Spatial non-uniformity of color features in projection displays: A quantitative analysis

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In this article, we investigate and study the color spatial uniformity of projectors. A common assumption in previous works is to consider that only the luminance is varying along the spatial dimensions. We show that the chromaticity plays a significant role in the spatial color shift, and should not be disregarded, depending on the application. We base our conclusions on the measurements obtained from three projectors. First, two methods are used to analyze the spatial properties of the projectors, a conventional approach, and a new one that considers 3D gamut differences. The results show that the color gamut difference between two spatial coordinates within the same display can be larger than the difference observed between two projectors. In a second part, we focus on the evaluation of assumptions commonly made in projector color characterization. We investigate if these assumptions are still valid along the spatial dimensions. Features studied include normalized response curve, chromaticity constancy of primaries, and channel independence. 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.

Keywords: Projection displays, color spatial uniformity, color gamuts

Introduction

This article presents a study of color spatial non-uniformity within a projection display. In many applications only a photometric correction is used within one projector, and it is shown as being an issue by Majumder and Gopi[1].

Color spatial uniformity for projection displays has been studied by many, notably Kwak and MacDonald[2] or by Seime and Hardeberg[3]. However, it is often considered that only the luminance is of critical importance, and in most applications only this aspect is corrected for. The chromaticity shift is often considered as negligible. Moreover, the analysis of the color shift along the spatial dimensions is mainly supported by either incomplete or qualitative results.

This article presents a quantitative analysis of projector spatial non-uniformity. We based our study on two aspects.

We first define our experiment. We then analyze our measurements. A conventional 2D approach is used, which considers the analysis of a projected maximum intensity patch. Then, we use a global comparison of the gamuts at different spatial locations to evaluate color non-uniformity. The second part focuses on the evaluation of assumptions commonly made in projector color characterization. We investigate if these assumptions are still valid with variation in the spatial dimension.

Background and motivation

A projection system displaying an image on a screen shows some color spatial non-uniformities. These non-uniformities can come from the system properties, such as lens alignment, but also simply from the position of the projection system relatively to the screen. Since the early analyses of CRT displays, it has been widely considered that only the luminance was critically changing along the spatial dimensions[4]. This is still the assumption made by many researchers when modeling newer displays, and they maintain that the chromaticity shift is negligible compared with the change of luminance. In this work, we demonstrate that the chromaticity shift can not be disregarded, especially for some modern projection system applications, such as tiled projection systems, and for color research and experiments linked with the human visual system.

Despite of the studies or tentative works that have started to examine the color shift along the spatial dimensions,[2,5] it is still common to consider that the color varies only in luminance along the spatial dimensions of a display. Many proposed correction algorithms only use a luminance attenuation map , such as the methods used by Brainard[4] for CRT monitors, and by Majumder and Stevens[6] for projectors or multi-projector system corrections.

In all their study of multi-projector systems, Majumder et al. assessed that the spatial chromaticity shift is negligible compared to the luminance shift. However, looking at the figures presented in the work of Majumder and Stevens[7], the gamut shows a severe shift, which at first seems to be comparable to the difference observed from one display to a completely different one.

While Majumder et al. looked at the projector gamuts in chromaticity diagrams, Bakke et al.[8] recently proposed a method for computing the difference between two gamuts in a 3-D color space. They suggested that a method using discretized representations of the gamuts can be used to compute the relative gamut mismatch between two gamut boundaries. First, a binary voxel structure is created for each gamut. The value of each grid position is determined using the following method. If the position is within the gamut, the value is set to one, otherwise it is set to zero. Determining the differences between two gamuts can then be simplified to counting the voxels where the values of the two gamut representations are different, and multiplying this count with the volume of the cube represented by a single discretized position. The resulting number can be divided by the volume of the reference gamut, giving the relative gamut mismatch.

Beside of this aspect and to complete our study of color non-uniformity, we are interested in the behavior of some of the characteristics involved in color characterization models related with the spatial dimensions. Many works have been done in order to characterize the color of projection displays (i.e. model the relationship between the displayed color and a given input). These models make different assumptions about the devices in order to establish the most simple and as fast as possible model. They are usually based on preexisting knowledge about the technologies utilized in the displays, or determined by empirically investigating the output of the devices. These assumptions are mainly: spatial color uniformity (or only a luminance shift), temporal stability, chromaticity constancy of primaries, independence between channels, gamma or s-shape intensity response curve, etc.

Problems arise when a model is used without verifying whether these assumptions are true for a specific display device. Many of these assumptions have been shown to be reasonably correct for a CRT monitor[4,9–11]. Some studies have performed analysis on LCD monitors[11,12], and a few studies have performed verification of these hypothesis on projectors[2,3,13–15]. With the exception of Bastani et al., these studies investigate mostly projector features as defined by the IEC draft[5]. Here, we extend previous works by analyzing the characteristics of several projection displays along the spatial dimensions. We focus on checking the validity of the most common assumptions.

Experimental setup

We performed our investigation on three displays, two LCD projectors of the same model and manufacturer (Sony VPL-AW 15), and one DLP projector (Projection Design Action One). They are named LCD1, LCD2 and DLP in the following. All the displays were used with the default settings. In order to have accurate measurements, we used the CS-1000 spectroradiometer from Minolta (Accuracy: luminance: ±2%, x: ±0.0015, y: ±0.001, Repeatability: Luminance: ±0.1%, xy: 0.0002 for illuminant A). The measurements were done in a dark surrounding, so that no light is involved except that from the display. A warming up time of at least one hour and fifteen minutes has been used before any measurement to reach a correct temporal stability. The geometry of the whole system was basically of the same type that the one used by Kwak and MacDonald[2].

In our first experiment, we used the same kind of approach as the one described in the IEC draft[5] and in the work of Kwak and MacDonald[2]. We measured only a full intensity white image (RGB=[255,255,255]) at 5×5 locations regularly distributed over the display area (Fig. 1), having positioned the measurement device in front of the screen at the observer's position.

In addition to this approach, we were interested in looking at the differences in the gamut volume of the projectors, and at some features of the projectors along the spatial dimensions. We chose to limit the measurement process to 9 spatial positions among the set of 25, because of the time needed to complete the measurements (Fig. 1). At these positions, we measured each ramp of primaries and grey, as well as the entire RGB cube surface with a sampling of 5×5, considering that the surface of the *RGB* cube is also the gamut boundary in an independent color space.

