SPATIAL COLOR CONFIDENCE FOR PHYSICALLY BASED RENDERING SETTINGS ON LC DISPLAYS

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Abstract: Color confidence is crucial regarding physically-based rendering settings in order to produce most promising visual results. Display characterization and in particular spatial inhomogeneity correction is often neglected in physically-based rendering applications, yet, are important to achieve color confidence. By evaluating relevant display characteristics, this paper recommends a strategy for selecting the most suitable characterization model for a given device. We indicate the importance of correcting spatial inhomogeneity and, on that account, provide an extension to the applied characterization models. All characterization models as well as our proposed extensions are implemented using modern graphics hardware, therefore, applicable to real time applications. The focus is on finding an optimal characterization model which can achieve color confidence across the display while reducing characterization time and effort. All models are created using a common, single point, consumer measurement device and applied to two LC displays.

1 INTRODUCTION

Always rising computing power allows for promising physically-based rendering systems with images even described as spectral radiance distributions of light (Pharr and Humphreys, 2004). Yet, the final quality of these renderings is determined by the way output devices display the simulated colors. For color critical applications, e.g., physically-based predictive renderings in design review, it is essential that the display of an image produces the same color stimulus in the observer's mind as the spectral radiance distribution of the simulation intends. Color confidence in this work refers to the colorimetric correct display of color on LCDs within the boundaries of the device gamut. As devices have different characteristics, different color stimuli result from the same color coordinates on various devices. To specify color unrelated to a certain device, device-independent color specifications exist, typically, the 1931 CIE XYZ standard observer color system (CIE, 2004). The characterization of a device aims to infer a transformation between device-dependent RGB values and a device-independent color space. For accurate colorimetric reproduction of CIE XYZ values the inverse transformation is required. The inverse model predicts device-dependent RGB values needed to provoke the same color sensation to the standard human observer as the corresponding device-independent CIE XYZ values.

Various characterization models exist which agree on certain display characteristics and prerequisite diverse characterization tests to be conducted. The test results provide information about the shortcomings of a display and allow for the selection of an appropriate characterization model in order to agree on the found deficiencies.

Display characterization and in particular spatial inhomogeneity correction is often neglected in physically-based rendering applications but are important to achieve color confidence. By evaluating important characterization tests this work proposes a recommendation for selecting the most suitable characterization model for a given device. Three characterization models are employed, comprising further display deficiencies in each case, and applied to two LC displays. Since characterization needs plenty of time and effort, the main focus is on the selection of a model that needs the fewest measurements to be set up while still allowing for precise colorimetric output. We indicate the importance of correcting spatial inhomogeneity and it is shown how all of the presented characterization models can be extended for spatial characterization using the processing power of the GPU, whereas a common, single point, consumer measurement device is utilized.

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The content is structured as follows: In Section 2 we give a brief outline of related work on display characterization models including spatial inhomogeneity correction. Section 3 introduces LC display characteristics and the associated characterization tests. Section 4 addresses the characterization models and their extension to spatial inhomogeneity correction. A strategy to choose the optimal inverse characterization model for a certain display is presented in Section 5. Subsequently, Section 6 presents the results of the applied characterization models and Section 7 summarizes and concludes the contribution.

2 RELATED WORK

Day et al. (Day et al., 2004) describe the process of characterization as modeling of the Optoelectronic Transfer Function (OETF). The OETF specifies the relationship between the digital input value used to drive a display channel and the radiant output produced by that channel.

