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LCDs Versus CRTs - Color-Calibration and Gamut Considerations

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Abstract: This paper presents a comparative evaluation of liquid-crystal display (LCDs) and cathode-ray tube (CRT) displays from a color-rendition and color-calibration perspective. Common display calibration models and assumptions are reviewed and their applicability to LCDs and CRTs is evaluated through an experimental study. The displays are compared with respect to the color-calibration accuracy, ease of calibration, and achievable color gamut. The offset, matrix, and tone-response correction model commonly employed for CRT color calibration is also suit- able for color calibration of LCDs for most applications, though the calibration error for LCDs is higher. For the prototype LCDs used in the experimental study, large color variations significantly above the calibration accuracy are observed with changes in viewing angle. Under typical viewing conditions, LCDs provide a significantly larger color gamut than CRTs primarily due to their higher luminances.

Keywords: Color calibration, CRT, CRT gamut, display color gamut, LCD, liquid-crystal displays.

I. INTRODUCTION

Liquid-crystal display (LCD) flat panels are befitting increasingly common as computer color displays due to their compact size and low power utilisation. These displays are now available at increasingly higher spatial resolutions and in larger screen sizes with image quality that meets or exceeds that of typical cathode-ray tube (CRT) displays [1]. While the market for CRTs carry on to grow at present, in the long run, flat-panel displays are expected to replace CRTs as the primary computer displays [2], [3].With the widespread use, there is also an increased need for color management for LCDs, which enables accurate control of color in displayed images. While the color characteristics of CRT displays and methods for their color calibration have been extensively studied and reported [4]–[9], the color characteristics of LCDs and methods for calibration have only come to the forefront in the last few years and have received only restricted attention in published literature [10]–[12]. Active-matrix LCDs (AMLCDs) represent the most commonly employed LCD technology for computer dis- plays. This paper reviews the color characteristics and the color-calibration requirements for AMLCDs and contrasts them with CRT displays which symbolize the predominant display technology employed today. Common physical assumptions and models for display color calibration are first reviewed in Section II.

The specializations of these models to CRT displays are sum up in Section III. The applicability of the models to the AMLCDs in light of their operational physics is considered in Section IV. Sections V–VIII present experimental calibration results for a prototype AMLCD [13] along with corresponding results for a CRT display. Color-calibration models, calibration accuracy, dynamic range, and achievable color gamuts for LCDs and CRTs are compared and contrasted in Section IX. The major conclusions upcoming from the comparative study are summarized in Section X.

II. DISPLAY COLOR-CALIBRATION MODELS

In order to consider the color calibration of displays, it is helpful to consider a mathematical model that represents their operation. A general mathematical framework for device calibration has been described in [14]. This section will focus on specifics and details applicable to display calibration. The display is driven by a set of control signals, typically in the form of an R, G, B triplet for each pixel corresponding, respectively, to the red, green, and blue channels for that pixel. In the most general case, the light emitted by a pixel location could be a function of the present and previous history of driving signals for the whole set of pixels on the display. Clearly, a model of this generality would be too hard to characterize.

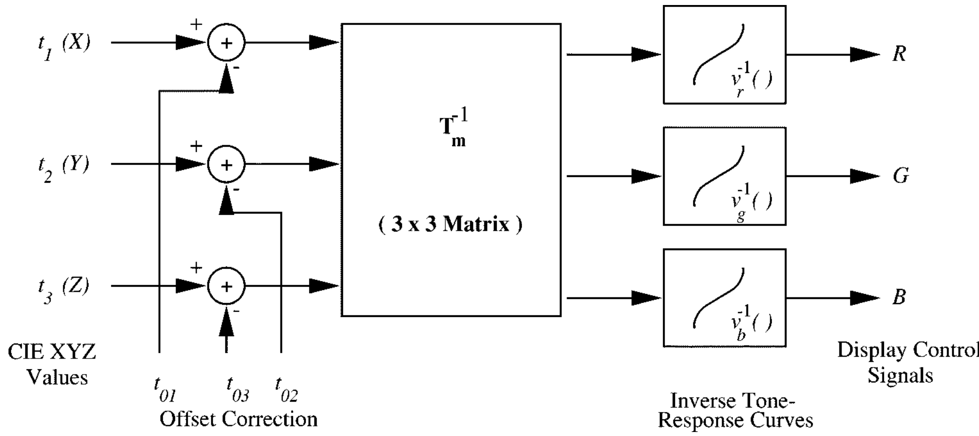

Fig.1: Graphical representation of the display inverse model.