Bakke et al.[8] showed that the gamut boundary descriptor algorithm suggested by Balasubramanian and Dalal[16]

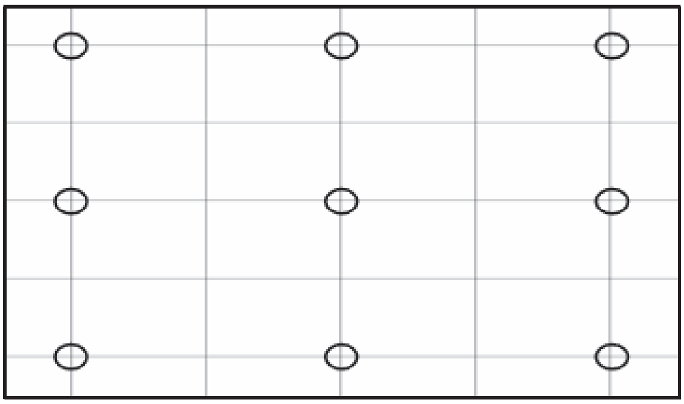


FIG. 1: Locations of the measurements on the screen. The circled intersections are the ones used for the reduced number of measurements.

performs well on most data sets when the preprocessing step is applied with the γ parameter equal to 0.2. We have therefore utilized this method to find our gamut boundaries. In order to perform the gamut evaluation, we used the ICC3D framework[17].

A part of our evaluation is performed in CIELAB color space. We encountered a challenging issue in using this space, since it is based on pointwise colorimetry and since we are looking at a spatial display. In the past studies we know, the luminance was supposed to be at its highest value in the center of the display and the observer was supposed to look at the center first. The measurement of a white patch at the center was used as the reference white. This follows the recommendation of the IEC draft[5]. However, considering the position of the display or the alignment of the lens, the highest luminance point can be severely shifted from the center. That can happen for instance when the projector is made to be used in an office and to project the image on a wall for presentation, such as the DLP projector we tested. We decided to use the brightest point of the white image displayed as reference white. This choice has some advantages in our case. If we consider the geometry of the system and the lens alignment, choosing the reference white at the brightest point is more in accordance with the physical properties of the device. Since we base our experiment on colorimetry, and we do not attempt to take more human factors into consideration, we have chosen to use this as our reference white.Note that in the case of a complex image, the white point should be the brightest point of the image. In our experiment, we used only digital uniform patches, so that we can consider the brightest area to be consistently at the same place (at the measurement spatial resolution confidence).

In the following, we refer to the measurement of the brightest white of a projector as the *global reference white* , while the *local reference white* is the white measured at each location.

Temporal stability

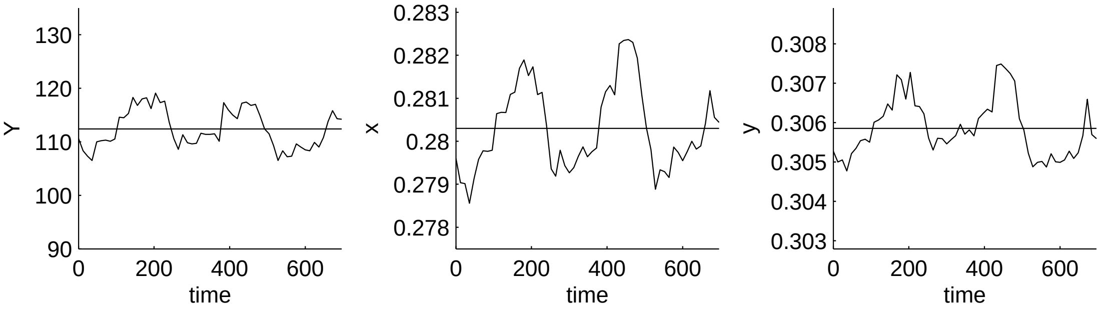
In order to ensure that our measurements at different locations were significant compared with the normal drift of the equipment, we performed a temporal stability check of the projectors we used. We started by performing an evaluation close to the one proposed in the IEC draft[5]. We measured a white 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 2. LCD1 is considered to show the same behavior than LCD2. 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 7 hours of use. The DLP projector varies in intensity from 106 to 118 $cd.m^{-2}$ in a regular way. The chromaticity values follow the same pattern.

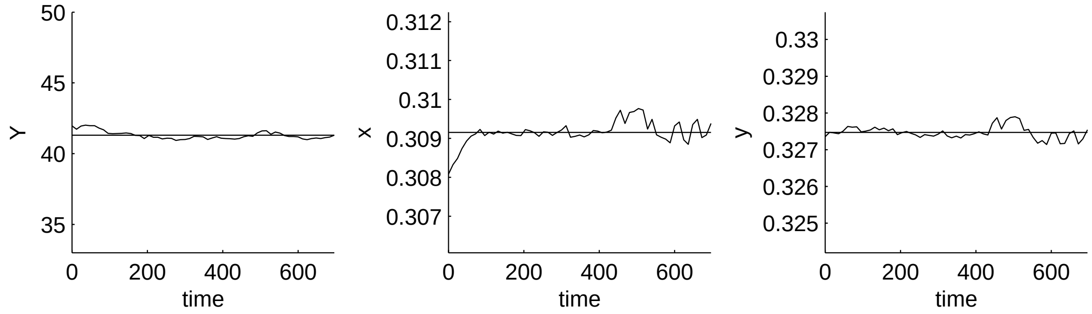
To complete this evaluation, and to have a better idea of the global temporal stability in normal use, we measured the primaries and the graylevel at full intensity every 12 minutes for the same time, and computed the difference with the average in $CIELAB$ for each color after one hour warming up. Results are presented in Table I.

These results confirm what is shown by the graphs. The LCD is shown to be more stable than the DLP. However, there is a large maximum shift of the red channel for the LCD, that appears at about 8 hours and 10 minutes after switching on.

In overall, the stability of these devices is representative of typical projectors that are currently being used , and should therefore be acceptable for use in our experiment.



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



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

FIG. 2: Visualizations of the temporal shift for the DLP and one of the LCD tested projectors. The ordinate boundaries of these graphs correspond to the 20% error around the mean for Y and the 1% around the mean for x and y. 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.

TABLE I: 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

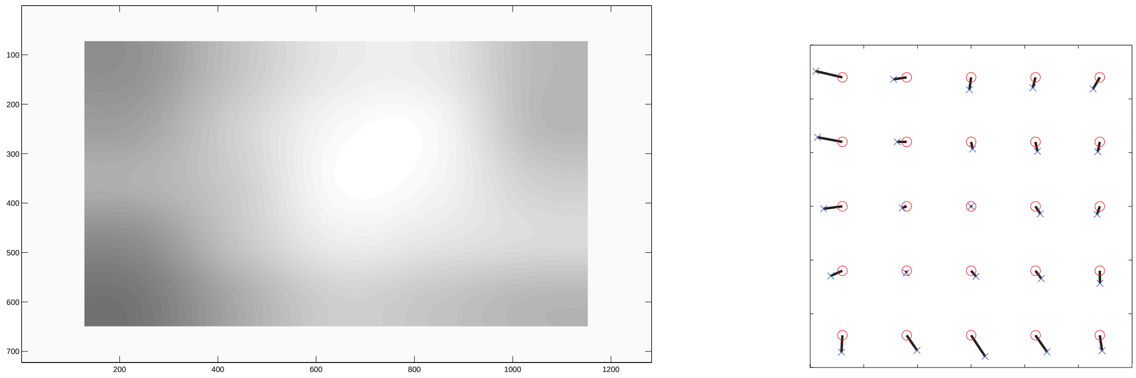
Analysis of the spatial non-uniformity

In this section we present and discuss the results we obtained, first with the conventional evaluation, secondly with the 3D gamut comparison approach.