Fundamental characterization models include the *Piecewise Linear interpolation assuming Constant Chromaticity coordinates* (PLCC) model, models that approximate the OETF by second-order polynomial functions or power functions, the Piecewise Linear interpolation assuming Variable Chromaticity coordinates (PLVC) model, or Berns' Gain-Offset-Gamma (GOG) model (Berns et al., 1993a; Berns et al., 1993b) for CRTs. Evaluations of these models were presented by Post and Calhoun (Post and Calhoun, 1989; Post and Calhoun, 2000). They also stated the importance of black correction (Post and Calhoun, 2000), whereas Day et al. presented a definition of the different types of black light (Day et al., 2004). Black correction can be incorporated in all characterization models. PLCC and the function models assume channel independence and constant chromaticity coordinates of the display's color channels. Thereby the use of the (3 x 3) primary transform matrix is justified for the transformation from RGB to XYZ (Fairchild et al., 1998; Thomas et al., 2008). On the contrary, PLVC only assumes channel independence. Here, a single (3 x 3) matrix cannot be applied due to the variable chromaticity coordinates assumption. Fairchild and Wyble tried to apply the GOG model to LCDs and found it inadequate for colorimetric characterization for research purposes (Fairchild et al., 1998). They resulted in good performance when replacing the GOG functions with 1D LUTs per channel to model the OETF together with a black corrected color transform matrix. Except for PLVC, the models are directly invertible. An inversion of PLVC can be realized by a geometrical backward transformation using a tetrahedral structure (Hung, 1992; Hung, 1993), as proposed by Thomas et al. (Thomas et al., 2008). For an in-depth review of existing characterization models we recommend a recent publication by Thomas et al. (Thomas et al., 2008).

Spatial inhomogeneity refers to the lack of consistency of a display's output characteristics with respect to different locations on the screen. A first approach for spatial correction of luminance across a CRT monitor has been introduced by Cook et al. (Cook et al., 1993). Their method is limited to a maximum uniform luminance of the algorithm grid cell with the lowest luminance, resulting in a gamut restriction for the display. Sharma (Sharma, 2002) as well states the importance of spatial inhomogeneity correction for scientific applications and notes changes in luminance across the screen of up to 25%. He also refers to the approach of Cook et al. Day et al. (Day et al., 2004) comment on the importance of characterizing a display at multiple positions and angles. They recommend to perform two colorimetric characterizations for paired comparison of images displayed side by side.

Another research area is the correction of single- (Hardeberg et al., 2003; Menu et al., 2005; Renani et al., 2009) and multi-projector images (Majumder and Stevens, 2002). Here, the perceived image is further influenced by the projection screen. Instruments as spatial radiospectrometers, colorimetric cameras, as well as consumer cameras or even webcams are used to correct spatial non-uniformities of the projector light as well as the projection screen. In this work, we concentrate on LC displays using a single point consumer color measurement device to achieve spatial color confidence with a minimum of measurements.

3 DISPLAY CHARACTERISTICS

Color confidence can only be achieved with a minimum of time and effort if the appropriate display characterization model is chosen. To determine a suitable model for a given device, several tests are to be performed in order to analyze the properties of the display (Fairchild et al., 1998; Day et al., 2004; Gibson and Fairchild, 2000; Berns, 1996). Since there are various display characteristics which can be considered (Brainard et al., 2002), we focus on the ones we think are the most critical to evaluate. We explicitly assume that additivity is given for a device, as the models which account for channel dependencies are rather complex, too inaccurate, or not readily invertible and thus impracticable if an inverse model is needed (Wen and Wu, 2006; Cho et al., 2006).

In this work, all tests are presented in reference to LCDs, yet, they are also applicable for other additive devices. The display devices being used are a midrange model (Samsung SnycMaster 244T) and a high-end model (NEC SpectraView 1690), in the following being abbreviated *Samsung* and *NEC*. As a measurement device a X-Rite i1-pro spectroradiometer has been utilized. Measurements have been performed in complete darkness.

Warm-up Phase. The back light of a LCD needs time to warm up and stabilize. This is a prerequisite for an accurate characterization and it needs to be tested when this state is reached. Our tests revealed that display devices can have a warm-up phase of up to 3 hours, much more then declared by the manufacturers.

Chromaticity Constancy. One of the main criteria to evaluate before choosing a suitable display characterization model is chromaticity constancy. Chromaticity constancy is the property of the primaries to maintain their chromaticity coordinates regardless of their intensities. When this criteria is fulfilled, simple characterization models only requiring a few measurements can be applied. To identify chromaticity constancy of the display primaries, RGB ramps can be measured and the resulting CIE XYZ values are transformed to chromaticity coordinates. Figure 1 shows the plotted results for the red, green, blue, and combined channels. Black correction (Post and Calhoun, 2000) can be employed to improve the results in order that chromaticity constancy is fulfilled, as e.g., for the NEC display.

Spatial Homogeneity. Spatial homogeneity refers to the differences of a display's color output at one location on the screen compared to another location on the screen. I.e., a certain configuration of R, G, and B digital input values can result in different color stimuli on various positions on the screen.