The physics of CRTs strongly supports these assumptions and they have also been extensively validated in experiments [5], [9].
For CRTs, the final model of Section II, can be further simplified by using a parametric mathematical model for the TRCs for the individual channels that is derived from the power-law relation between grid voltage and beam current for a vacuum tube [19]. The expression for the red- channel TRC resulting from the power-law relation can be written as [8]

$$c_1(\mathrm{R}) = \left((1-\beta_r)\frac{\mathrm{R}}{\mathrm{R}_{\max}} + \beta_r\right)^{\gamma_r}$$

where $\mathrm{R}_{\max}$ corresponds to the maximum value for the red- channel signal and β_r and γ_r represent the offset and exponent parameters of the model. Analogous expressions apply for the green and blue channels.
For appropriate setup of the monitor offset and brightness controls [8], the offset term $\beta_r = 0$ and the relation simplifies to

$$c_1(\mathrm{R}) = \left(\frac{\mathrm{R}}{\mathrm{R}_{\max}}\right)^{\gamma_r}$$

Which, γ_b is the commonly used power-law relation for CRTs .Similar relations can be obtained for the blue and green channels with corresponding exponents γ_g and γ_b , respectively, in the power-law relation. The exponents γ_r and γ_g are typically equal and their value is commonly referred to as the "gamma" of the CRT. The numerical value of gamma for a CRT is typically around 2.2, though the effective "gamma" seen by an application may be influenced by the display and operating system settings .
With the parametric form of for the TRCs, reduces to

$$[\mathrm{R}, \mathrm{G}, \mathrm{B},] = \left[(\mathrm{R}')^{1/\gamma_r}\mathrm{R}_{\max}, (\mathrm{G}')^{1/\gamma_g}\mathrm{G}_{\max}, (\mathrm{B}')^{1/\gamma_b}\mathrm{B}_{\max}\right]$$

which is commonly referred to as gamma correction. It is worth mentioning that uniform quantization of gamma-cor rected signals results in wider quantization intervals at higher amplitudes where the sensitivity of the eye is also lower. Therefore, just like speech companding, gamma correction of color tristimuli prior to quantization in a digital system (or transmission in a limited bandwidth system) reduces the per- ceptibility of errors and contours in comparison to a scheme in which no gamma correction is used. Most present-day CRT monitors are manufactured using the same set of red, green, and blue phosphors and the power-law relation is a fundamental characteristic of vacuum tubes. CRTs, therefore, tend to be fairly close to each other in their basic color characteristics. Because of the extremely widespread use of CRTs, it is common for images to be stored and transmitted in a using a color representation that is suitable for direct display on a

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CRT. Recently, the RGB color-space has been defined to bless and crystallize this *de facto* standard and to provide extensions that allow for incorporation of additional information on the viewing conditions, which can have a significant impact on human perception of displayed images which is commonly referred to as gamma correction. It is worth mentioning that uniform quantization of gamma-cor- rected signals results in wider quantization intervals at higher amplitudes where the sensitivity of the eye is also lower. Therefore, just like speech companding, gamma correction of color tristimuli prior to quantization in a digital system (or transmission in a limited bandwidth system) reduces the perceptibility of errors and contours in comparison to a scheme in which no gamma correction is used.