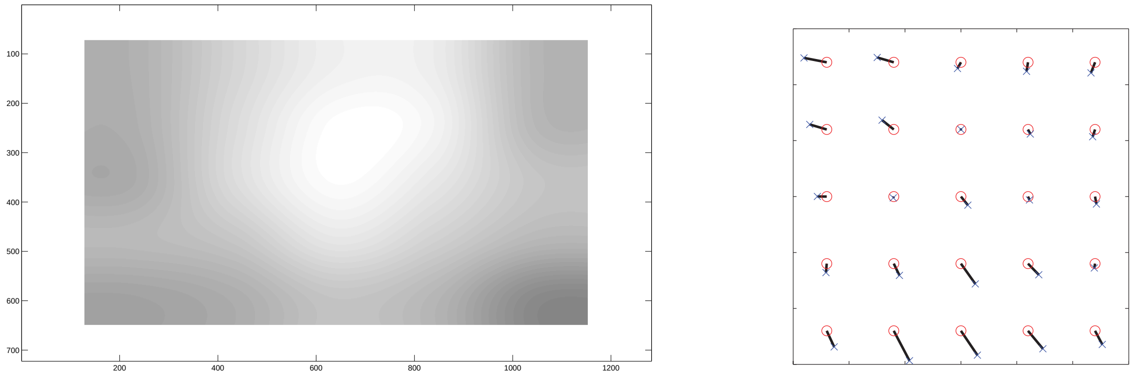
Conventional evaluation

By displaying the white patch and measuring the projected color at each position, we get an overview of the global behavior of the display. In Fig. 3, we can see the lightness shift along the spatial dimensions in the left part of the figure.

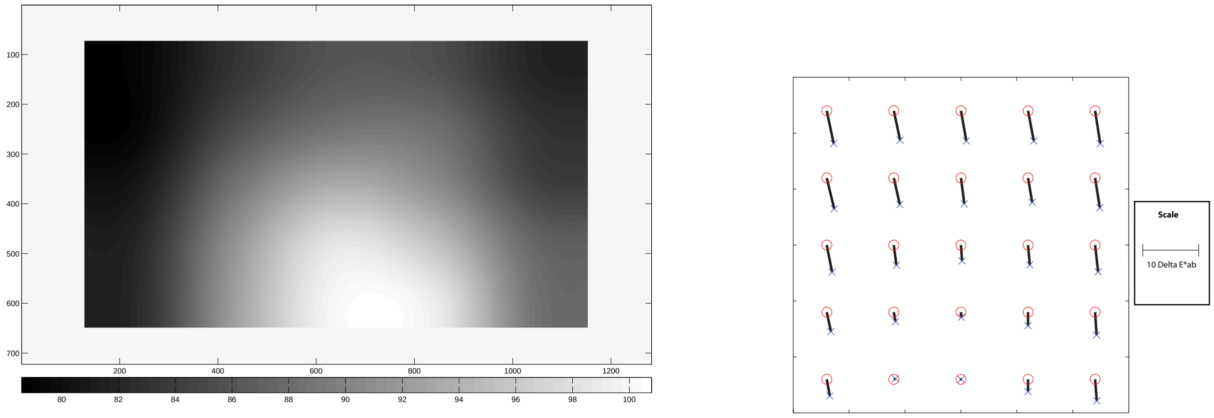
This visualization is based on the measurements at 25 locations. The white surround comes from the fact that we have no information on this part of the displayed area, while we can interpolate the data inside this rectangle. We can see that the brightest point is not necessarily in the center of the screen. The color shift is illustrated in the right part of this figure. We can see the same effect as the one described by Kwak and MacDonald[2], a shift in the color around the center of the lens displayed on the screen (i.e., the brightest point). The LCDs projectors show a shift



(a)Lightness, chroma and hue shift for display LCD1



(b)Lightness, chroma and hue shift for display LCD2



(c)Lightness, chroma and hue shift for display DLP

FIG. 3: Visualization of the color shift throughout the display. On the left, we show a visualization of the lightness shift. The maximum lightness is 100 (white), the minimum (black) is around 79. On the right, hue and chroma shift are plotted relatively to their spatial position. The position of the circles (red) is the reference, the crosses (blue) indicate the measured value. The angle of the segment represents the hue shift, and the norm the chroma shift in the (a^*,b^*) plane. The reference on the right shows a difference of 10 units.

TABLE II: Relative shift in lightness and chroma at 25 locations for the three tested displays.

Shift in lightness							Shift in Chroma					
LCD1												
ΔL^*	1	2	3	4	5		ΔC^*	1	2	3	4	5
1	-8.92	-4.85	-1.61	-1.60	-5.55		1	5.09	2.46	2.29	1.99	2.49
2	-7.66	-3.72	-0.37	-0.36	-5.55		2	4.68	1.78	1.36	1.81	1.97
3	-6.42	-4.09	0.00	-0.58	-3.74		3	3.53	0.87	0.00	1.65	1.56
4	-9.29	-4.77	-1.29	-1.91	-2.81		4	2.37	0.40	1.39	1.80	2.31
5	-11.27	-7.02	-3.78	-4.64	-5.84		5	3.16	3.41	4.73	3.77	1.91
LCD2												
ΔL^*	1	2	3	4	5		ΔC^*	1	2	3	4	5
1	-6.49	-3.43	-1.14	-1.53	-6.09		1	4.13	3.09	1.26	1.63	2.03
2	-6.63	-2.93	0.00	-0.90	-5.96		2	3.17	2.68	0.00	0.92	1.38
3	-6.90	-2.85	-0.11	-2.00	-4.78		3	1.67	0.24	1.97	0.66	1.35
4	-5.71	-4.68	-1.94	-3.79	-5.89		4	1.60	2.32	4.44	2.77	0.78
5	-7.59	-6.75	-4.82	-6.09	-9.66		5	3.18	6.03	5.25	4.18	2.76
DLP												
ΔL^*	1	2	3	4	5		ΔC^*	1	2	3	4	5
1	-20.88	-16.72	-13.84	-14.40	-18.14		1	5.97	5.37	5.47	5.47	5.92
2	-20.90	-14.79	-11.49	-11.83	-16.80		2	5.68	4.85	4.65	4.44	5.40
3	-19.39	-11.46	-6.63	-9.29	-15.60		3	4.94	3.62	2.81	3.56	4.81
4	-18.06	-8.61	-1.68	-4.87	-12.63		4	3.53	1.70	0.92	2.41	4.09
5	-17.77	-7.62	0.00	-1.21	-11.58		5	3.01	0.31	0.00	2.18	3.85

from green/cyan to blue/red as a general behavior from the top left corner to the bottom right. The DLP shows a shift to the blue from the top to the bottom. The causes of this shift can be found in the literature[18], and are probably mainly due to lens alignment and chromatic abberation.

