle, viewing location, and the use of different eye wear when measuring luminance and crosstalk profiles for the three devices respectively.

Crosstalk is an important issue when discussing stereo display devices. It is defined as the undesired leakage luminance from one view to another. Many stereoscopic display devices such as the ones based on active shutter, passive polarized, or passive interlaced technology suffer from crosstalk. Active displays are the ones that require shutter glasses that are synchronized with the display to show the left and right image using temporal interlacing, while passive stereo displays filter the constant streams of binocular inputs to separate the left and right views. Studies have shown that crosstalk can cause visual discomfort, increases perceived workload, and reduces image quality of the viewable content for stereo displays that suffer from crosstalk.[11] It also affects the perceived depth from the disparity inherent in stereo image pairs. There has been extensive research on crosstalk measurement methodologies for 3D displays.[12–14] Some methods display on-screen patterns [13] while others [15] use luminance measurements with full screen gray level displayed to measure signal interference between the left and the right view. Crosstalk is defined by multiple authors with subtle differences.[14,16–19] Reference 17 defines crosstalk as:

$$C_L^S = \frac{\beta_2}{\alpha_1}, \tag{1}$$

$$C_L^V = \frac{B\beta_2}{A\alpha_1}, \tag{2}$$

where C_L^S is the system crosstalk and C_L^V is the viewer crosstalk for the left eye; α_1 describes the percentage luminance of the left eye observed in the left eye; β_2 is the percentage luminance of the right eye image leaked into the left eye; A is the luminance of a point in the left eye image, and B is the luminance of the corresponding point in the right eye image. In this approach, the system crosstalk defined in Eq. (1) is independent of the content, while the viewer crosstalk Eq. (2) is dependant upon the contents being viewed. Another simpler definition of crosstalk is stated in Ref. 20 as

$$C_W = \frac{L_W}{S_W} \times 100, \tag{3}$$

where L_W is the luminance that leaks from the unintended source, and S_W is the signal luminance from the intended channel. Using the earlier definitions, maximum black and maximum white images are generally used to calculate inherent crosstalk of the system. Crosstalk in this case is considered to be a linear phenomenon, and a single percentage amount is used to define its occurrence within the display. In some 3D displays, particularly the ones using active shutter technology, crosstalk is not always a linearly additive process.[14] In situations where crosstalk is nonlinear, the gray-to-gray crosstalk measurement provides a more complete description. The gray-to-gray crosstalk is defined by Ref.15 as:

$$C_{L_{ij}} = \frac{L_{L_{ij}} - L_{L_{ii}}}{L_{L_{jj}} - L_{L_{ii}}}, \tag{4}$$

$$C_{R_{ij}} = \frac{R_{R_{ij}} - R_{R_{ii}}}{R_{R_{jj}} - R_{R_{ii}}}, \tag{5}$$

where C is the crosstalk for the left eye (L) calculated, while gray level i is displayed on the left image and gray level j is displayed on the right and in $L_{L_{ij}}$. L is the luminance in the left eye (L), where gray level i is displayed on the left image and gray level j is displayed on the right. Similar representation is used for the equation of the right eye. A full review of the evolution of crosstalk definitions and equations is presented by Refs. [14,16]. We use a variation of the gray-to-gray level crosstalk measurement method based on four sets of measurements of the luminance output. We record the complete luminance versus gray level output of the stereoscopic display device and the effect of crosstalk through the glass lens required by the display device. This helps characterize the complete luminance and crosstalk profiles of the respective display.

Although some methods of crosstalk reduction [21] have been proposed for active stereo display devices, its quantitative impact on performance and visual tasks remains a topic of interest. It is very laborious to conduct a human observer study on every single type of 3D display device and technology, and quantify its image quality. Thus, we intend to emulate the device using its luminance characteristics and using that data to model a computational observer, which assess performance through simulation. The first step is to conduct in-depth analysis of the device luminance response function and measure device crosstalk used as an input data to a stereo model observer. This methodology can help assess different experimental parameters for stereo viewing such as viewing angles, viewing location, and the quality of 3D glasses using an approach similar to Ref. 22.

Measuring crosstalk in display systems has been known to be often difficult because of stereo technology design complexity, practical measurement implementation difficulty, and reluctance of manufacturers to release data.[13] Some methods that use limited measurements to calculate the *Matrix of Lightness Differences* [12] have been proposed, and they highlight that only when we have good characterization methods, we will be able to compare stereoscopic display performance and understand the source and nature of crosstalk which in essence will lead to improvement in 3D performance.

In this work, we present the automated measurement technique for high density data that fully characterizes the luminance and crosstalk for the 3D display device. Additionally, each of the displays has been measured with one other changing parameter. These parameters include viewing angles, viewing location, and different glasses when viewing 3D content. Using a stereo model observer to emulate the device and assess its performance and explore factors such as viewing angles and 3D technologies, using this rich data remains part of our future work going forward.