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IV. AMLCD DISPLAY PHYSICS AND COLOR CHARACTERISTICS

The most common LCDs for computers are backlit AMLCDs of the "twisted nematic" type .These are manufactured by deposition and patterning of (active) pixel electronics on a glass substrate. Each pixel element comprises of a pair of linear polarizers with liquid-crystal (LC) material sandwiched in between. It illustrates a pixel element. The two linear polarizers are orthogonally oriented; light does not pass through the display except for actions of the LCs. The surfaces adjacent to the LC molecules are typically designed so that (in the absence of any electric field) the LC molecules align in a 90 twisted configuration, which rotates the plane of polarization of incident linearly polarized light by a 90 angle . The "input" polarizer on the backside polarizes the light coming from the lamp behind the display. This polarized light encounters the LC molecules, which rotate its plane of polarization by 90 , allowing it to pass through the output polarizer, consequently resulting in an ON pixel. The pixel is turned off by the application of an electric field.

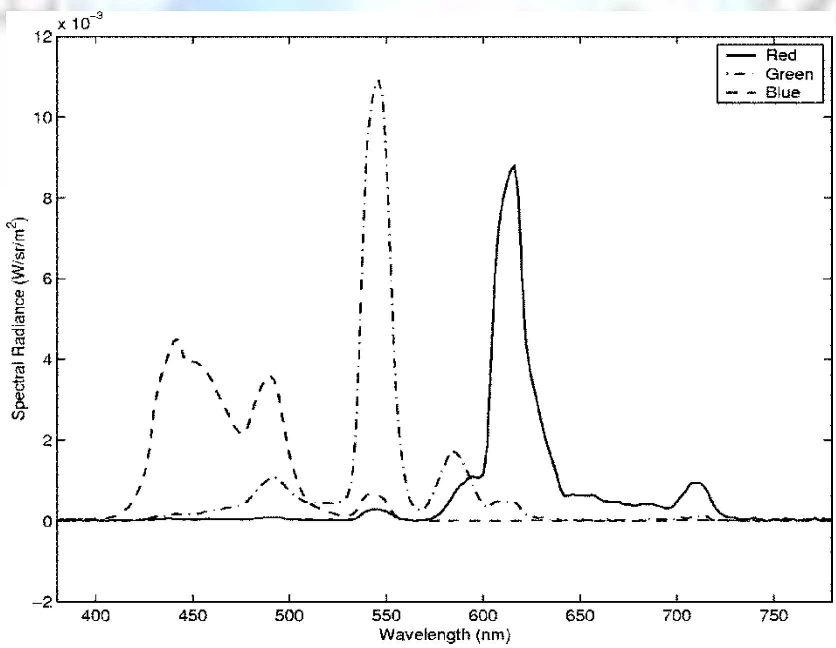


Fig.2: Spectral radiance of LCD red, green, and blue channels at maximum amplitude

This corresponds to all the RGB pixels turned on and this spec- trum stand for the average of the spectra obtained when the backlight is filtered through the mosaic of RGB filters. Note that the black spectrum has a much lower absolute value than the white (the ratio of luminance of black to white is approx- imately 1 : 357), but the shape of the black spectrum is sim- ilar to that of the white. This suggests that the pixels (and the region between the pixels) transmit a small fraction of the backlight even in the OFF state. This residual light from the display is a constant "additive offset," which is present in all measurements (just like flare). The additive offset is readily accounted for in the model of by simply incorporating it in the term (along with any flare). Assuming channel independence, the individual RGB channel spectral terms in then model of are then attained by subtracting this offset from the spectral measurements for the red, green, and blue ramps constituting the characterization set. It shows the (offset-corrected) spectra for the red, green, and blue display channels at the maximum driving signal (i.e., a digital value of 255) for each of the channels. If, in addition to channel-independence the constant-channel-chromaticity assumption of is also assumed to hold, the TRCs of the red, green, and blue channels can also be computed from the measurements for the individual channel ramps using least-squares. This process is illustrated for the red channel as

$$(f(\lambda; \mathrm{R}) s_r(\lambda))$$

$$f_0(\lambda)$$

In order to partly test the validity of the model assumptions for LCDs, residual spectral differences were computed be- tween the measurements and the model of (4) using the least- squares approximation of .The residual errors are rather small in comparison to the measurements themselves with spectral mean-squared errors (SMSEs) of 37.65, 36.25, and 29.57 dB, respectively, for the red, green, and blue channels, where the SMSE for the red channel is defined as