The results of the quantitative analysis are presented in Tables II and III. The first shows the ΔL^* and ΔC^* relative to the brightest point. The second shows the ΔE^*_{ab}.

The largest ΔE^*_{ab} observed are 11.64, 10.17 and 21.71 for LCD1, LCD2 and DLP respectively. The differences are definitively over the just noticeable difference from a colorimetric point of view.

For the LCDs, we noticed a maximum lightness shift of 11.27 ΔE^*_{ab} units in the bottom left corner for LCD1, and of 9.66 units in the bottom right corner for LCD2. The corresponding chroma shifts are respectively of 3.16 and 2.76. The maximum chroma shifts for these displays are 5.09 in the upper left corner for LCD1 and 6.03 at the bottom left for LCD2, with associated lightness shifts of 8.92 and 6.75. The DLP projector shows a maximum lightness shift of 20.90 units in the upper left part of the displayed area, and 5.68 units in chroma at the same position. The maximum chroma shift is of 5.97 units in the upper left corner for 20.88 units in lightness.

In some locations we can clearly see that the lightness variation is smaller than or equivalent to the chromaticity shift, such as below the center for LCD2, which shows a ΔL^* of 1.94 and a ΔC^* of 4.44 compared to the reference location. When we consider the hue shift which is shown in Figure 3 on the right, the chromaticity difference from a spatial coordinate to another can easily be larger than the lightness shift, and the hypothesis which considers the color shift as negligible can be disputed.

3D gamut evaluation

The reference gamut for each projector was constructed from the measurement data of the position with the highest luminance value. Table IV contains the percentage of gamut mismatch for each position compared with this reference.

As we can see, the gamut at some locations can be as much as 52% smaller than the reference, which is illustrated in Figures 4a and 4c. The luminance shift is responsible for a large part of this difference. Compensating for the luminance shift by using the local white point for calculating CIELAB values still leaves a significant maximum gamut mismatch of 8.51%, 9.42% and 9.57% for the three projectors. Figures 4b and 4d show the gamuts computed using

TABLE III: Relative shift in CIELAB unit at 25 locations for the three tested displays.

Shift in CIELAB unit					
LCD1					
ΔE^*_{ab}	1	2	3	4	5
1	9.26	5.24	2.80	2.93	7.53
2	7.89	4.14	1.41	1.81	7.26
3	6.61	4.41	0.00	1.05	5.14
4	9.57	5.10	1.89	1.95	3.68
5	11.64	7.97	6.05	5.75	6.64
LCD2					
ΔE^*_{ab}	1	2	3	4	5
1	6.80	3.80	1.70	3.45	7.36
2	6.77	3.07	0.00	2.82	6.75
3	7.03	2.92	1.97	2.02	5.07
4	5.76	5.44	4.84	4.44	6.11
5	8.07	7.94	7.13	8.57	10.17
DLP					
ΔE^*_{ab}	1	2	3	4	5
1	21.71	17.60	14.88	15.36	19.09
2	21.58	15.45	12.40	12.78	17.73
3	19.97	12.00	7.20	9.97	16.36
4	18.52	8.94	1.92	5.16	13.11
5	18.18	7.92	0.00	1.25	11.97

the local white point.

This mismatch in relative volume is comparable to the error introduced when using a strictly convex hull to represent the gamut of an arbitrarily chosen device, and is greater than many inter-device gamut differences. In our experiment, the gamut mismatch between the two LCD projectors (at the reference position) is 2.75%, giving an intra-device difference 3.43 times larger than the inter-device difference.

The DLP shows large differences in gamut depending on the spatial location, similar to what we showed in our analysis of lightness. Compared with the two LCDs, a larger part of the differences can be explained by the luminance shift. The remaining gamut mismatch volume mainly consists of the volume that is contained within the reference and is not a part of the gamut of the other spatial locations, which is illustrated in Figure 5. This means that there are effects in addition to the luminance shift which contribute to the reduction of the gamuts.

Discussion

Based on our analysis of these results, there appears to be sufficient evidences to claim that the chromaticity shift has to be taken into account in some cases. Some applications might not be affected, while some might suffer seriously from this fact. It appears important for us to compensate for this problem in at least two situations: While performing psychophysical experiments for color science purpose with a projector, and while tiling projectors together to build a multi-projector system.

Related to the choice we made in our experiment by using the brightest white point as a reference, we found that the gamut of the position with the largest luminance results in the largest estimated gamut volume. It is then a logical choice to use this as the basis for the reference gamut.

Considering the case of a multi-projector system, since the chroma shifts in two opposite hue directions from the center of the lens, the area around the overlapping edges will show two really different colors. Note that even though the computed chrominance shift is major (we observed some ΔC^* of about 6 from a position to another and greater differences can be found between extreme positions), if we consider the spatial content of an image, it is not certain that the chrominance shift will break the perceived uniformity.

Similarly, the reduction in gamut volume of up to 52% when using the global white point does not appear to

TABLE IV: Relative gamut mismatch for each position compared with the gamut of the position with the highest luminance. The gamuts are calculated using the global white point as well as the local white point for each of the 9 selected locations.

Gamut mismatch, global white point					Gamut mismatch, local white point			
LCD1								
%	1	3	5		%	1	3	5
1	27.23	4.90	17.08		1	9.57	3.30	5.72
3	23.92	0.00	16.15		3	7.49	0.00	5.53
5	32.66	9.48	13.50		5	7.90	2.07	4.09
LCD2								
%	1	3	5		%	1	3	5
1	24.84	5.83	19.75		1	9.42	2.48	4.46
3	20.18	0.00	18.79		3	6.00	0.00	2.40
5	29.75	11.01	20.82		5	5.98	1.98	2.48
DLP								
%	1	3	5		%	1	3	5
1	52.36	38.02	41.06		1	8.51	6.86	6.91
3	47.73	18.29	36.28		3	7.96	3.92	6.38
5	43.22	0.00	26.93		5	6.62	0.00	4.87

be indicative of the perceived color capability of the projectors. However, using the local white point seems to underestimate the real difference. This is endorsed by the conventional approach. When we look at the full intensity white patch, the perceived difference does not seem to be as large as the measured one.

