Common assumptions in color characterization of projectors

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Abstract

This work focuses on the evaluation of assumptions commonly made in projector color characterization. We investigate how these assumptions are valid along the spatial dimension. Features studied include normalized response curve, chromaticity constancy of primaries and channel independence along the display. We provide qualitative and quantitative data analysis from different projectors to support our discussion. Some features seem to vary noticeably spatially, such as the normalized response curve. Some others appear to be quite invariant, such as the channel independence.

1 Introduction

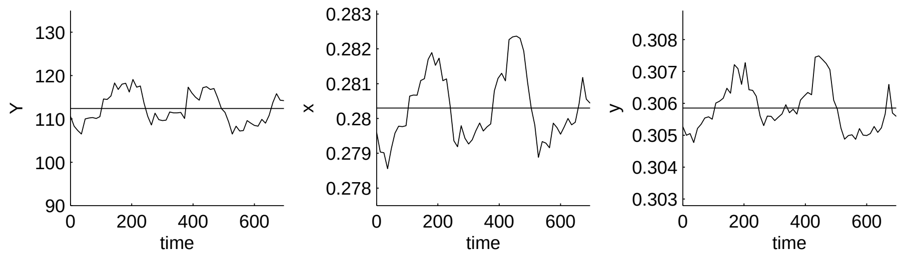
There are a variety of models that are used for colorimetric characterization of projection displays. These models make different assumptions about the devices, usually based on preexisting knowledge about the technologies utilized in the displays, but also sometimes determined by empirically investigating the output of the devices. Problems arise when a model is used without verifying whether these assumptions are true for a specific display device. We have previously shown[10] that there can be a strong spatial color shift for some displays. In this study, we check out some of the major hypothesis involved in color characterization models related with the spatial dimension.

One issue with some models is that they originally were introduced to characterize devices using a different technology to that which is currently in use today, e.g., models for CRT monitors are used for LCD projector displays. In physical color characterization models, assumptions are made considering the display in order to establish the most simple and as fast as possible model. These assumptions are mainly: spatial color uniformity (or only a luminance shift), temporal stability, chromaticity constancy of primaries, independence between channels, gamma or s-curve response curve, etc. Many of these assumptions has been shown to be reasonably correct for a CRT monitor [2, 3, 9].

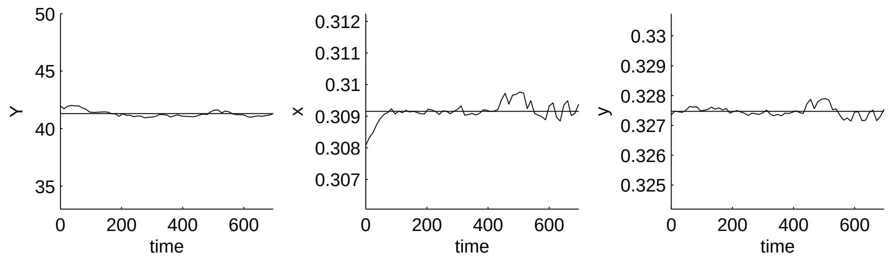
Many studies have investigated LCD monitors [9, 11, 5], and only a few studies have performed verification of these hypothesis on projectors [1, 6, 5, 8, 7]. With the exception of Bastani, these studies investigate mostly projector features as defined by the IEC draft [4].

In this work, we extend previous works by analyzing the characteristics of several projector displays along the spatial dimension. We focus on checking the validity of the most common assumptions.

In the following, we present our experimental setup, then we analyze the normalized response curves of the displays, the chromaticity constancy of primaries, and the independence between channels. We use a method described by Bastani et al.[1] in order to analyze the cross-channel interaction of the displays. By keeping the input of two channels at either full or no intensity, and varying the input of the third channel, the amount of channel interaction can be found.



(a) Y, x and y versus time in minute for display DLP



(b) Y, x and y versus time in minute for display LCD2

Figure 1: Visualizations of the temporal shift for the DLP and one of the LCD tested projectors. One can notice that the DLP is less stable than the LCD. However, both devices appear to be stable enough to be used in normal applications. We can notice that for the LCD projector, there is an optimal time between the warming up time and a overheat time.