SMSE(dB)

$$(f(\lambda; \quad 10\log_{10}\left(\frac{\sum_{\lambda}\sum_{\lambda} \quad \mathrm{R}) - v_r(\mathrm{R}) s_r(\lambda))^2}{\sum_{\lambda}\sum_{\lambda} f^2(\lambda; \mathrm{R})}\right)$$

and the SMSE for the other channels is similarly defined. The model of (4) is, therefore, a fairly accurate model for the individual ramps. Plots of the spectral residuals also do not show any systematic trends except in the blue region of the spectrum for the green and blue ramp residuals. Wavelength reliance of the LCD switching mechanism is one poten- tial cause for these observed systematic deviations. The TRCs $v_r(\cdot)$, $v_g(\cdot)$, and $v_b(\cdot)$ for the red, green, and blue channels obtained from the above described method are shown in Fig. 7. Note that the TRCs have the character- istic S-shape expected from the raw optoelectronic responses for an LCD pixel. Also note that the TRCs for red, green, and blue channels are not identical. For the purposes of comparison, the data measured from CRT was analyzed using identical methods.
The model of (4) using the least-squares approximation of (18) for the TRCs was also evaluated for the CRT. In this case, the SMSEs were 38.30, 43.01, and 41.92 dB, re- spectively, for the red, green, and blue channels. The signifi- cantly smaller values of the SMSEs specify that the model of (4) models the behavior of CRTs to a greater degree of accuracy than LCDs.

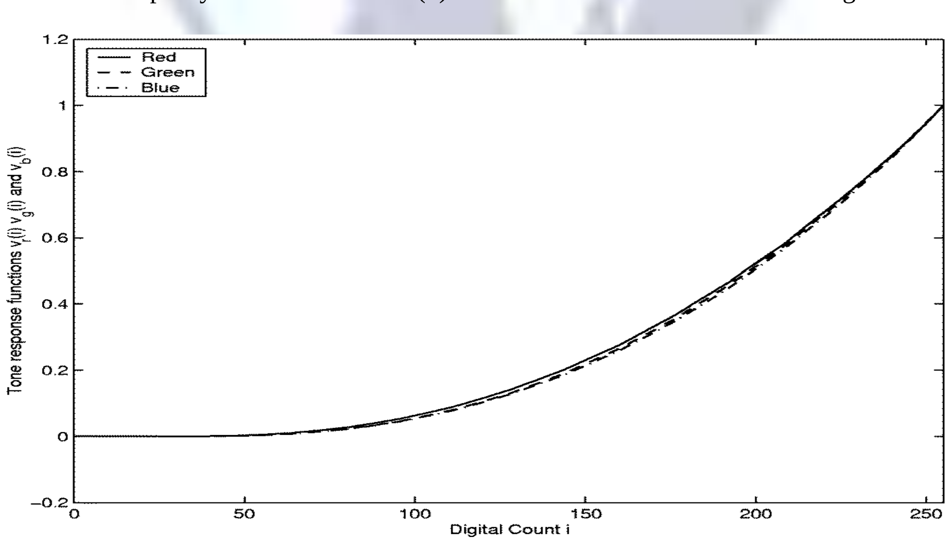


fig.3: TRCs for the CRT display red, green, and blue channels.