2 Methods

The devices used in this work are presented in Table 1 and are referenced using their index from the table throughout this paper. Our measurement approach is to record four sets of independent measurements and combine them to output a luminance map for the left and the right screen for the respective 3D display device. Figure 1 shows that the $L_L(i)$ and $L_R(i)$ are calculated purely from the left and right screens, respectively, while the other one is turned off. The second row in Fig. 1 shows that $L_L(i)$ and $L_R(i)$ represent the lens crosstalk measured through the glasses. i is the complete range of gray levels that is displayed full screen, hence $0 \le i \le 255$. These gray levels are varied on the screen that is turned on. For instance, when measuring $L_L(i)$, all gray levels are cycled through on the left screen and when $L_L(i)$ is being recorded, the gray levels are displayed only on the right screen. It should be noted here that $L_L(i)$ is the luminance response from the left screen, while $L_L(i)$ is the crosstalk leaking through the left lens. A similar approach is used for measuring $L_R(i)$ and $L_R(i)$.

There were some difficulties setting up the experiment as not much software support is present that provides a unified solution to display 3D content on different types of stereoscopic display technologies. A C# program was written to automatically cycle through the gray levels displaying a full screen gray level based on the display technology while taking measurements using a luminance camera. For P1, the monitor that was not being used was turned off, while for P2 and A1, because only one screen is present, gray level 0 was displayed as the alternative. We note that the vertical viewing shift might have caused shrinkage in the effect of 3D view angle for the P2 display device.

2.1 Luminance measurements

One physical device used in crosstalk measurements is P1, the passive 3D display system (Fig. 2) with a stereo mirror (also known as the beam-splitter), which is displayed in all the schematics. The two 20-inch LCDs (PL2010M-BK, Planar Systems, Inc., Hillsboro, USA) with a 0.297 mm-pitch have an angular separation of 110 degrees and the mirror is placed on the bisect-plane between the two displays. The image of the bottom display is transmitted through the mirror, whereas the image of the top display is flipped vertically upon reflection off it. One side has a reflective coating, and the other side has an anti-reflective coating, which minimizes secondary reflections. The linear polarizing glasses allow the left eye to view the bottom display and the right eye to view the top display. P2 is a passive interlaced display device where even rows on the pixel grid display the left image, while the odd rows display the right image. The consequence of this technology is the reduction of resolution in the y-axis. A1 is only the active 3D display in our experiments, where a dual back buffer is used that displays the left and right images side by side. Using the correct Graphics Processing Unit function calls, setting the display to stereo mode splits the full image into two images with half the dimension in the x-axis, and time-sequentially interlaces them displaying the left and right images at 120 Hz.

Figure 2 shows the experimental setup used to measure the luminance (L_L, L_R) and luminance leakage (L_L and L_R) values for device P1. The polarizing glasses were positioned at approximately 430 mm away from the bottom display surface. A photometric charge-coupled device camera (P199F, Westboro Photonics Inc., Ottawa, Canada) equipped with a macro lens (NIKON AF Micro-Nikkor 60 mm f/2.8D, Nikon Inc., Tokyo, Japan) was positioned at 60 mm behind the glasses directly perpendicularly to the bottom screen. The center of the camera lens was located at a height of approximately 200 mm from the lower limit of the bottom screen.

TABLE 1 — Displays used in experimentation.

Index	Manufacturer	Model	Resolution	3D Technology	Display	Screen Size (inches)
P1	Planar systems	PL2010M-BK	1600×1200	Passive stereo mirror and two independent screens.	LCD	20
P2	ASUS	VG23A	1920×1080	Passive with vertical interlacing.	LED	23
A1	DELL	Alienware M17x	1920×1080	Active with 120 Hz display.	LED	17

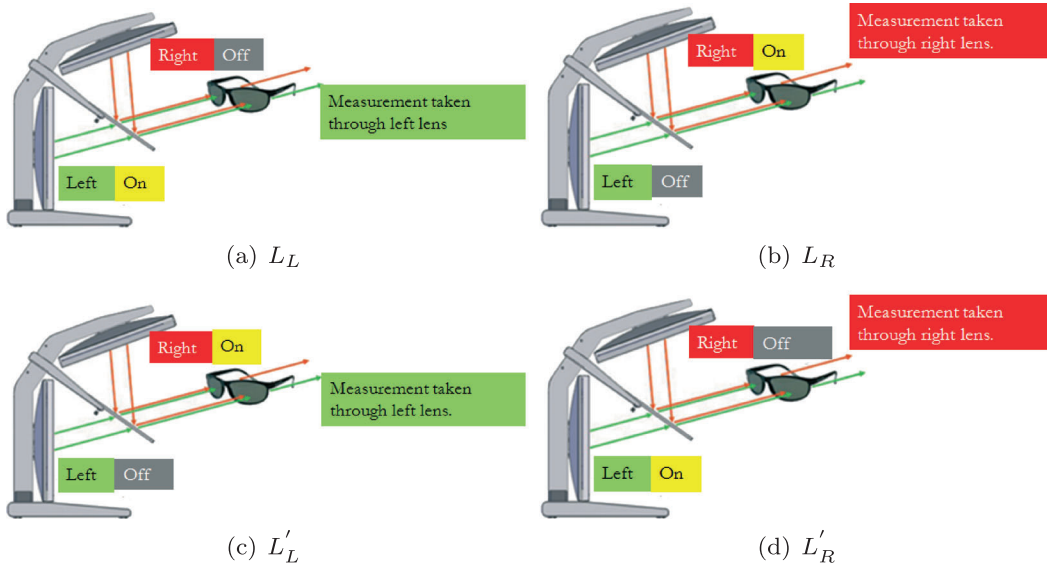LED, light-emitting diode; LCD, liquid-crystal display