2 Experimental setup

We have used measurements of three projection displays as the basis for our analysis, two of them are LCD projectors and one is using DLP technology. The LCD projectors are both manufactured by Sony and are of the same model (VPL-AW 15), from now on referred to as LCD1 and LCD2. The DLP projector is the Projection Design Action One, which is named DLP throughout the rest of this paper.

All measurements were done using a CS-1000 spectroradiometer in a dark room, after the devices were allowed to warm up for a period of one hour and fifteen minutes in order to achieve a satisfactory temporal stability. Measurements of the RGB cube using 5 subdivisions were taken at 9 locations corresponding to the center and extreme horizontal and vertical positions of a 5 x 5 spatial grid, using a geometrical setup similar to [6]. The decision of reducing the number of positions from 25 to 9 was made due to time constraints, after having verified the spatial caracteristics of the projectors by measuring white patches at all 25 locations.

2.1 Temporal stability

In order to ensure that our measurements at different locations are significant compared with the normal drift of the equipment, we performed a temporal stability check of the projectors we used. We started by performing an evaluation close to what is proposed in the IEC draft [4]. We measured a white full screen patch (full intensity) at regular intervals of 12 minutes, for about 700 minutes (11h40min). The Y, x and y coordinates are plotted for projectors DLP and LCD2 in Figure 1. We used another range for x and y than the one proposed in the IEC draft since we could not see any information while plotting between 0.25 and 0.35 chromaticity diagram unit.

It appears that the LCD projector is really stable after one hour warming up, and before approximately

Table 1: Temporal stability estimation

	DLP						LCD2				
	R	G	B	W	All		R	G	B	W	All
ΔE^*_{ab} Mean	1.29	1.21	0.78	1.17	1.11		0.60	0.33	0.58	0.22	0.43
ΔE^*_{ab} Max	2.79	2.73	1.64	2.41	2.79		4.74	1.32	1.83	0.64	4.74
ΔE^*_{ab} STD DEV	0.72	0.66	0.37	0.56	X		0.86	0.25	0.46	0.11	X

7 hours of use. The DLP projector however vary in intensity from 106 to 118 $cd.m^{-2}$ in a regular way. The chromaticity values are following the same pattern.

To complete this evaluation, and to have a better idea of the global temporal stability in normal use, we measured the primaries and the graylevel at full intensity at 12 minutes interval for the same time, and compute the differences compared with the average in $L^*a^*b^*$ for each colors after one hour warming up. Results are presented in Table 1.

We notice the same thing as can be seen in the graphs, that the LCD is pretty stable, and the DLP is slightly less stable. However, there is a big maximum shift of the red channel for the LCD that appears at around 8h10 minutes after switching on.

In overall, the stability of these devices is pretty good for normal use, and should be good enough for our experiment.

3 Normalized response curves

A pretty common assumption in display characterization is to consider the normalized response curve of each channel to have the same shape. By extension, each channel may have the same shape as the graylevel response curve. In many common methods this assumption can reduce the number of intensity measurements or evaluations that have to be taken or done. This assumption has been shown to be valid for CRT monitors but not for LCD ones [9]. For projectors, if we look at the works of Seime and Hardeberg [8, 7] or of Kwak and MacDonald [6], the LCD projector does not show to fit this assumption, however the DLP in [8, 7] seems to show approximately equivalent normalized response curves for ech channel. Note that in [5], one LCD projector they tested seems to fit the hypothesis. However, no quantitative data is given in these studies to assess this. The purpose of this section is to evaluate this with quantitative data, and to extend the investigation to the spatial dimension.

In Figure 2 we show the response curve of a normalized graylevel intensity ramp at the reference location of the DLP we tested, and a normalized sRGB response curve sampled as the first curve. We propose a simple indicator of similarity that consists in the absolute difference between the integrals (i.e. the surface between both curves). We multiplied the surface found by 1000 to avoid king sized numbers. We compared the sRGB and the response curve of our three projectors and found a δ of 4.31, 4.29 and 5.26 for LCD1, LCD2 and DLP. That enables us to relate the following results to something known.