Plots of the model residual spectra are also devoid of any systematic trends. The CRT TRCs for the red, green, and blue channels are shown in given figure. The TRCs are in agreement with the power-law (gamma) relationship of (15) (the best approximations for the gamma for the red, green, and blue channels were 2.34, 2.36, and 2.43, respec- tively). Compared to the LCD TRCs, the TRCs for the CRT RGB channels are fairly close to each other. With the assumptions of channel-independence and channel-chromaticity constancy, the per-channel spectral characterizations can be used with the model of (3) and (4) to predict the spectral radiance for the display corresponding to any RGB value. For both the LCD and the CRT display, predictions for the 64 independent test patches (representing a 4 4 4 uniform sampling of the RGB cube) were made using the TRCs determined in (18).

These predictions were compared with the actual measurements for the test patches and SMSEs were evaluated. The SMSE for the LCD was 32.07 dB and for the CRT display the SMSE was 37.14 dB. Both values are quite small specifying that the model predictions provide close approximations to the measure- ments. The 5-dB lower value for the CRT SMSE indicates that the CRT measurements for the test patches are in better agreement with the model than the LCD measurements, a trend that was also observed in the per-channel case. Plots of the spectral errors reinforce this observation: while the errors for the CRT appear random, for the LCD the errors are not completely random. The predominant trend is the occurence of mostly positive errors around the spectrum locations corresponding to the three predominant peaks in the white-patch spectrum.

V. COLORIMETRIC CHARACTERIZATION

The measured characterization and test spectra and the spectral predictions attained by using the models were converted to CIEXYZ tristimulus values [as indicated in (2)] from which CIELAB values were calculated using the respective display white measurements as the white point. These CIELAB values were then used to compute the color errors in the characterization in $\triangle E^*_{ab}$[15] and $\triangle E^*_{94}$[16] units, which provide better agreement with the perceived extent of the color error than SMSE or mean-squared error in tristimulus space [18]. These errors are tabulated in Table 1 for the LCD and in Table 2 for the CRT display. Both tables report the errors over the characterization RGB ramps and the test patches discretly and both the average and maximum color errors over each of these data sets are tabulated.

For the CRT display, the color errors from the calibration model are extremely small, with even the maximum color error $1.0\triangle E^*_{94}$ under unit. This specifies that the model of (5)–(8) models the operation of the CRT remarkably well. For the LCD, the average color error over the test set is just around 1.0 unit and the maximum errors is around 2.0 colors tend to desaturate as the viewing angle increases. The major effect seen in offaxis viewing is a reduction in contrast and saturation.

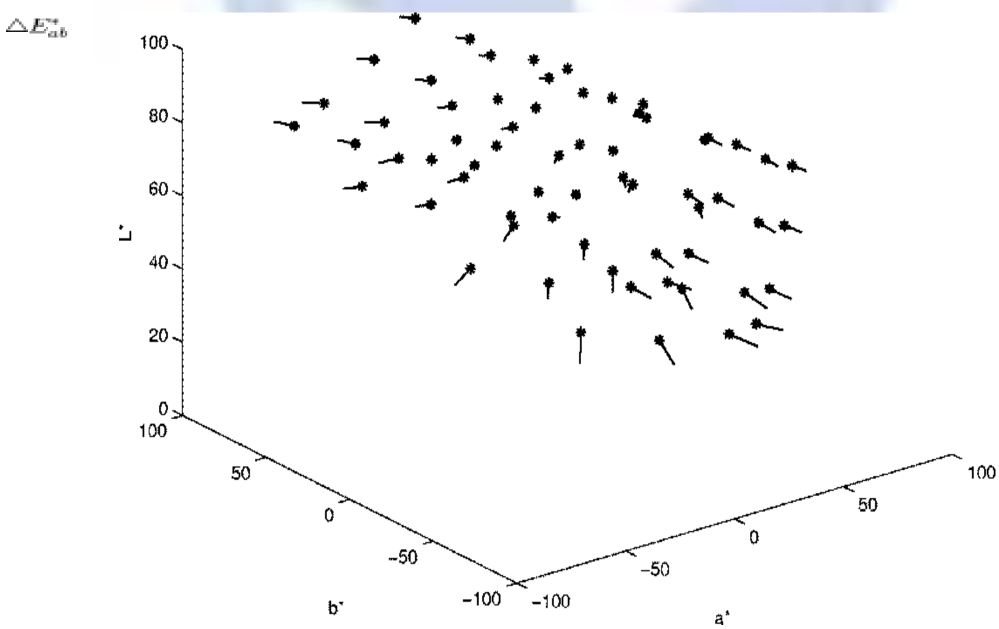


Fig.**4 3-D plot of color shifts in CIELAB for the LCD test patches for a change in viewing angle from 0 to 30 .**