This is due to contrast sensitivity limitation. Contrast threshold function defines the minimum contrast required to detect a sinusoidal waveform of a particular mean and spatial frequency[19].

This means that within a display area the transition is smooth and spreaded enough on the distance between two locations that it is not detected as a large color difference by the observer.

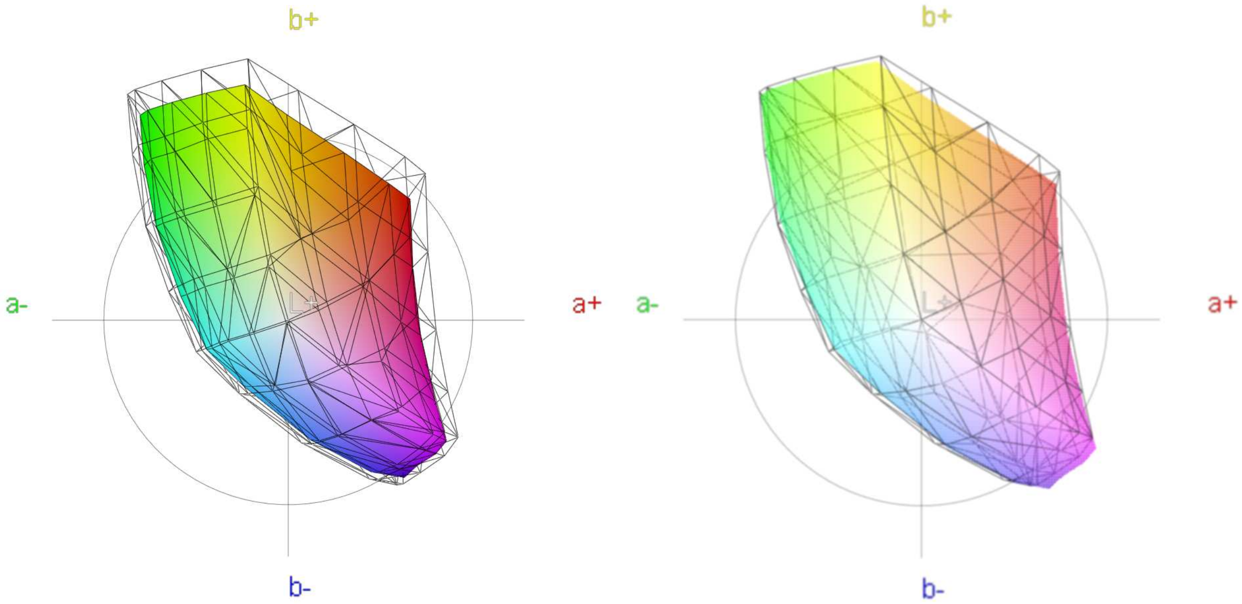
In order to make a model which fits our perceived color appearance, we need to consider both more psychovisual features, such as the color adaptation at the local and at the global level, cognition and physiology and spatial features such as contrast sensitivity.

Common assumptions in color characterization of projectors: A spatial point of view

In this section we present and discuss the common assumptions used in display color characterization. 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.[13] 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.

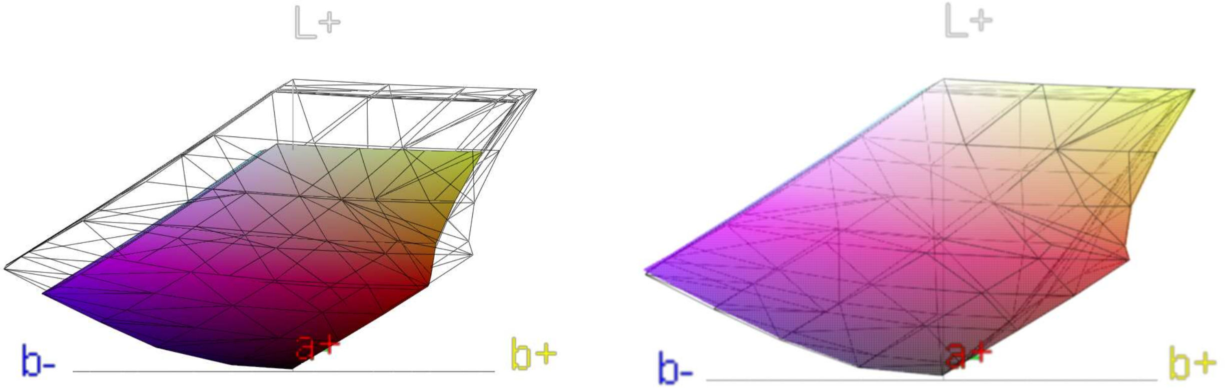
Normalized response curves

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 LCDs[11]. For projectors, if we look at the works of Seime and Hardeberg[3,15] or of Kwak and MacDonald[2], the LCD projector does not appear to fulfill this assumption, however the DLP studied by Seime et al.[3,15] seems to show approximately equivalent normalized response curves for each channel. Let us note that at least one LCD projector seems to fit the hypothesis[14]. 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 dimensions.



(a)LCD1, global white point

(b)LCD1, local white point



(c)DLP, global white point

(d)DLP, local white point

FIG. 4: The gamut boundaries for two of the projectors at the position with the highest luminance (wireframe) compared with the gamut of the top left corner (solid and wireframe). CIELAB measurement values were computed relatively to the global white point for (a) and (c), while 4(b) and 4(d) utilizes the white point of each location.

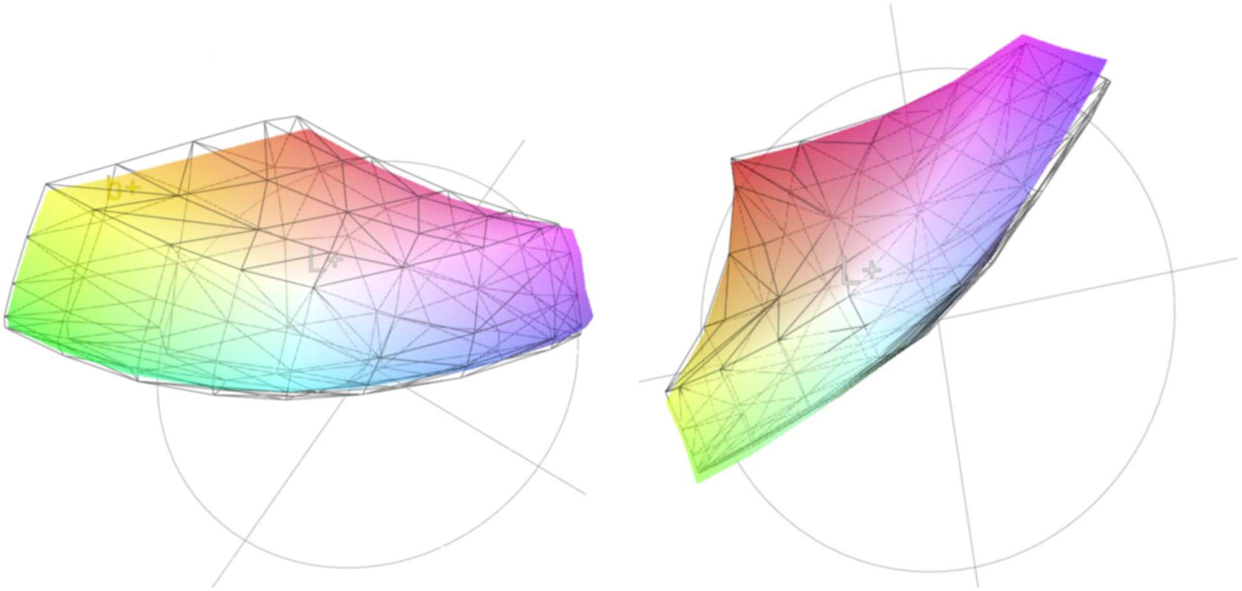
In Fig. 6 we show the response curve of a normalized graylevel intensity ramp at the reference location of the DLP we tested, and a normalized sRGB response curve sampled as the first curve. The sRGB response curve being the one used by default in many cases, we used it as a reference.