Based on this indicator, we perform three experiments:

First we compute the average and maximum mismatch δ_{mean} between the intensity response curve of each channel and the graylevel response curve at each position. If there is no mismatch it can be enough to measure only the graylevel response curve at each spatial location. Results are reported in Table 2. We observe that the centers of the displays are among the locations with the largest shift between curves for each display. The mismatch does not appear as negligible for many colorimetric accurate applications, while a *sRGB accuracy* could be reached considering normalized response curves equivalent at each location whatever the channel.

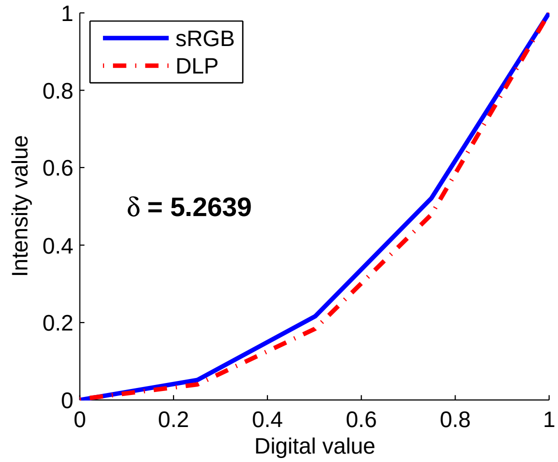


Figure 2: Visualizations of the normalized response curves of the DLP projector compared with the normalized sRGB response curve. The indicator δ is the surface between both curves $\times$ 1000.

Table 2: Mismatch between the intensity response curves of each channel and the graylevel curve, depending on the location on the screen. The maximum and average mismatches are reported.

Average mismatch					Maximum mismatch			
LCD1								
	1	3	5			1	3	5
1	0.96	2.59	2.61		1	2.63	3.88	4.54
3	1.15	3.00	2.43		3	2.57	4.85	3.71
5	2.01	2.64	1.87		5	2.87	3.69	3.42
LCD2								
	1	3	5			1	3	5
1	1.21	2.01	2.24		1	2.05	3.30	3.68
3	1.29	2.15	1.72		3	2.76	3.30	3.01
5	2.05	1.53	1.31		5	3.31	3.27	3.14
DLP								
	1	3	5			1	3	5
1	1.43	1.24	0.98		1	3.44	3.16	1.46
3	1.34	2.05	1.01		3	2.49	4.03	2.64
5	2.62	1.37	0.84		5	4.38	2.82	1.68

Our second experiment consists in computing the mismatch between each primary at different locations, and the same primary at the reference location. If there is no mismatch, we could consider that measuring the response curves at one random location is enough for each primary. Results are reported in Table 3. It seems to be a valid assumption for DLPs. However, for the LCDs it is approximately as different as supposing an sRGB answer (that can be a correct hypothesis depending on the accuracy one want to reach).

Our last experiment testing this assumption is to compare response curves at all locations and for all channels with the reference location graylevel normalized response curve (as it can be measured in some

Table 3: Mismatch between channels for each primary and the channel response curve at the reference location. The graylevel response curve mismatch is shown as well.

Average mismatch					Maximum mismatch			
LCD1								
Red	Green	Blue	Gray		Red	Green	Blue	Gray
3.02	1.49	1.26	1.71		5.15	3.71	3.40	3.87
LCD2								
Red	Green	Blue	Gray		Red	Green	Blue	Gray
1.94	2.36	2.02	2.38		3.85	5.50	3.43	4.99
DLP								
Red	Green	Blue	Gray		Red	Green	Blue	Gray
0.48	0.24	0.97	0.57		1.83	0.80	1.67	0.95

case for applying a classic physical color characterization model). If there is no mismatch, it is enough to measure only one ramp at a given location. We found an average mismatch of 2.13, 2.48 and 1.10, and a maximum of 6.29, 8.30 and 3.85 for LCD1, LCD2 and DLP. In average, the difference is not as big as the difference compared with an sRGB curve, especially for the DLP. However, the maximum error found in LCDs shows that for this technology (or at least for these projectors) one can introduce a critical error through this approximation.