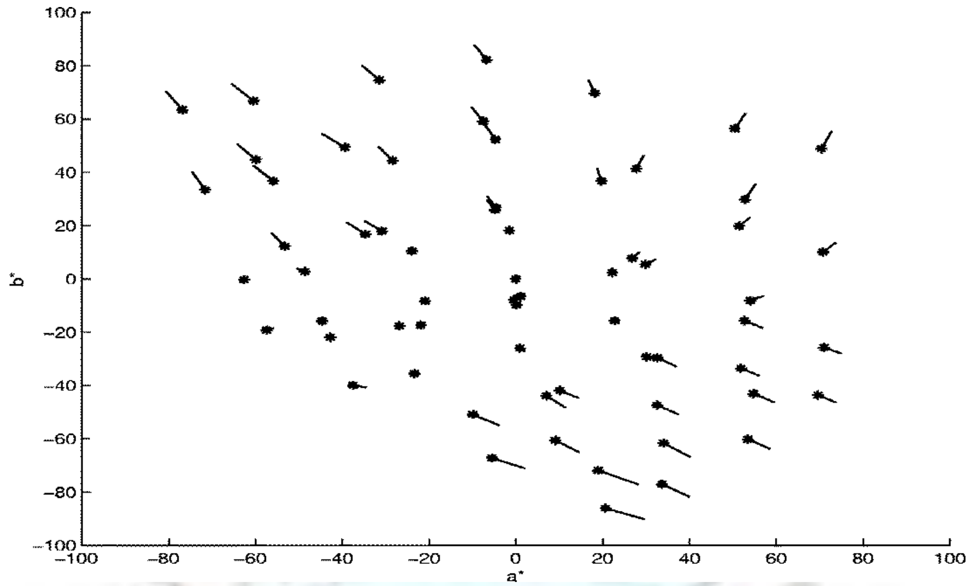


Fig.5: Color shifts in a and b for the LCD test patches for a change in viewing angle from 0 to 30

VI. COMPARISON OF LCD AND CRT DISPLAYS

The AMLCD technology has several advantages over the conventional CRT technology. LCDs have smaller size and are less heavy and bulky than the CRTs, which is the driving force for their increasing use in moveable and desktop de- vices. From an image-quality standpoint, the predominant and most clearly visible advantage is the higher spatial res- olution of the LCD devices, which translates into sharper images. The color reproduction capabilities and achievable gamut for the LCD and CRT display are essentially compared in the remainder of this section.

1) Color Calibration: From the preceding sections, it is clear that LCDs and CRTs are similar in several respects from the perspective of color calibration. Identical models based on channel self governance and channel-chromaticity constancy can be used for the calibration of either type of display and the runtime mapping of images to display color coordinates can also be performed using the inverse model of it in either case. For the CRT, these models provide extremely good accuracy, whereas for LCDs, the accuracy is good enough for most applications. For the CRT, the use of parametric "gamma-offset" models for the individual channel TRCs can further simplify the characterization process and potentially reduce the number of measurements required. The S-shaped TRCs for LCDs are not modeled well by the parametric "gamma-offset" models and, therefore, additional dimensions may be required for the characterization of these devices. For the same reason, images that are "gamma-corrected" for display on a CRT will not have the exact tone response if displayed on an LCD, unless appropriate TRCs are used in hardware/software. Scientific applications involving very precise manage of the displayed color require more intricate calibration schemes for the LCD. Note also that due to the significant difference in spectral characteristics of the CRT and LCDs, the impact of chromatic aberration in the eye will be different for the two displays and may need to be compensated when displaying complex images for precise psychophysical experiments .