We propose a simple method to give an 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 too small 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 gray level response curve at each position. If there is no mismatch it can be enough to measure only the gray level response curve at each spatial location. Results are reported in Table V.

We observe that the centers of the displays are among the locations with the largest shift between curves for each display. If we relate these numbers with the one found between the gray level reference curve and the sRGB curve, it is possible to consider normalized response curves equivalent at each location whatever the channel for *sRGB accuracy*. However, the mismatch is not negligible for applications that require high colorimetric accuracy.

Our second experiment consists in computing the mismatch between each primary at different locations, and the



(a)LCD1

(b)DLP

FIG. 5: While using the white point of each location reduces the difference between the gamuts by compensating for the luminance shift, we still see some differences between the gamuts.

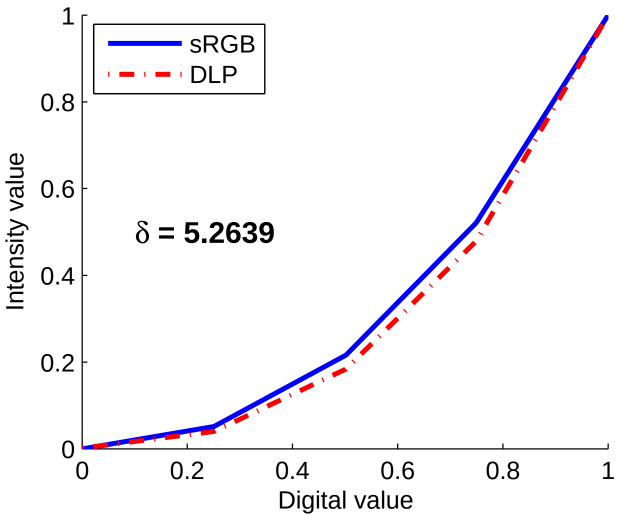


FIG. 6: Normalized response curve of the DLP projector compared with the normalized sRGB response curve. The indicator δ is the surface between both curves × 1000.

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 VI.

It seems to be a valid assumption for DLPs. However, for the LCDs it is approximately as different as supposing the display to be sRGB (which can be an adequate hypothesis depending on the accuracy one wants to reach).

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

TABLE V: Mismatch between the intensity response curves of each channel and the gray level 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

TABLE VI: Mismatch at each location, 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

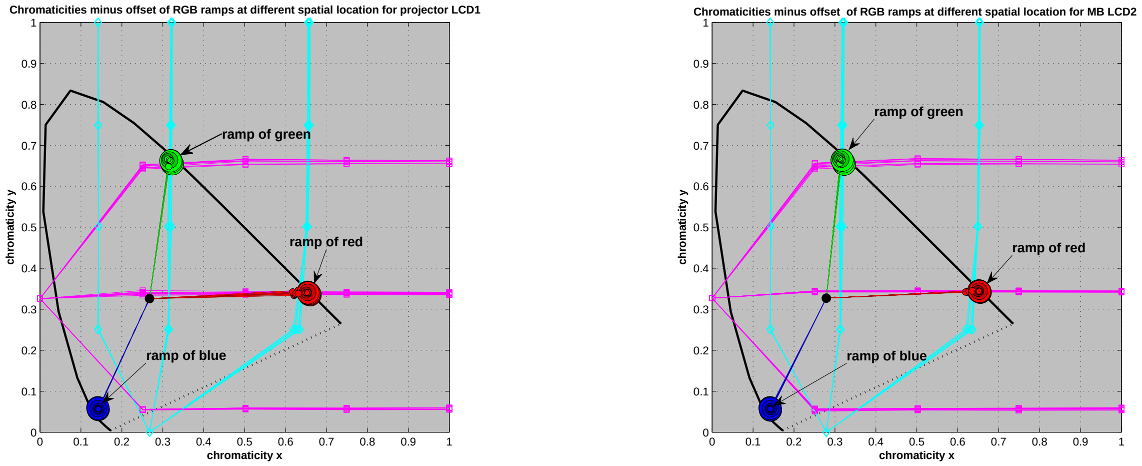
However, the maximum error found in LCDs shows that for this technology (or at least for these projectors) one can introduce a critical error through this approximation.

More analysis should be performed, especially to find a just 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 feasible compromise.

Chromaticity constancy

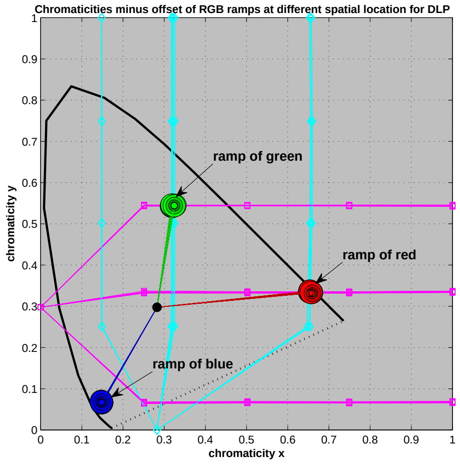
The assumption of chromaticity constancy is important in many physical display color characterization models while performing the colorimetric transform. In this section, we want to see if the behavior of the chromaticity of primaries changes with the spatial location.