More analysis should be performed, especially to find a not noticeable difference. As a first conclusion, we would not use this assumption for projectors for accurate color rendering. However, it seems that within DLP technology, one can consider the normalized response curve of a given channel as invariant along the spatial dimension. If a *sRGB accuracy* is enough for a given application, then it seems that measuring only one ramp for one projector could be a compromise to do.

4 Chromaticity constancy

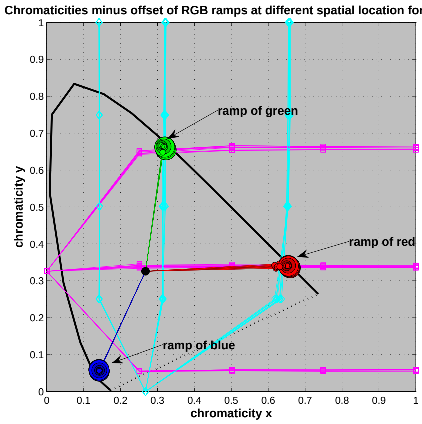
We present in Figure 3 the chromaticity values of the ramps of red, green and blue for each projector and a different locations. In these figures the offset has been removed using the local offset for each location. We can observe a slightly better chromaticity constancy for the DLP projector (Fig. 3 (c)) than for the two LCD projectors, each chromaticity of each ramp at the various level and location being almost identicals.

We still miss a good quantitative indicator, but it does not seem that the primaries spatial shift of chromaticity is a big issue for projector color characterization.

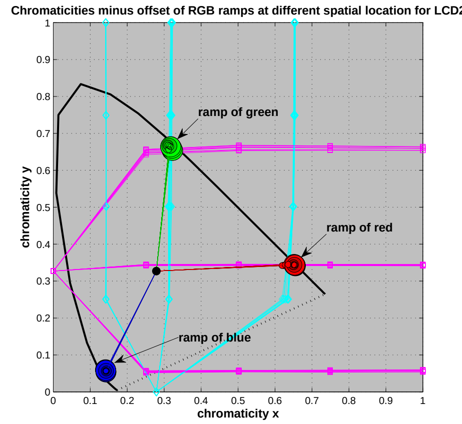
5 Channel independence

An assumption made by several models is that of channel additivity, e.g., that the output of a gray ramp is equal to the sum of the three R, G, and B ramps. For each projector, we have plotted the measured gray ramp and compared it with the computed sum of the individual ramps in Figure 5.

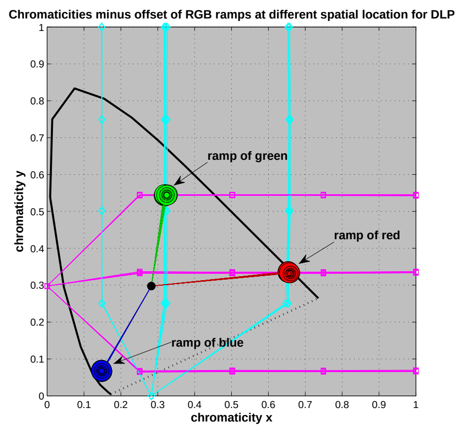
The lack of additivity we can observe in Figure 5 is due to the existence of channel interaction. Bastani et al. suggested that the amount of interaction for a channel at a given intensity can be calculated using the formula in Equation 1, where $L(r,g,b)$ represents the luminance that is measured for a specified RGB input. a and b are constant values for two of the channels, while v is the varying input of the third



(a) LCD1

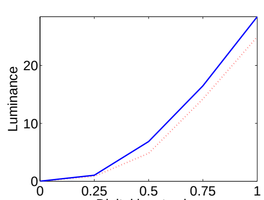


(b) LCD2

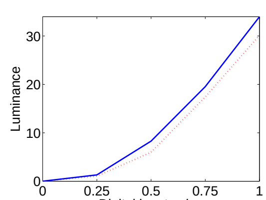


(c) DLP

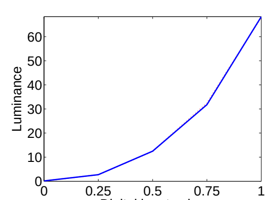
Figure 3: Illustration of the chromaticity constancy for the projectors at different locations, in (a) for projector LCD1, in (b) for projector LCD2 and in (c) for the DLP projector. In each figure the x and y chromaticity values are shown twice: once as a regular chromaticity diagram and secondly in the background of the figure in line and square versus the ramp digital steps in horizontal axis for the chromaticity x and in line and diamond versus the ramp digital steps in vertical axis for the chromaticity y. For clarity the chromaticity of the average offset over the various locations has been used in the graphs.