2) Angular Dependence: CRTs are almost Lambertian [18] radiators within typical viewing angles and can, therefore, be viewed over a wide range of viewing angles without loss of contrast or undesirable variations in hue. While many improvements have been made in increasing AMLCD viewing angles, the problem has not been completely eradicated and the useful viewing-angle range of most LCDs is limited in comparison to CRTs. The limited viewing angle of LCDs is often a limitation when precisely color-corrected images are to be displayed before an audience of more than one or two persons.

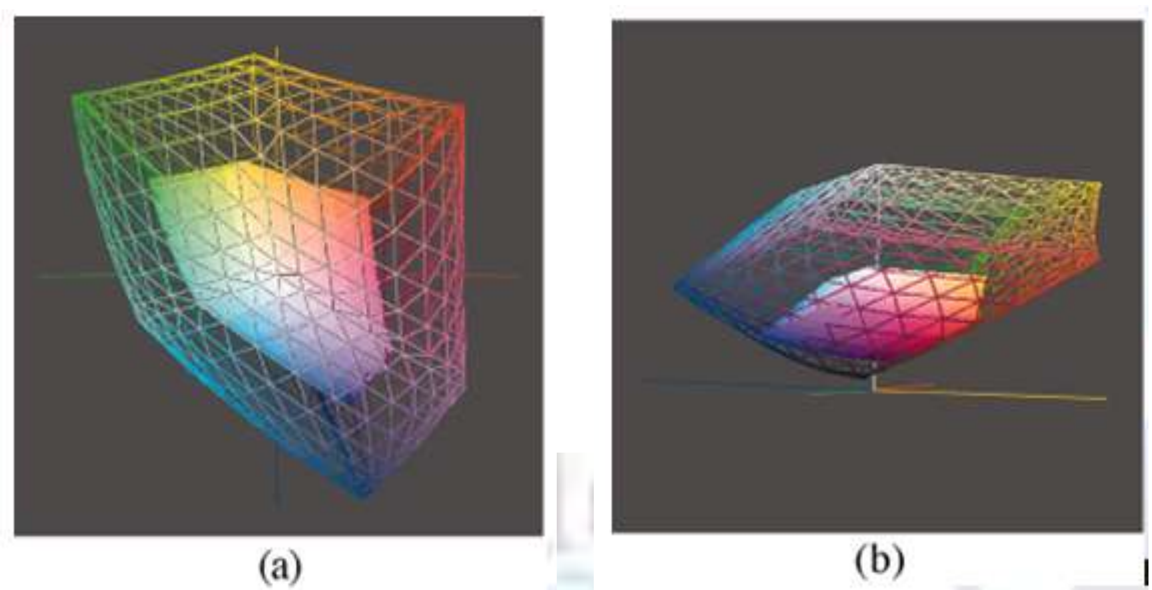
3) Spatial Homogeneity: LCDs significantly surpassed CRTs with regard to spatial homogeneity. While there is neg- ligible variation in the color of a displayed pixel with change in the pixel's position over the screen for an LCD [10], the assumption of spatial homogeneity does not strictly hold for CRTs. In most CRT monitors, for the same driving signals, the light intensity is brightest at the center and falls off toward the edges. The change in luminance over the screen can be as high as 25% [7, p. 104]. In casual image display applications, this is not as objectionable as measurements would point out because the eye's sensitivity itself is not uniform over the entire field of view and because the eye adapts well to the smooth variation in intensity across the screen. However, in scientific applications where precise control of the displayed color is required, it is necessary to correct for this spatial in- homogeneity in CRTs