Fig. 7 illustrates the chromaticity values of the ramps of red, green and blue for each projector and at different



(a)LCD1

(b)LCD2



(c)DLP

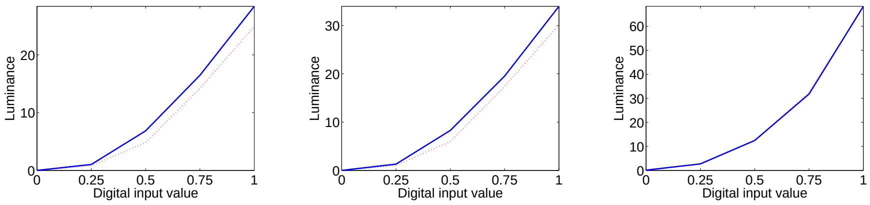
FIG. 7: Illustration of the chromaticity constancy for the projectors at different locations, in (a) for projector LCD1, in (b) for projector LCD2 and in (c) for the DLP projector. In each figure the x and y chromaticity values are shown twice: once as a regular chromaticity diagram and secondly in the 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.

locations. In these figures the offset has been removed using the local offset (the black at each measurement location). We can observe a slightly better chromaticity constancy for the DLP projector (Fig. 7 (c)) than for the two LCD projectors, each chromaticity of each ramp at the various level being almost identical. The primaries are quite consistent spatially within the DLP. However, we can observe a slightly different behavior with the variation of location, especially in the low luminance red primary along the x axis.

Channel independence

An assumption made by several models is that of channel independence, 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, see Figure 8.

The lack of additivity we can observe in Fig. 8 is due to the existence of channel interaction. Bastani et al.[13] suggested that the amount of interaction for a channel at a given intensity can be calculated using the formula in Eq. (1), where $L(r, g, b)$ represents the luminance that is measured for a specified RGB input. a and b are constant



(a)LCD1 (b)LCD2 (c)DLP

FIG. 8: The luminance of the gray ramp (solid line) compared with the sum of the individual ramps (dashed line) for the three projectors.

values for two of the channels, while v is the varying input of the third channel. Eq. (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[5] for visualization purpose.

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

Fig. 9 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 Fig. 10 for LCD1 and DLP. We noticed more interaction in the corners of the image in DLP technology. One factor that could cause this is the motion of the color wheel being less synchronized with the micro-mirrors motion at the corner. Another possible cause is a lens diffraction effect.

Discussion

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, which found that LCDs projectors have a high degree of channel interaction, and their channel additivity is bad. However, DLP technology shows more independence, and a good additivity. The study of the chromaticity constancy shows as well better performances for the DLP. Considering the spatial effect, there is limited difference between spatial locations in terms of channel interaction. We can say that the independence between channels remains quite invariant along the spatial dimensions.

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 dimensions, it could be enough to take some model's parameters at one location.

Conclusion and further work

We have shown that the measured chromaticity shift along the spatial dimension of a projector is important, and that considering only the luminance to be non-uniform can be a critical mistake in some applications. Through the analysis of features, we have shown that most of the color shift, not induced by the lens system, was coming from the spatial differences in response curve in LCD projectors, and from a spatial variation of the channel interaction for DLP technology. These features will be of major interest for designing a spatial color characterization model for projectors.

However, considering the image content, it is reasonable to think that the perceived uniformity would not be broken in many cases. Further experiments could be done in this direction to find what can be considered as perceived spatial uniformity, including contrast sensitivy limits of the human vision.

In any case, considering a given application and its required accuracy and precision, we would recommand to test each parameter on each different type of projectors involved in order to choose the best (the simplest corrections that fit the requirement) color characterization model and the best spatial correction.

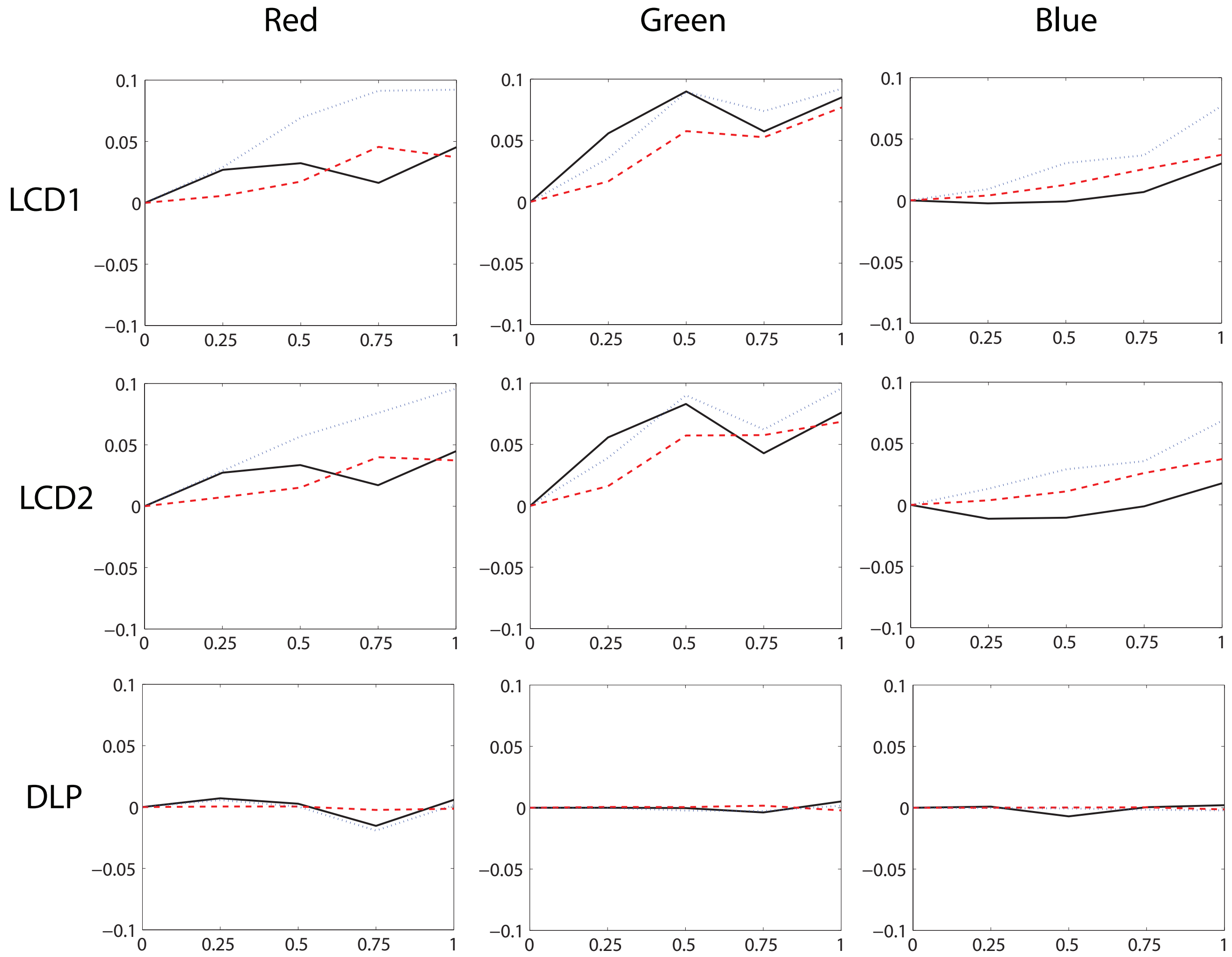


FIG. 9: Channel interaction for three displays. The horizontal axis represents the input value of the denoted channel, while the vertical axis represents the calculated interaction value. The solid black line is the interaction found when the two other channels are kept at maximum input value, while the dashed and the dotted lines are when the *a* or *b*, respectively, is set to 0 when computing the interaction metric.