(a) LCD1



(b) LCD2



(c) DLP

Figure 4: The luminance of the gray ramp (solid line) compared with the sum of the individual ramps (dashed line) for the three projectors.

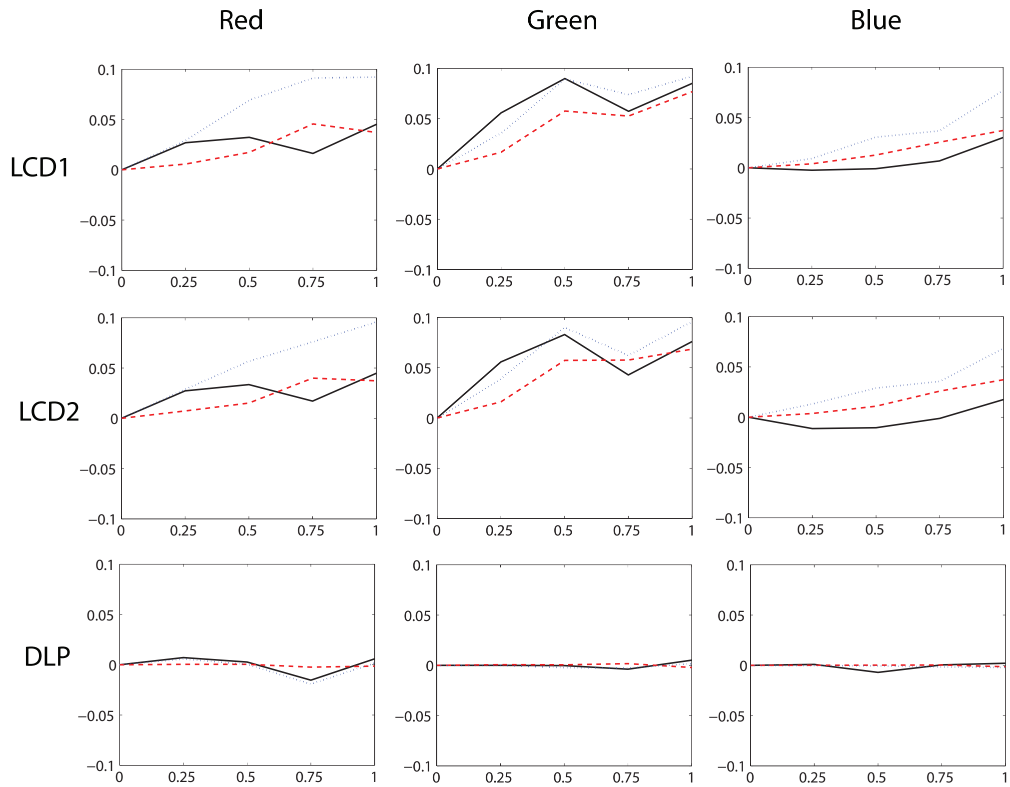


Figure 5: Channel interaction for three displays. The horizontal axis represents the input value of the denoted channel, while the vertical axis represents the calculated interaction value. The solid black line is the interaction found when the two other channels are kept at maximum input value, while the dashed lines are when the *a* or *b*, respectively, is set to 0 when computing the interaction metric.

channel. Equation 1 defines the interaction for the red channel. The interaction for the other channels are found in a similar manner. We preferred this method to the more complete, but more complex, method proposed in the IEC draft [4] for visualization purpose.