FIGURE 1 — Measurement setup for calculating the four sets of measurements for P1 display (Table 1). All measurements were taken through the glass lenses for the respective 3D display device. Only the passive stereo mirror 3D display is presented in the schematic. (a) L_L, (b) L_R, (c) L_L', and (d) L_R.
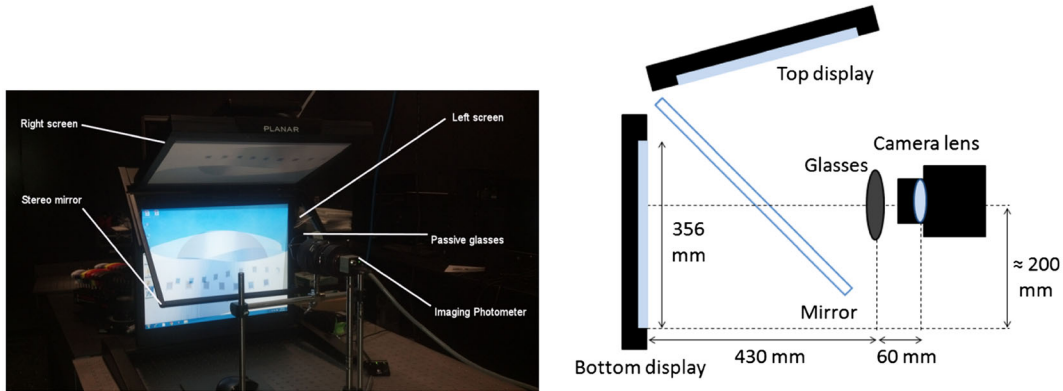

FIGURE 2 — (Left) Experimental setup with the dual panel passive stereo display (P1), luminance camera, 3D passive glasses, and stereo mirror. (Right) A schematic diagram with measurements displayed for the P1 display.

We captured the images through the stereo mirror and the glasses. When measuring the luminance for the devices P2 and A1, we used a similar setup replacing the display and the correct set of glasses, respectively.

We wrote a custom software that displays luminance corresponding to any gray level on the left/right screen in full screen mode and has the ability to record the measurement and write it to disk. The luminance camera records approximately 200 pixel values across a square region. These values are averaged to calculate one data point for each value in the four sets of independent measurements. The camera exposure time was 4.259 s per gray level. Once all four measurements are recorded, we calculate the complete luminance output response for the left and right stereo views as follows:

$$L_L^{\text{Map}}(l, r) = L_L(l) + L_L(r), \tag{6}$$

$$L_R^{\text{Map}}(l, r) = L_R(r) + L_R(l), \tag{7}$$

where l is the gray level displayed on the left screen, and r is the gray level displayed on the right screen and $0 \le l \le 255$, $0 \le r \le 255$.

We varied one additional experimental parameter for each display. For P1, we used three different viewing angles. The rotation was applied along the horizontal direction at 0, 10, and 20 degrees, where the 0 degrees represents the luminance camera orthogonally aligned to the screen. Only the luminance camera was rotated while the 3D glasses were fixed orthogonal to the screen at all times. This type of viewing angle measurement incorporates three changing parameters per trial. When the camera is rotated, it looks through a slightly different part of the glass lens, stereo mirror, and location on the screen.

The viewing location was varied for the P2 display device, and measurements were taken through the center of the glasses at five different locations on the screen such as top left (TL), top right (TR), center (C), bottom left (BL), and bottom right (BR). The camera and the glasses were orthogonally aligned to the screen at all times.

We used two different types of active 3D glasses for A1. The first set (V1) is the older Nvidia 3D glasses (Nvidia, Santa Clara, CA, USA) that were part of the 3D Vision 1 kit. The second set (V2) is the newer version of the glasses with wider viewing angles and improved lens quality, part of Nvidia 3D Vision 2 kit (Nvidia). All measurements were taken at the same screen patch. In the next sections, $P1_{L/R}(x)$ refers to the x angle of rotation, $P2_{L/R}(y)$ refers to the y screen location, and $A1_{L/R}(z)$ refers to the z glasses used when measuring the left or right view luminance or crosstalk, respectively. All luminance measurements were recorded in a controlled dark room display lab environment.

3 Results

Using the methodology described earlier, we measured the luminance response for all three displays by varying either viewing angle, viewing location, or 3D glasses for each set of trials.

The full screen gray level was displayed using the appropriate 3D technology and different code functions for each display. The luminance camera code that recorded the measurements was shared between all the experiments.

3.1 Luminance response

Figure 3 shows the L_L, L_R, L_L, and L_R values measured for the three display devices and all the trials conducted with varying viewing angles, viewing location, and 3D glasses. All measurements were recorded in cd/m^2 and are plotted using a *log* scale. The first row displays the luminance responses from the screens. There is a slight difference in the responses for P1 and P2 when looking at Fig. 3(a) and (b). Taking measurements at different screen locations for P2 did not show any notable difference in L_L and L_R recorded measurements. A1, however, showed a slightly higher difference between the measured luminance responses when using two different sets of 3D glasses. L_L and L_R luminance recorded for the V1 set of glasses proved to be brighter by approximately 10% when compared with V2 in our measurements.