Spatial inhomogeneity can be examined by measuring and comparing different colors or primary ramps at different locations on the screen with respect to their change in chromaticity coordinates and luminance, as well as differences in lightness, chroma, and hue in CIE LAB. Figure 2 depicts the differences in lightness ΔL^*, chroma ΔC^*_{ab}, and hue ΔH^*_{ab} for 52 increasing intensity steps of the red channel measured at the center of the screen compared to the same measurements at the bottom right of the screen.

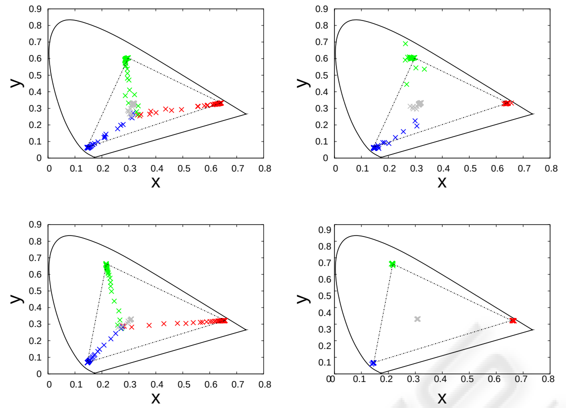

Figure 1: Chromaticity coordinates of the red, green, blue, and combined channels. On the left without black correction; on the right with black correction (top: Samsung, bottom: NEC).

Both, the Samsung and NEC show a rising difference in lightness and chroma with increasing input intensity. The Samsung e.g., has a maximum difference in lightness of 7.16 ΔL^* and in chroma of 11.29 ΔC^*_{ab}. Since lightness and chroma differences more or less increase proportional, the ramps exhibit a constant chroma-lightness difference ratio, meaning that colors are more saturated at the center of the displays with rising channel input values. The overall low hue differences point out the almost hue constancy for the different positions. Analyzing maximum luminance differences, both displays vary between up to 45 to 50 $cd \cdot m^{-2}$ across the screen. The other channels as well as different measurement locations behave in a similar way. From the results it can be inferred that spatial inhomogeneity should be accounted for in display characterization models.

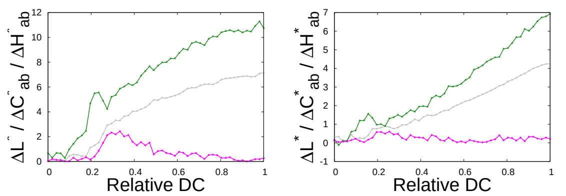

Figure 2: Differences in lightness ΔL^* (gray), chroma ΔC^*_{ab} (green), and hue ΔH^*_{ab} (magenta) between 52 red channel intensity steps measured in the middle and at the bottom right of the screen (left: Samsung, right: NEC).

4 CHARACTERIZATION MODELS AND STRATEGY

This section presents an overview of the inverse display characterization models that are considered in our proposed procedure to find the optimal characterization model (see Figure 4). The characterization models try to agree on different characteristics of a device in order to model it adequately and to limit the number of measurements. They have been selected to sequentially build upon each other with respect to the characteristics they agree on. Later on, we show how all models are extended for spatial characterization by utilizing contemporary graphics hardware.

Matrix and Gamma (MG) Model. This model is subject to the most assumptions: It assumes that the primaries of a display device are independent and exhibit perfect chromaticity constancy. Furthermore, this model is constraint to an OETF with the characteristics of a power function, having an exponent of the native gamma value of the display. With the help of this model, the RGB values that reproduce a certain CIE XYZ stimulus can be estimated as follows:

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = \begin{pmatrix} X_{r,max} & X_{g,max} & X_{b,max} \\ Y_{r,max} & Y_{g,max} & Y_{b,max} \\ Z_{r,max} & Z_{g,max} & Z_{b,max} \end{pmatrix}^{-1} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}, \quad (1)$$

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} R'^{1/\gamma} \\ G'^{1/\gamma} \\ B'^{1/\gamma} \end{pmatrix}, \quad (2)$$

where $(X_{k,max}, Y_{k,max}, Z_{k,max})^T$, $k \in \{r, g, b\}$ denote the CIE XYZ values measured for the red, green, and blue primaries set to their maximum intensity. The first step transforms a desired CIE XYZ stimulus to linear R'G'B' values. In the second step, the linear R'G'B' values are transformed by a power function with the reciprocal of the display's gamma value as the exponent to non-linear RGB values which are sent to the framebuffer. Although the γ value can be different for all three primaries, in consideration of the simplicity of the model, only a single value has been used.