4) Luminance and Dynamic Range: For the displays used in the experiment, the luminance of white on the LCD is about 4.7 times the luminance of white on the CRT monitor. This difference is typical for most LCD and CRT displays [10]. For the measurements made in a completely dark room with almost no additive flare, the luminance of black on the LCD was about 58 times the luminance of black on the CRT and the dynamic range (ratio of white to black luminances) is around 357 : 1 for the LCD and 4 351 : 1 for the CRT. On the face of it, the CRT appears to have a larger dynamic range. However, in practice, the exact converse is true because a large region of the CRTs dynamic range is lost to additive flare under typical viewing conditions. In the presence of typical viewing flare, the ratio black to white luminance for the CRT falls to 16 : 1, whereas the corresponding ratio for the LCD remains significantly higher at 209 : 1. This swapping is owing to the fact that the typical viewing flare has a much higher luminance than the CRT black in a dark room but is quite negligible as evaluated compared to the light leakage through the LCD cells already present in the LCD black. The higher white luminance for the LCDs gives them a higher effective dynamic range than typical CRTs, which is clearly apparent in practice.

5) Intrinsic Gray Balance: It was observed in Sec- tion VI that individual red-, green–, and blue-channel TRCs of the CRT display were moderately close while those for the LCD were not. The difference between the LCD RGB TRCs would imply that a "device gray wedge along $R=G=B$ would not appear visually neutral (gray balanced) when displayed on the LCD, but would appear almost neutral when exhibitson the CRT. This is actu- ally observed in practice. Since graphics programs often create images or sweeps directly in display device color space, it is desirable to have the display gray-balanced and the CRTs characteristics are, therefore, preferable. Note, however, that this limitations of the LCD is easily overcome once the display is calibrated and the inverse TRCs are incorporated into the video path.

6) Channel Chromaticities: It shows the location of the channel chromaticities (the end points of the re- spective triangles) for the CRT and the LCD in relation to the spectrum locus on the CIE xy chromaticity diagram [16]–[18]. Note that the red channel chromaticity for the CRT and the LCD are reasonably close to each other on the chromaticity diagram, but the blue and green channel chro- maticities are diverse from each other. Also plotted on the same diagram are the chromaticities for the white point for the CRT (labeled as letter C on the plot), the LCD (L), and the CIE D50 and D65 daylight illuminants. Note that the LCD white point is somewhere between the D65 and D50 white points, while the CRT white point is close to D65 in chromaticity, which concurs with the selected 6500-K color temperature for the CRT. The differences in white point and in the channel chromaticities means that the 3×3 color calibration matrices for the LCD and the CRT display in the model of are different. This implies that transformation of an image in CRT RGB coordinates to LCD RGB coordinates entailfull color rectification and cannot be achieved by using 1-D corrections for each of the channels. While only one LCD was considered in the experiment of this paper, this implication is probably true in general because there are bound to be changes in LCD channel chromaticities due to developed tolerances in the fabrication of the LCD filters and backlights.

The difference between the uncorrected TRCs for AMLCDs and CRTs implies that images designed for CRTs will not have the proper tone reaction on these displays, unless appropriate tone-response corrections are used in hardware/software. The LCD channel-chromaticity coordinates are determined by the backlight and color filter spectral characteristics, and may not correspond to the chromaticity coordinates for commonly employed CRT phosphors. Therefore, a simple per-channel 1-D correction cannot be used to globally map CRT RGB to LCD RGB. The prototype display studied in this paper showed a durable changes in color with change in viewing angle. This viewing-angle dependence limits the utility of the display in accurate color demonstrations where the display is to be concurrently viewed by multiple observers. While significant viewing-angle improvements have been made in commercial displays [10], further improvements are still needed to match CRT viewing angles. Typical AMLCDs possess a significantly larger gamut than typical CRT displays, with the AMLCD gamut ex- tending significantly beyond CRT gamut in the dark color regions. The differences in gamut arise primarily due to the higher luminance of LCDs and provide AMLCDs a significant advantage over CRTs in the reproduction of images with high dynamic range and shadow detail.



Comparison of “absolute” CIELAB gamuts of an LCD (wire frame) and a CRT (solid). (a) Top view. (b) Side view.

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