Figure 3(d)–(f) plots the luminance crosstalk measurements (L_L and L_R) through each lens. Crosstalk varied notably with viewing angle for P1, and the left lens generally suffers from higher leakage than the right one. In Fig. 3(e), we see
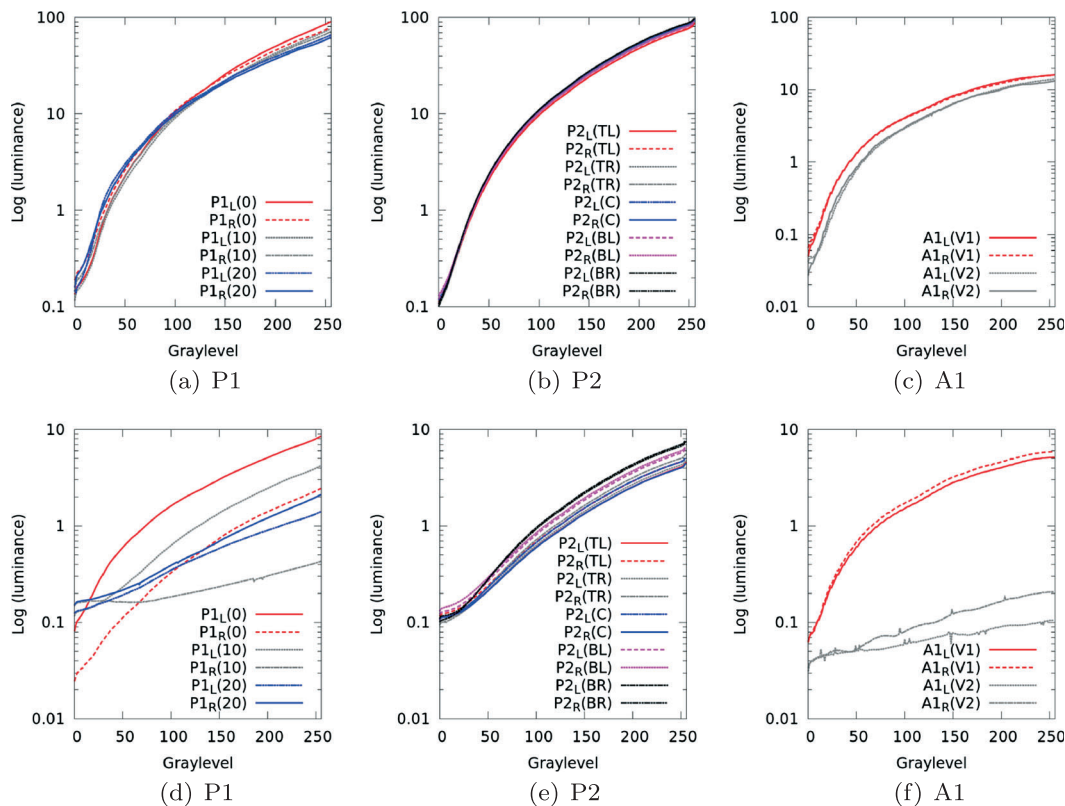

FIGURE 3 — *(Top row)* Shows the measured luminance output values, L_L and L_R for devices P1 (0, 10, and 20 degree viewing angles), P2 (TL, TR, C, BL, and BR viewing location), and A1 (V1 and V2 3D active viewing glasses). *(Bottom row)* Shows the measured lens crosstalk luminance values, L_L and L_R for devices P1, P2, and A1. (a) P1. (b) P2, (c) A1, (d) P1, (e) P2, and (f) A1.

a noticeable difference in recorded luminance at different viewing locations when viewing P2. There is higher leakage at the bottom two locations compared with the top left, top right, and central viewing locations. Between the L_L and L_R measurements for P2, the left view suffers from higher leakage. For the active stereo display A1, there is marked difference in crosstalk measurements for both the left and right views between the two sets of 3D glasses used. V2, which is the newer version of the 3D glasses, has reduced crosstalk compared with the older V1 version.

It is interesting to note that crosstalk and luminance values for the left and right views were different. The viewing angle, viewing location, and the use of certain eye wear can cause different perceived luminance to each eye. Due to these differences, even for a single stereoscopic display, multiple use cases can arise where detection performance might be affected resulting from varying luminance and crosstalk. These results encourage us to model the stereo viewing tasks and run simulations to assess the differences in observer performance through computational methods.