Matrix, Gamma, and Offset (MGO) Model. Displays often exhibit variable chromaticity coordinates for different channel intensities. Black correction (Post and Calhoun, 2000) accounts for this problem up to a certain degree. This model assumes that after black correction, the display's primaries exhibit chromaticity constancy. Thus, Eq. (1) becomes:

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = M^{-1} \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix}, \quad (3)$$

$$M = \begin{pmatrix} X_{r,max} - X_0 & X_{g,max} - X_0 & X_{b,max} - X_0 \\ Y_{r,max} - Y_0 & Y_{g,max} - Y_0 & Y_{b,max} - Y_0 \\ Z_{r,max} - Z_0 & Z_{g,max} - Z_0 & Z_{b,max} - Z_0 \end{pmatrix}. \quad (4)$$

The light emitted when all primaries are set to zero is given by (X_0, Y_0, Z_0).^{T} The second step in this model is the same as in Eq. (2). If the measurement device is not capable of measuring the black light, it can be estimated using methods proposed by Berns et al. (Berns et al., 2003).

3D Tetrahedral LUT and Offset (3D LUT) Model. If the displays primaries do not exhibit chromaticity constancy (even after black correction) a model which agrees on variations in chromaticity has to be applied. We use a simplified version of the inverse model of Thomas et al. (Thomas et al., 2008) which is based on their forward PLVC model (Thomas et al., 2008) to reduce the number of measurements.

Since the forward model is not directly invertible analytically, a 3D LUT forms the basis of the inverse model. Dividing the RGB axes in arbitrary steps and summing up all combinations of RGB values establishes a grid in device-dependent (destination) space. As channel independence and thus additivity is assumed, the grid can also be constructed in device-independent (source) space by summing up the CIE XYZ tristimulus values of the measured RGB channel ramps in all combinations. Tetrahedral devision after the model of Hung (Hung, 1992; Hung, 1993) is performed on the grid in source and destination space. Thus, a point in a tetrahedron in source space is linearly related to a point in the correspondent tetrahedron in destination space by its barycentric coordinates:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = M_{RGB} \cdot M_{XYZ}^{-1} \cdot \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix} + \begin{pmatrix} R_0 \\ G_0 \\ B_0 \end{pmatrix}, \; with \quad (5)$$

$$M_{RGB} = \begin{pmatrix} R_1 - R_0 & R_2 - R_0 & R_3 - R_0 \\ G_1 - G_0 & G_2 - G_0 & G_3 - G_0 \\ B_1 - B_0 & B_2 - B_0 & B_3 - B_0 \end{pmatrix}, \; and$$

$$M_{XYZ} = \begin{pmatrix} X_1 - X_0 & X_2 - X_0 & X_3 - X_0 \\ Y_1 - Y_0 & Y_2 - Y_0 & Y_3 - Y_0 \\ Z_1 - Z_0 & Z_2 - Z_0 & Z_3 - Z_0 \end{pmatrix},$$

where vector $(R, G, B)^T$ is the corresponding point in destination space to the desired CIE XYZ stimulus vector $(X, Y, Z)^T$ in source space. The matrix components $(X_k, Y_k, Z_k)^T$ and $(R_k, G_k, B_k)^T$ with $k \in \{0, 1, 2, 3\}$ denote corresponding vertices of a tetrahedron in source and destination space. The barycentric coordinates α, β, and γ of a point $(X,Y,Z)^T$ in a tetrahedron are determined using Eq. 6:

$$\begin{pmatrix} \alpha \\ \beta \\ \gamma \end{pmatrix} = M_{XYZ}^{-1} \cdot \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix}. \quad (6)$$

If all barycentric coordinates $j \in \{\alpha, \beta, \gamma\}$ lie in $[0,1]$ the point is inside the tetrahedron. In order to be more efficient, a bounding box approach has been used to reduce the number of tetrahedra to be tested for point inclusion. The downside of this approach is the interpolation error, which is introduced since the shape and size of the tetrahedra may change when transforming the tetrahedra structure into the source space.