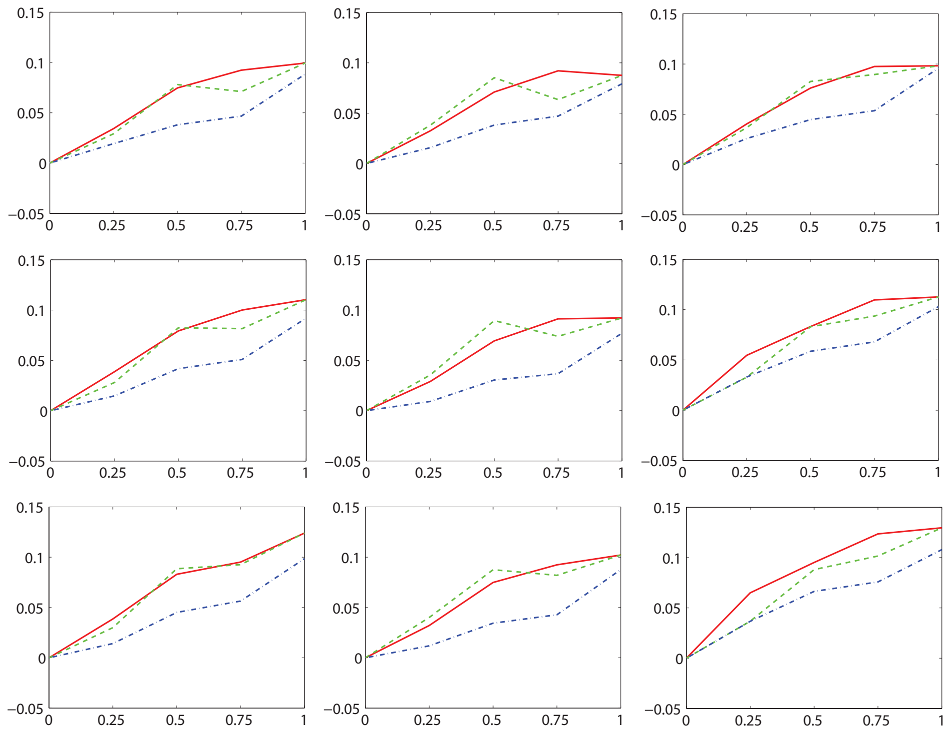
$$CI_{RED}(v,a,b) = \frac{(L(v,a,b) - L(0,a,b)) - (L(v,0,0) - L(0,0,0))}{L(255,255,255) - L(0,0,0)} \quad (1)$$

Figure 5 shows the interaction between the channels for the three projectors. We can clearly see that the LCDs have much more interaction than the DLP. The LCDs feature quite similar interaction characteristics, which is unsurprising given that they are of the same manufacturer and model.

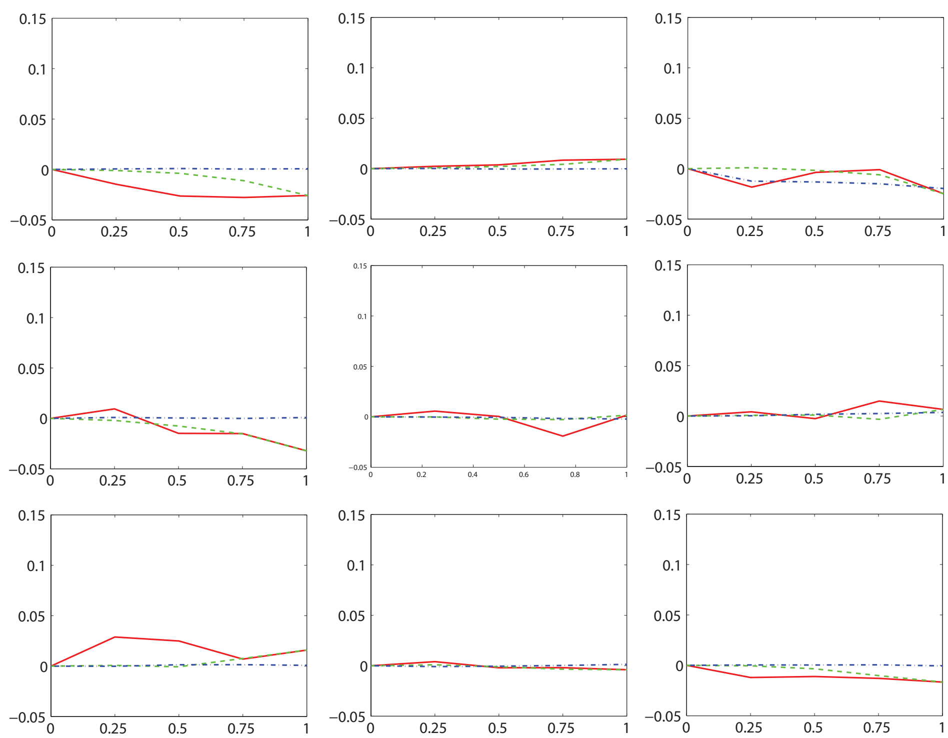
The spatial effect on the interaction is shown in Figure 6(a) and 6(b) for LCD1 and DLP, respectively. We noticed more interaction in the corners of the image in DLP technology. That could be due either to the motion of the color wheel that is less synchronized with the micro-mirrors motion at the corner or to some lens diffraction effect.