3.2   Crosstalk across technologies

We interpolated the four measurement sets for each device to create a full gray level luminance map of the display device for each screen. These maps now incorporate the crosstalk characteristics of the display, glasses used, and/or the stereo mirror used in the experiment. Figure 4, first two columns show the complete luminance map for P1 for each screen. Note that for the left screen image, the luminance plot should only have vertical lines (for an ideal display), but due to the inclusion of crosstalk, the lines tend to curve. Similarly for the right screen maps, the flat horizontal lines are curved because of the leakage. In order to clearly visualize crosstalk differences per trial, we defined percentage crosstalk as,

$$C_L^{\%}(l,r) = \frac{L_L(r)}{L_L(l) + L_L(r)} \times 100, \qquad (8)$$
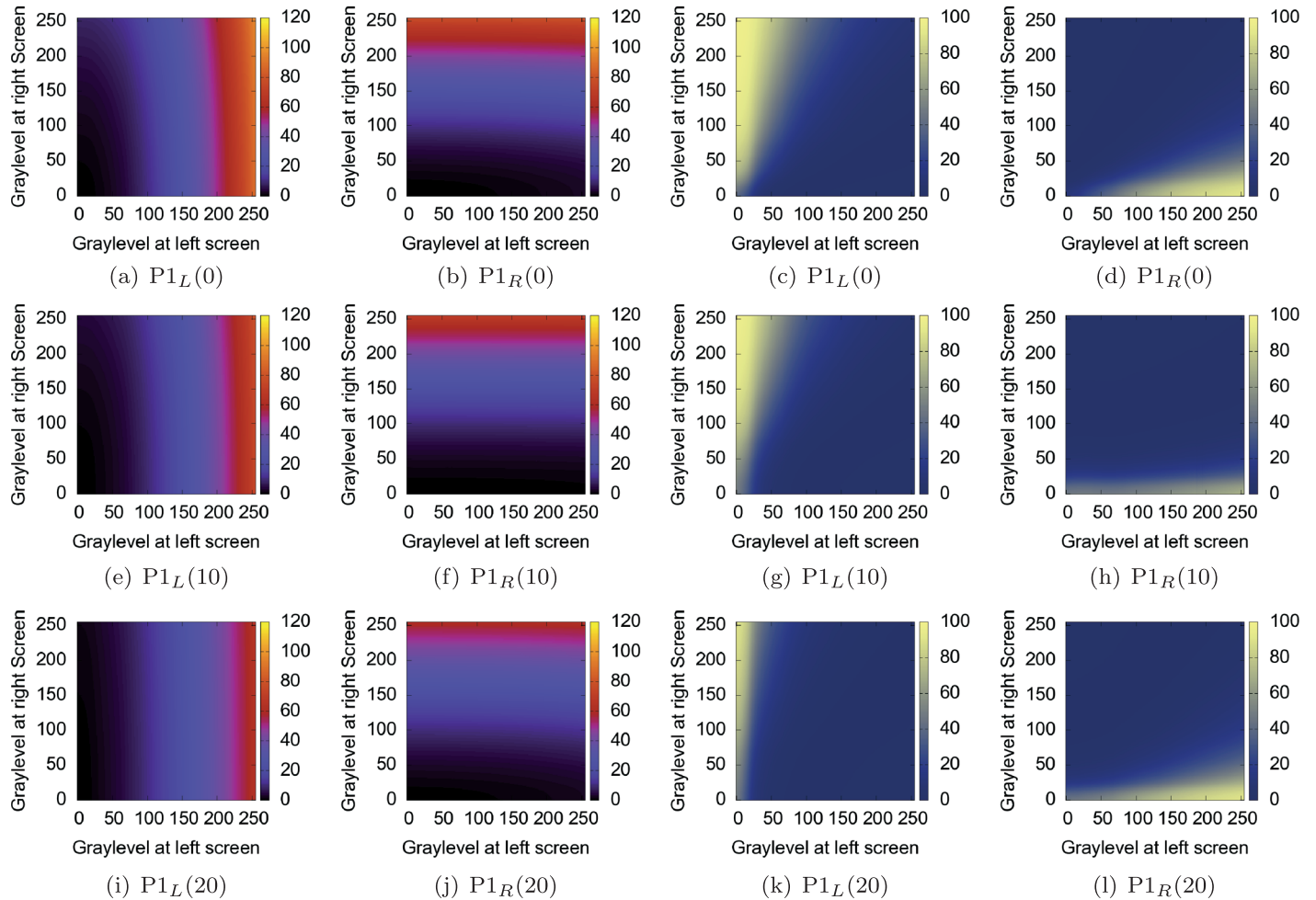

FIGURE 4 — *(Columns 1 and 2)* Luminance maps (L^{Map}) in cd/m² for the P1 stereoscopic display device. *(Columns 3 and 4)* Respective percentage crosstalk ($C^{\%}$) in the stereo views for P1 for three different viewing angles (0, 10, and 20 degrees). (a), P1$_L$ (0), (b) P1$_R$ (0), (c) P1$_L$ (0), (d) P1$_R$ (0), (e) P1$_L$ (10), (f) P1$_R$ (10), (g) P1$_L$ (10), (h) P1$_R$ (10), (i) P1$_L$ (20), (j) P1$_R$ (20), (k) P1$_L$ (20), (l) P1$_R$ (20).

$$C_R^\%(l,r) = \frac{L_R(l)}{L_R(r) + L_R(l)} \times 100 \qquad (9)$$

Hence, the crosstalk percentage maps show how much of the luminance reaching the eye is actually leakage against what luminance should actually be visible. The last two columns of Fig. 4 show the crosstalk profiles of P1, left and right screen for varying stereo angles. We can see that the left view suffers from higher crosstalk compared with the right view, and it spreads over a larger gray level range. At lower gray levels, the crosstalk experienced by the viewer is very high and it slowly reduces as the luminance is increased. As the viewing angle increases, crosstalk is reduced in the left and right views. The trend is not entirely consistent as presented in Fig. 4(d), (h), and (l), which might be because of the particular screen location or the viewing angle through the stereo mirror or the glasses.