In order to achieve a more uniform grid in source space, and therefore reduce the interpolation error, Thomas et al. (Thomas et al., 2008) propose to optimize the tetrahedral structure by a function describing the generation of the 3D grid, whereby its parameters are optimized using a globalized Nelder-Mead simplex downhill algorithm.

GPU Assisted Spatial Characterization. One way to extend all of the presented models for spatial characterization is to perform the characterization independently of each other at different locations on the screen. By using this strategy, it is possible to exploit the maximum capabilities of the display device. Furthermore, this approach is very well scalable and could also be taken to the extreme by performing a display characterization per pixel if a suitable measurement device is available.

If a CIE XYZ value is to be displayed between the locations for which the characterization was performed, bilinear interpolation can be used to interpolate between the characterization data for these measurement locations as depicted in Figure 3. For the MG and MGO Model, interpolation can be performed between the columns of the primary transform matrix, each representing a CIE XYZ tristimulus value. For the 3D LUT Model it is most feasible to interpolate between the final RGB values which result from transforming the desired CIE XZY value at each of the surrounding measurement locations. The interpolation can be done straightforward with help of the built-in texture interpolation of current graphics hardware so that no additional computational costs occur. For example, if the MGO model is used the data of $n \times n$ measuring positions is written to textures of size $n \times n$. One texture for each row of the primary transform matrix and one texture for the black value. If the shader displays the image, it uses the current texture coordinate of each fragment to access the textures storing the calibration data. If bilinear filtering

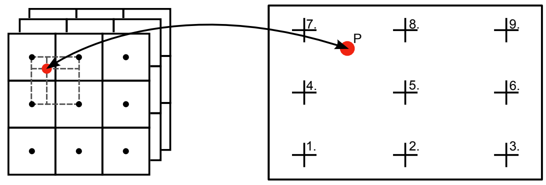

Figure 3: The characterization data of nine positions is written to textures of size 3×3. If a pixel is displayed, the data of the four nearest characterized locations (4,5,7 and 8) is automatically interpolated with the help of the built-in bilinear texture interpolation.

is turned on, the graphics hardware automatically interpolates the textures and the resulting values can be used to evaluate Eq. 3.

We recommend to characterize nine positions on the screen for the spatial characterization as shown in Figure 3. This number of locations provides a good coverage of the screen and also a good trade-off between the quality of the spatial characterization and the time it takes to perform the measurements necessary for the given characterization model.

5 MODEL SELECTION STRATEGY

Display devices should be characterized at least once a week if they are used for critical applications like virtual design review. The goal is to find a model which provides the best trade-off between quality and measurement time. We propose to use the procedure depicted in Figure 4 to determine the most suitable characterization model for a particular device.

After the warm-up phase, the device has to be tested for chromaticity constancy. If the device exhibits chromaticity constancy, the MG Model can be used. Otherwise, black correction should be employed. If this does not improve the results, the 3D LUT Model needs to be used. In all other cases, the MGO Model is most suitable. After determining the characterization model, the display has to be tested for spatial inhomogeneity. If present, spatial characterization needs to be employed as described above, otherwise, a global characterization at the center of the screen is sufficient.

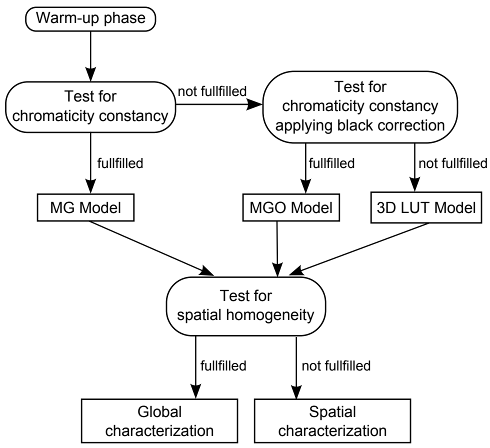

Figure 4: A flow-chart describing the process of choosing the optimal characterization model for a particular display device.

6 RESULTS

We apply our proposed strategy (see Figure 4) to two LC displays and show how an optimal characterization for each of these displays can be found.