6 Conclusion

To summarize, we can say that the normalized response curves vary enough with the spatial location to influence strongly the accuracy of the characterization, except for the tested DLP where the spatial normalized response curve seems to be consistent by channel. We confirm previous studies, saying that



(a) LCD1



(b) DLP

Figure 6: Spatial channel interaction for two of the projectors, where each graph represents the interaction at the corresponding spatial location. The combination of a and b that give the highest interaction are chosen for each channel.

LCDs projectors have a lot of interaction, and their channel additivity is bad meanwhile, DLP technology shows more independence, and a good additivity. However, LCDs show a more consistent behavior along the spatial dimension than DLP for this feature. The study of the chromaticity constancy shows as well better performances for the DLP.

If we relate these results with the color shift measured in our previous study [10], we can say that,beside a small temporal shift and a lens effect, a strong contribution to the spatial color shift could come from the difference in response curve for LCDs technology. That induces a spatial different mix of primaries for the same input. For the DLP tested the spatial difference considering channel interaction can play a role as well as a more important temporal variation.

To construct a spatial color characterization model, performing measurements at many spatial locations on the displayed area might be required. However, the number of measurements could be reduced depending on the display characteristics. For instance, considering the DLP we tested, it could be enough to evaluate each channel normalized response curve at one location. Or considering the interaction between channels stable along the spatial dimension, it could be enough to take some model's parameters at one location.

Further work includes performing a more in-depth statistical analysis of the results, and testing more projectors to improve the significance of the experiment.

References

[1] Behnam Bastani, Bill Cressman, and Brian Funt. Calibrated color mapping between LCD and CRT displays: A case study. *Color Research & Application*, 30(6):438–447, 2005.

[2] D. H. Brainard. Calibration of a computer-controlled color monitor. *Color Research & Application*, 14:23–34, 1989.

[3] W.B. Cowan and N. Rowell. On the gun independency and phosphor constancy of color video monitor. *Color Research & Application*, 11:S34–S38, 1986.

[4] IEC:61966-6. *Color measurement and management in multimedia systems and equipment, part 3: Equipment used for digital image projection, committee Draft*. August 1998.

[5] Y. Kwak, C. Li, and L. MacDonald. Controling color of liquid-crystal displays. *Journal of the Society for Information Display*, 11(2):341–348, 2003.

[6] Y. Kwak and L. MacDonald. Characterisation of a desktop LCD projector. *Displays*, 21(5):179–194, 2000.

[7] Lars Seime and Jon Y. Hardeberg. Colorimetric characterization of LCD and DLP projection displays. *Journal of the Society for Information Display*, 11(2):349–358, 2003.

[8] Lars Seime and Jon Yngve Hardeberg. Characterisation of lcd and dlp projection displays. In *Color Imaging Conference*, pages 277–282. IS&T - The Society for Imaging Science and Technology, 2002.

[9] G. Sharma. LCDs versus CRTs: Color-calibration and gamut considerations. *Proc. IEEE*, 90(4):605–622, Apr. 2002. special issue on Flat Panel Display Technologies.

[10] Jean-Baptiste Thomas and Arne Magnus Bakke. A colorimetric study of spatial uniformity in projection displays. In *Lecture Notes in Computer Science*, number 5646, pages 160–169. Springer, 2009.

[11] Yasuhiro Yoshida and Yoichi Yamamoto. Color calibration of LCDs. pages 305–311. IS&T - The Society for Imaging Science and Technology, 2002. Scottsdale, Arizona, USA.