Figure 5 shows luminance output and crosstalk exhibited by P2. We noticed that there is no notable difference in the crosstalk profiles for the five different measured locations (TL, TR, C, BL, and BR) on the screen. The bottom left and bottom right patches are slightly brighter than the top, with a very small increase in crosstalk spread across the gray levels for both the left and the right screens. The spread of crosstalk across the gray level range is also similar. Only three location trials are presented in Fig. 5.

The luminance probe used in our setup had a lower limit of exposure of 1 s, which allowed us to take some measurements with an active stereo display device A1. The luminance measured was found to be lower by approximately 70% than the luminance viewed without the use of active glasses directly from the screen. The actual luminance viewed in the left/right eye is diminished when measured because active stereo frames are interlaced, and the active shutter glasses black out the unwanted frame 60 times per second in the 120 Hz stream for each eye. Although it can be argued that the eye might aggregate the entire luminance per second and the final output is always dimmer than the intended intensity, we note that these luminance values are not fully representative of the display luminance through the active shutter glasses because
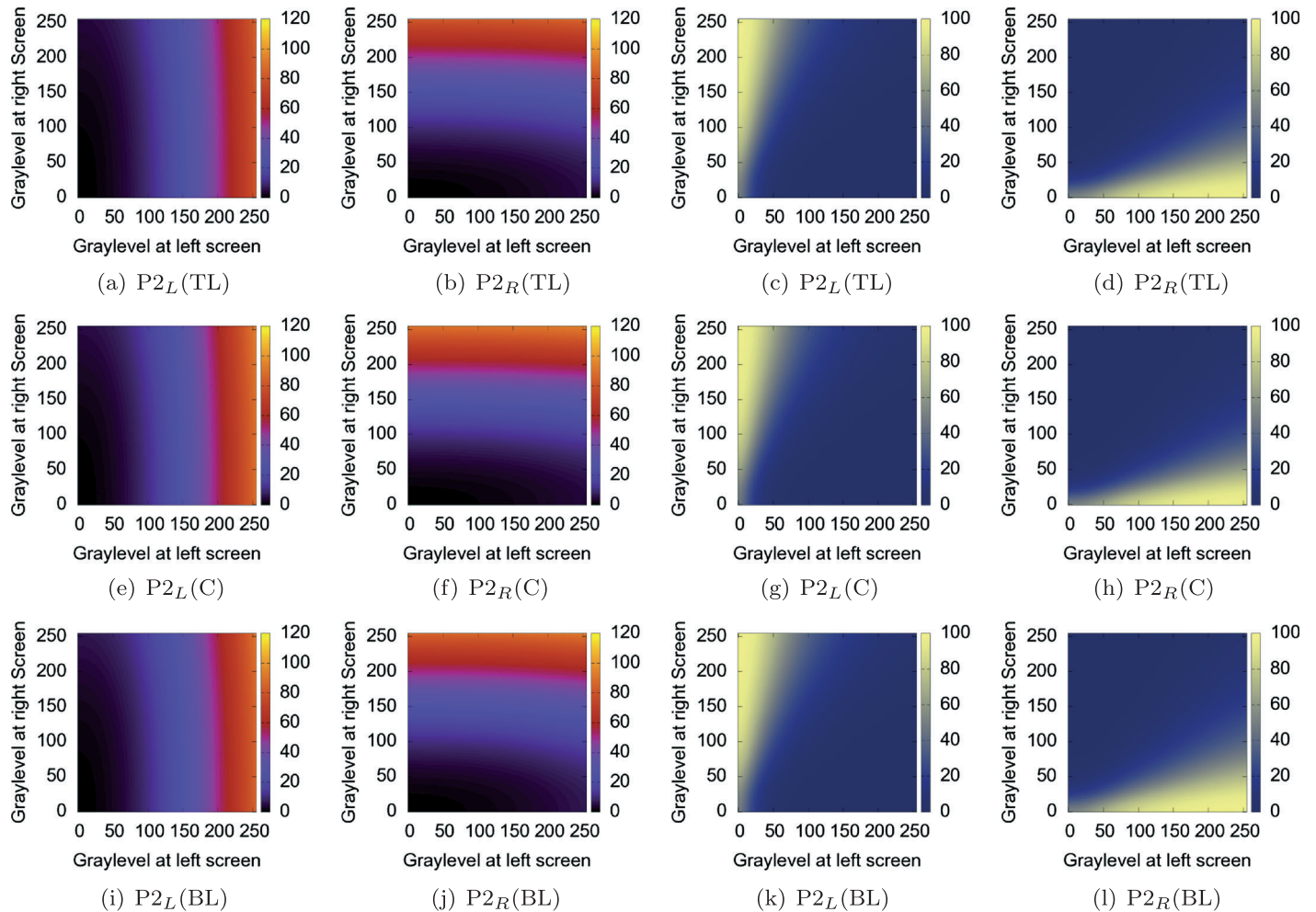