After the warm-up phase, the primaries of the display devices are tested for chromaticity constancy. As illustrated in Figure 1, the assumption of chromaticity constancy is not fulfilled by both devices. Thus, black correction is employed. Afterwards, the primaries of the Samsung device still do not exhibit chromaticity constancy and the 3D LUT model is applied. For the NEC, the MGO model is sufficient, since chromaticity coordinates are constant (cf. Figure 1).

Global Characterization. In a first step, the test for spatial inhomogeneity is ignored. The characterization results for the center of the screen are shown to demonstrate the applicability of the first half of the proposed flow-chart.

The chosen characterization model is applied to 24 patches of absolute CIE XYZ tristimulus values obtained by measurements of the ColorChecker. For comparison, we applied all characterization models to each display device and computed the CIE ΔE^*_{ab} color difference. The results are listed in Table 1. The display characteristics already revealed that the Samsung device does not exhibit chromaticity constancy even after black correction, thus the CIE XYZ values could not be reproduced accurately with the MG and MGO model. According to our proposed procedure a model which accounts for variations in chromaticity constancy should be selected. The 3D LUT model was able to reproduce the given CIE XYZ values more precisely. The primaries of the NEC device exhibit chromaticity constancy after black correction and therefore the MGO Model was sufficient for an excellent reproduction of the CIE XYZ tristimulus values.

Table 1: Results of the global characterization models.

Model	LUT size	ΔE^*_{ab}			
		Samsung		NEC	
		Av.	Max.	Av.	Max.
MG	-	4.92	8.49	1.61	2.67
MGO	-	4.71	8.48	1.24	2.86
3D LUT	9	6.90	18.79	7.10	19.65
	18	3.08	9.28	3.79	11.03
	24	3.18	7.50	2.35	5.91
	33	2.56	5.52	1.40	4.37
	86	2.69	4.26	0.99	2.43

Spatial Characterization. The results of Section 3 revealed that spatial inhomogeneity is present on both devices. Following our proposed procedure, the characterization models have to be extended for spatial characterization. We use nine different, equally distributed positions across the screen for the spatial characterization process. To test the performance of our spatial characterization shader, the 24 patches of the ColorChecker are shown at three positions on the screen which seem to exhibit the greatest differences on both devices.

Table 2 lists the results for the Samsung device for which the 3D LUT model was extended for spatial characterization.

Table 2: Spatial characterization results for the Samsung (3D LUT Model). The column "Shader" indicates whether spatial characterization was performed with the help of the GPU or not.

Shader	ΔE^*_{ab}					
	Middle		Bottom Left		Bottom Right	
	Av.	Max.	Av.	Max.	Av.	Max.
Off	2.24	4.27	5.36	8.31	8.70	12.57
On	2.47	4.95	2.50	5.28	2.65	4.60

The results reveal that color confidence across the display can only be achieved if spatial characterization is performed. For example, the bottom right position has a mean ΔE^*_{ab} of 8.70 and a maximum ΔE^*_{ab} of 12.57 if the spatial characterization shader is turned off. With spatial characterization enabled, mean and maximum ΔE^*_{ab} drop to 2.65 and 4.60, respectively. To visualize the results in another way, Figure 5 depicts two luminance relief maps for Patch 11 of the ColorChecker. Without spatial characteri-