Further work includes performing a more in-depth statistical analysis of the results, and testing more projectors to improve the significance of the experiment. As a straightforward continuation of this work, we think it could be of great interest to utilize a spatial gamut mapping algorithm using a spatially varying gamut in multi-projector systems.

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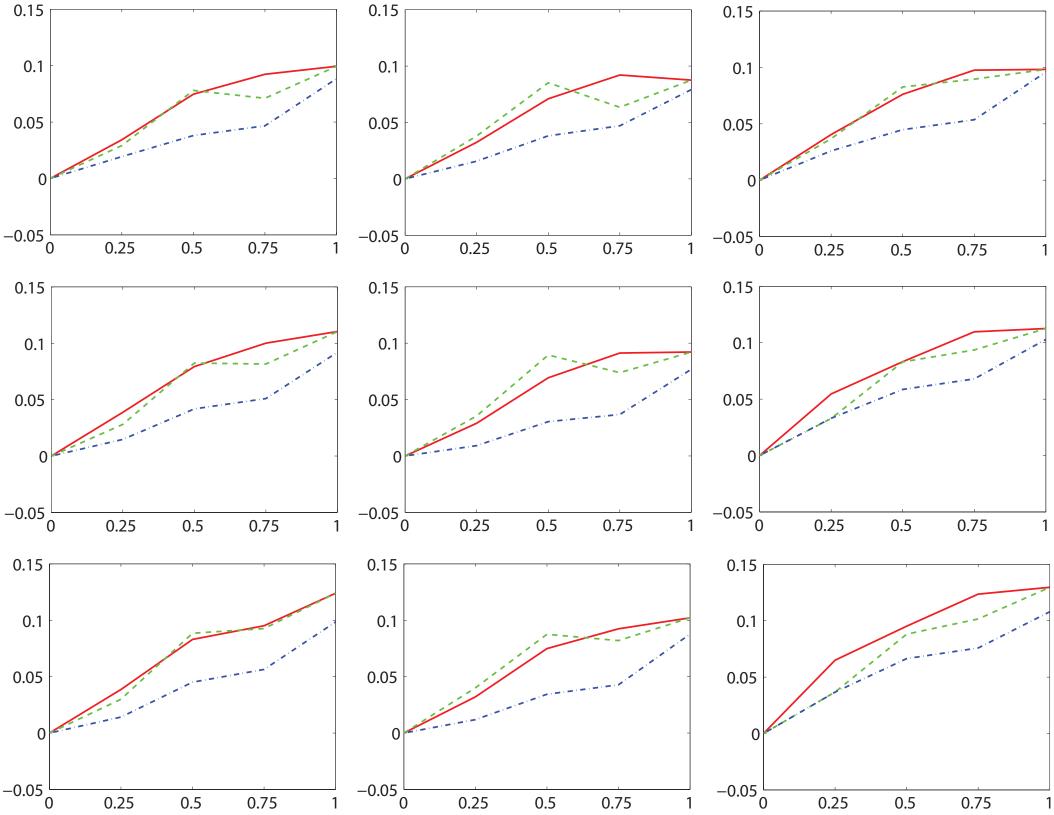
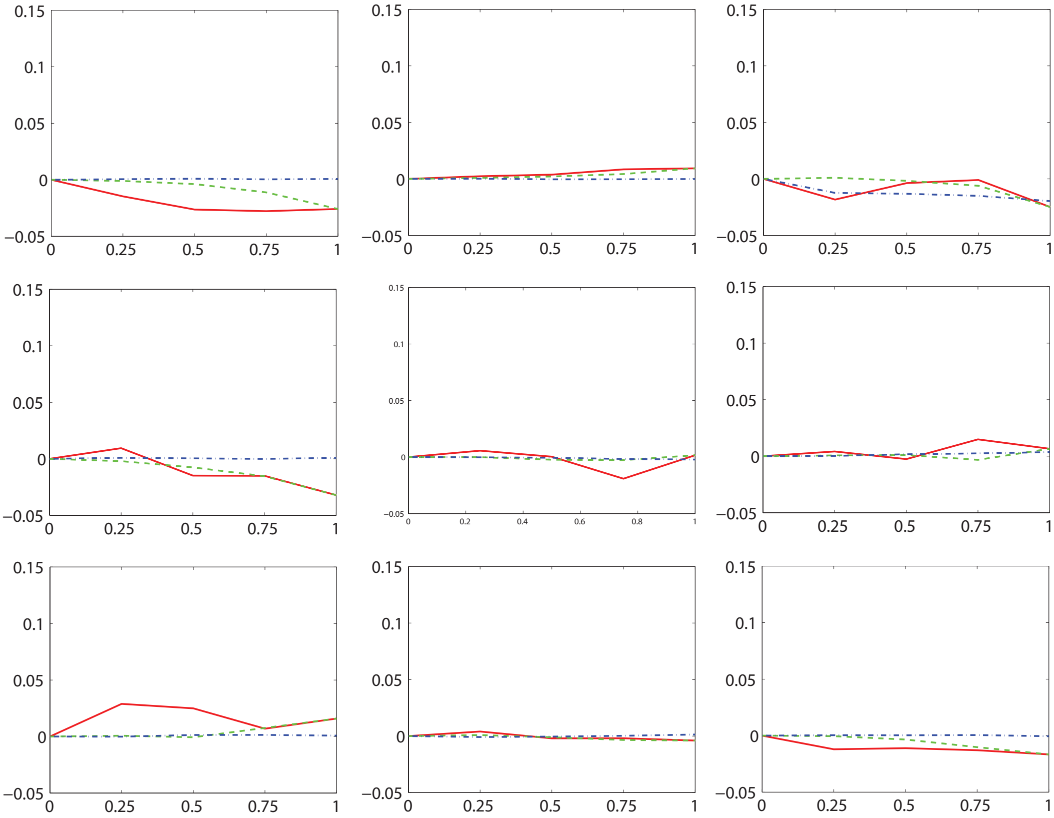


(a)LCD1



(b)DLP

FIG. 10: 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 gives the highest interaction is chosen for each channel.

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