FIGURE 5 — *(Columns 1 and 2)* Luminance maps (L^{Map}) in cd/m^2 for the P2 stereoscopic display device. *(Columns 3 and 4)* Respective percentage crosstalk ($C^\%$) in the stereo views for P2 for three different viewing locations (top left (TL), center (C), and bottom left (BL)). (a), P2$_L$ (TL), (b) P2$_R$ (TL), (c) P2$_L$ (TL), (d) P2$_R$ (TL), (e) P2$_L$ (C), (f) P2$_R$ (C), (g) P2$_L$ (C), (h) P2$_R$ (C), (i) P2$_L$ (BL), (j) P2$_R$ (BL), (k) P2$_L$ (BL), and (l) P2$_R$ (BL).

of the nature of our setup and the temporal interlacing of active stereo technology. Better measurement methodologies for active 3D displays with shutter glasses have been proposed [23] based on temporal characterization. We, however, do present the crosstalk difference that was measured for A1 in Fig. 6. It is interesting to note that the crosstalk measured in the older generation of 3D glasses (V1) was about 4–5 times higher than the newer one.

In order to quantify the differences between crosstalk profiles with different experimental parameters, we define the scalar mean crosstalk value $\overline{C}$ for each $C^\%$ as follows:

$$\overline{C} = \frac{1}{256^2} \sum_i \sum_j C^\%_{\mathrm{L/R}}(i,j), \qquad (10)$$

where $0 \leq i < 256$, $0 \leq j < 256$, and $\overline{C}$ is a scalar mean value averaged over the entire $C^\%$. Figure 7 shows the mean crosstalk exhibited by the devices based on the changing experimental parameters. The two-dimensional $C^\%$ maps
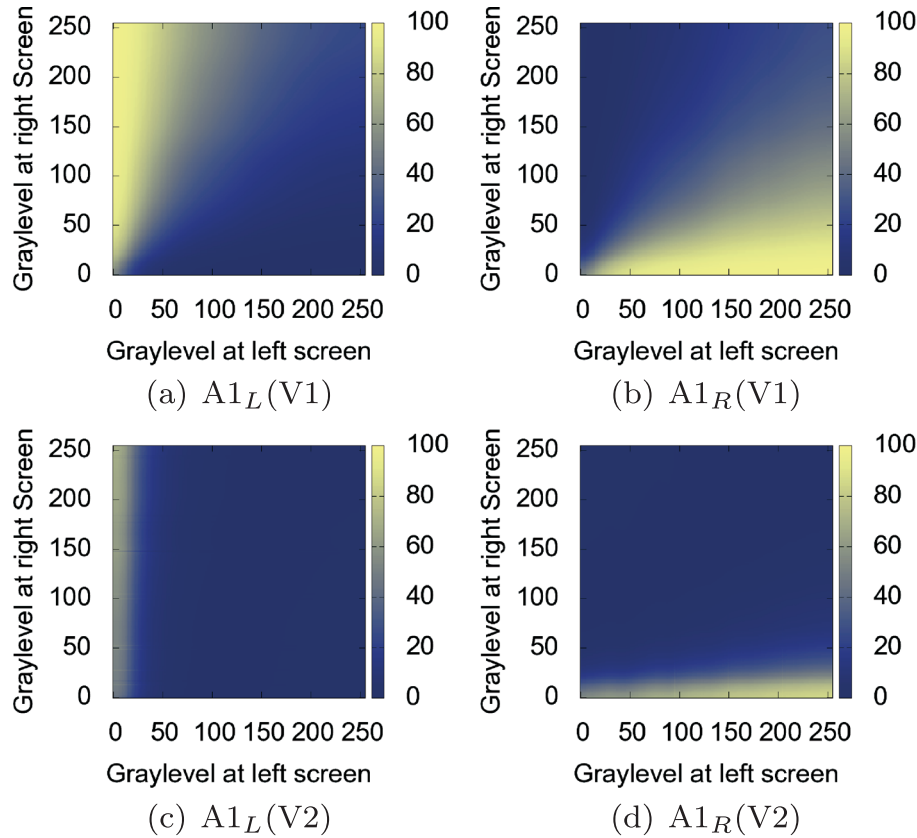