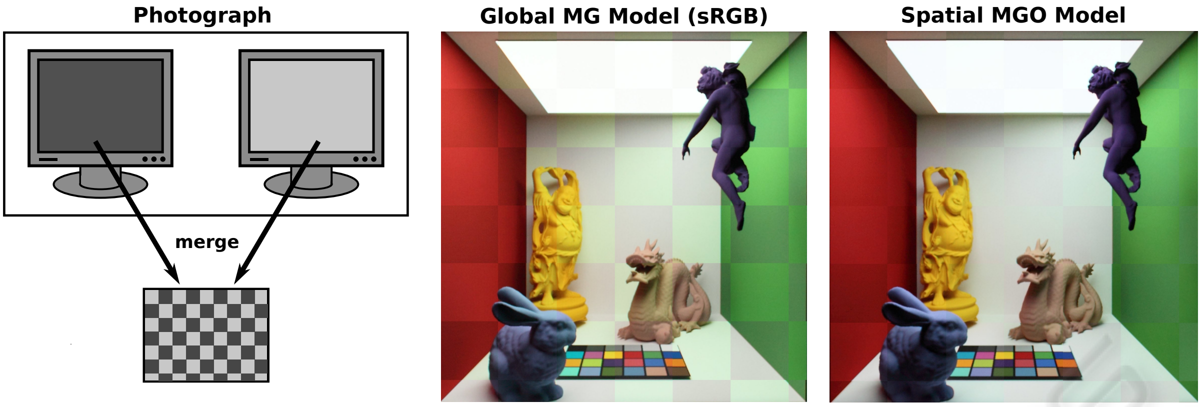

Figure 6: Two LC displays were characterized with two different characterization methods. A picture was taken of the two devices displaying the same CIE XYZ tristimulus image. The parts of the picture containing the output of the two displays were merged. The spatial characterization was able to reduce the differences in the output.

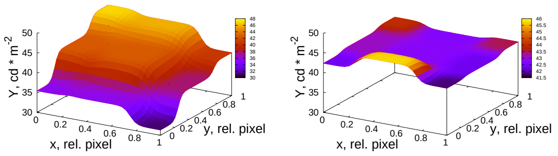

Figure 5: Luminance relief map of Patch 4 of the ColorChecker with global characterization (top) and spatial characterization (bottom) for the Samsung device. Measurements were taken at nine different positions across the screen.

zation the patch exhibits a maximum luminance difference of 15.71 $cd \cdot m^{-2}$ across the screen. With activated shader, the differences are reduced to 3.91 $cd \cdot m^{-2}$ indicating that a luminance compensation across the screen is achieved.

The results for the NEC device are shown in Table 3. Overall improvements become apparent since all mean and maximum color difference values ΔE^*_{ab} are hardly perceptible across the screen when the shader is applied resulting in an excellent spatial characterization.

Table 3: Spatial characterization results for the NEC (MGO Model). The shader state indicates whether spatial characterization was performed with the help of the GPU or not.

Shader	ΔE^*_{ab}					
	Middle		Top Left		Top Right	
	Av.	Max.	Av.	Max.	Av.	Max.
Off	0.78	2.07	2.62	4.04	3.29	6.72
On	0.84	2.22	1.88	2.79	1.17	2.34

Visual Comparison. If two displays are characterized successfully, the output of the same image on both devices should be indistinguishable from each other. We have conducted an experiment in which such a visual evaluation is performed. A global and a spatial characterization was applied to two LC devices (NEC SpectraView 1690 and EIZO S2000). The global characterization assumed that the two devices adhere to the sRGB specification as stated in their device manuals. The appropriate model for spatial characterization was chosen according to the proposed strategy which suggested using the MGO Model and nine different measurement locations. The displays were positioned in a way so that a picture could be taken of both displaying the same image that resulted from a physically-based rendering system. An uncharacterized digital consumer camera has been used. The images of both monitors were merged as illustrated in Figure 6. Please note that it is very hard to reproduce such a visual comparison, as there are many factors which alter the result (e.g., the response curves of the digital camera, angular dependencies of the displays, external flare, ...). Still, it is clearly visible that a spatial characterization yields in results superior to a global characterization and is necessary to achieve color confidence across the display and across different devices.

7 CONCLUSIONS AND FUTURE WORK

In this work, we introduced a strategy for selecting the most suitable inverse display characterization model for a given device by evaluating important characterization tests. The tests incorporate the evaluation of a display's warm-up phase, the behavior of the channels' chromaticity at various input levels, the impact of black correction, as well as spatial inhomogeneity.

Furthermore, the need for spatial characterization has been pointed out and a method has been proposed to extend the presented characterization models for spatial characterization. All of the models have been implemented entirely on the GPU, making them applicable to real-time applications. In addition, we showed that spatial characterization can by employed by the use of a single point consumer measurement device.2

For future work, we try to incorporate consumer digital cameras as measurement device in order to facilitate the process of spatial characterization and make a per-pixel characterization of a display device feasible. Furthermore, we analyze if the recommended strategy can be applied to other devices, e.g. projection devices, or has to be extended. An evaluation of existing models that incorporate channel-dependencies would also be an interesting task in order to further improve color confidence for displays with poor additivity characteristics and to integrate such models in our proposed strategy.

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