FIGURE 6 — Percentage crosstalk ($C^\%$) in the stereo views for A1 with two different sets of 3D shutter glasses (V1 and V2). (a), A1$_L$ (V1), (b) A1$_R$ (V1), (c) A1$_L$ (V2), and (d) A1$_R$ (V2).
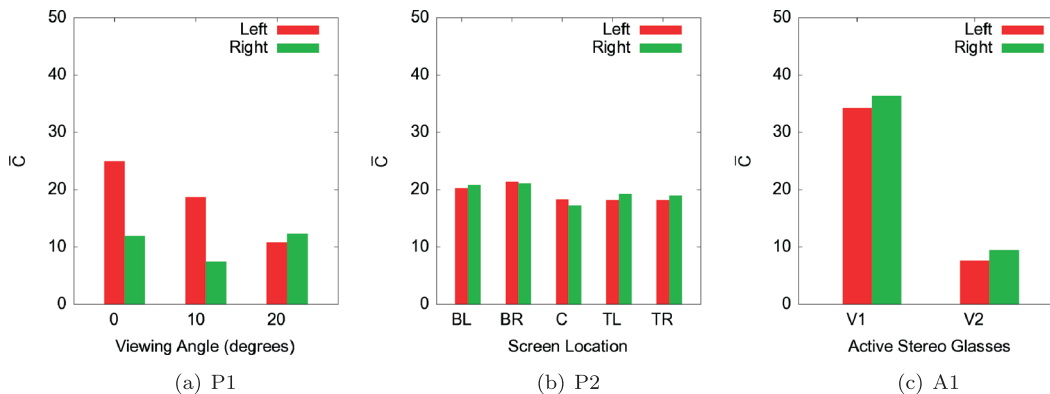

FIGURE 7 — The scalar mean value averaged over the entire $C^\%$ ($\overline{C}$) plots for the three displays used in our experiments and their varying experimental parameters. (a) P1, (b) P2, and (c) A1.

highlight the spread of the crosstalk profile across gray levels, while the scalar $\overline{C}$ quantifies the aggregate intensity. It can be seen in Fig. 7 that crosstalk for P1 generally decreases as the viewing angle increases. The change in viewing location did not affect the aggregate crosstalk in P2 and has a similar $\overline{C}$ value at all measured locations. Using two different versions of active stereo glasses had a clear contrast for the A1 display. The higher $\overline{C}$ values for both the left and right views are present for V1 glasses compared with the newer V2 version. There was approximately 70% reduction in crosstalk when using V2 compared with V1.

4   Discussion

We presented results for a detailed set of luminance measurements conducted on three different types of stereo display devices targeted for consumers. The results present an interesting outlook of how different physical parameters, when viewing 3D content, affect the crosstalk experienced by the observer. Viewing angle did affect the contrast and inherent crosstalk exhibited by the device (Fig. 3(a) and (d) and Fig. 7(a)). Our intention was to simulate the viewing angle as the eye moves at a fixed head position orthogonal to the screen. Other variations of rotation using the camera and the glasses can also be tried which might have a different effect compared to our method, for instance simulating a head rotation along either of the three axes. The measurements at different screen locations did not show any significant changes in crosstalk so it is safe to assume that this parameter has minimal affect on observer performance when using a passive-interlaced stereo display device. Reference 23 has showed that different screen locations have a noticeable impact for active stereo displays using shutter glasses when the luminance is measured based on temporal characterization. Our results show that the use of different types of glasses when viewing content affects observer performance.

It must also be noted that crosstalk cannot simply be referred to as a single number defining the performance of the 3D display device. It is a varying parameter that changes across the entire display luminance range and can be increased or decreased by viewing angles and viewing locations. The spread and the intensity of crosstalk and the display luminance can also vary based on additional peripherals needed to view the 3D content correctly. Reliable objective crosstalk measurements should be taken, keeping these factors in mind for assessment of 3D display image quality.

With so many varying parameters and types of displays, we are encouraged to move towards a modeling approach that can simulate many, if not all the cases. Human observer studies for each and every 3D display device in multiple experimental conditions would be quite infeasible. This is the motivation for our work forward. We plan to use this physical device data and incorporate it into our stereo model

observer [9,10] for assessing the performance of the display device in signal detection tasks. It has been shown that crosstalk has a negative effect on perceptual performance, hence more crosstalk correlates with degradation of performance. However, our interest lies in figuring out answers to different and more insightful questions, such as how much degradation has occurred as a function of viewing angle, or what is the combined effect of changing contrast versus crosstalk exhibited during certain conditions. These types of simulations will allow us to emulate devices and find the acceptable limits of crosstalk that vary across a large spectrum based on multiple parameters.

5   Conclusion

We have demonstrated how recording detailed luminance measurements for stereoscopic display devices can help profile their crosstalk characteristics while allowing us to explore parameters such as viewing angle, viewing location, and the use of different sets of 3D glasses. We found that crosstalk varies significantly between different types of 3D technologies and sometimes based on these viewing parameters. The measured luminance leakage was not consistent throughout the left and the right views for the stereo mirror 3D display device, which can potentially affect observer performance. Viewing angles also visibly affected the amount of crosstalk exhibited in this 3D display. Crosstalk measured at either of the five viewing locations did not have any notable difference for the passive interlaced 3D display device. Using different versions of stereo glasses reduced the overall crosstalk by 70% for the active shutter 3D display. These results can help emulate stereoscopic display devices using a computational stereoscopic observer model that is purely based on simulation to assess image quality without conducting human observer experiments. The reduction in image quality due to viewing angles, viewing location, and 3D glass lens quality can be studied using this measurement approach as well, and all stereoscopic display devices can be compared based on their complete luminance output profiles. A different methodology for active 3D displays luminance measurements might be needed for a robust quantitative analysis based on temporal characterization. In the future, we intend to extend our approach and use this data to emulate and compare stereo display devices with different display technologies using a stereoscopic model observer approach based on statistical decision theory. This approach will automate image quality assessment for multiple types of 3D display devices and viewing parameters.

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