Evaluating Color Shift in Liquid Crystal Displays with the Primary Stability Metrics

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Abstract

One of the major issues that obstruct the consistency and interoperability of medical color LCDs is the challenge of accurately characterizing and modeling the LCD color response. The challenge originates from the instability of the primaries – the chromaticity of primaries varies with the digital driving level. The primary instability also manifests itself in other forms such as color gamut shrinkage, color shift, gray imbalance, and contrast reduction. In this paper we describe a quantitative metric, primary stability, for measuring the stability of the primaries. Two metrics were then derived from primary stability to measure the color shift of a display: (a) the area-between-curves metric measures gray imbalance, and (b) the area-under-curve metric measures the reduction in color gamut. Characterization data from 9 displays are used to demonstrate the capability of the primary stability-based metrics.

Introduction

The foundation of modern display technologies is based on the concept of *trichromatic generalization*, which states that "…*over a wide range of conditions of observation, many color stimuli can be matched in color completely by additive mixtures of three fixed primary stimuli whose radiant powers have been suitably adjusted*" [1]. This principle has been implemented using different ways of mixing primary stimuli. For example, most flat panel displays mix RGB subpixels in the spatial domain; the color sequential displays mix RGB fields in the time domain; the 3-gun or 3-LCD projectors mix RGB fields on the same image plane. Ideally, as stated in the trichromatic generalization, the chromaticity of the primaries should be *stable*, which means that as the digital driving level (DDL) varies, the normalized spectra should be nearly identical [2]. In other words, the chroma and hue of the primaries should not change with radiant power. In practice, however, most displays bear unstable primaries. As the DDL decreases, the primary chroma diminishes and the primary hue shifts. Some display technologies, such as LCD, exhibit more pronounced primary instability than others such as organic light-emitting diode (OLED) displays. Notice that the term "stable" in [2] and this study is used to describe the independence of DDL, not time.

The two major causes of LCD color shift have been discussed in [3]: light leaks at the black point and the normalized spectra vary with DDL. The former comes from the fact that the LCD panel cannot block the light completely. The outcome is equivalent to adding a very dim but constant gray shade to a perfect display. The gray shade, usually bluish, starts to dominate when the DDL is low. The latter, the spectral variation, is associated with the optical properties of liquid crystals and results in a hue shift. On the other hand, OLED displays can turn off light emission completely and do not have spectral variation. However, some OLED displays still show light leakage because the black point is set too high.

The LCD primary instability raises difficulties for color reproduction in the following ways. First, the output colors become more difficult to predict, which complicates the tasks of color characterization and calibration. Second, the unstable primaries change the gray balance and therefore require appropriate calibration and correction. Third, the color gamut is reduced so a number of shades can no longer be reproduced. These difficulties hinder faithful color reproduction and might affect the performance of a medical device for diagnostic purposes.

Let's consider pathology as an example. Pathologists used to examine tissue slides with optical microscopes. They needed to align their eyes with the eyepieces, adapt to the orangish incandescent light source, gaze on a very limited field of view through a pair of dark tubes, and keep panning the slide while tweaking the focusing knob to explore the whole area of the tissue sample. All of the inconvenience could be eliminated by the emergence of digital pathology, or *whole-slide imaging* (WSI) framework, in which the tissue slide is scanned and converted into a huge image file and then

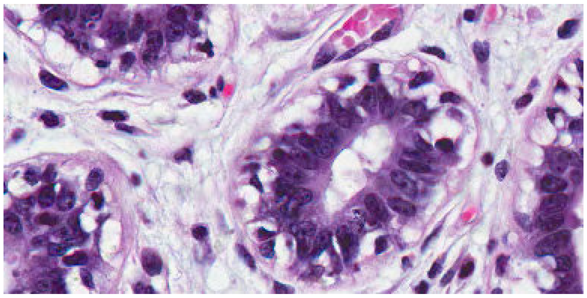

Figure 1: H&E-stained tissue sample of human breast (US Biomax, Inc., Rockville, Maryland, USA). Texture inside the dark blue nuclei is difficult to discern on an LCD due to the reduced chroma.

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displayed on a local or remote computer display for the pathologist(s) to review.

Using WSI devices for diagnosis is common in Europe but is still pending market clearance in the US. One unanswered question is the relationship between a display's primary color stability and the diagnostic accuracy of image interpretations made using the display. Methods for characterizing and reporting a display's primary color stability like those introduced here will enable investigators to address this question.

Figure 1 shows a tissue slide that was stained by the hematoxylin and eosin (H&E) protocol, the most common staining method in histology. H&E turns nuclei of cells into dark blue and other structures into red, pink, or purple shades. Since the chroma decreases in the dark range on an LCD, discerning the internal nucleus structure becomes laborious compared with using an optical microscope.

The goal of this study is to derive a set of objective yet simple metrics for evaluating the color shift phenomena of displays, especially for inter- and intra-display comparison. The metrics can be used to evaluate not only the displays but also the color management system such as a color calibration kit or an ICC color profile.

The paper is organized as follows. The primary stability function is defined in Section 2. Section 3 introduces how to use primary stability to measure gray imbalance and color gamut reduction. Experimental results are presented in Section 4. Section 5 summarizes the findings of this work.

Primary Stability

The goal of the primary stability metric is to quantify the relative color shift of the primaries when driven at lower DDLs, which are usually desaturated. Our approach is to calculate the required mix ratio for the original primaries (i.e., at DDL=255) to reproduce the desaturaed primaries as illustrated in the chromaticity diagram in Figure 2. As the DDL decreases, the red primary R' become desaturated compared with the original primary R. In order to reproduce R', R has to be mixed with a little original green primary G and a little blue primary B. This mix ratio of *R:G:B* indicates the degree of color shift of R' -- the smaller the percentage of R, the more color shift of R'. Therefore, we define the R percentage of the normalized *R:G:B* mix ratio as the primary stability of R'.

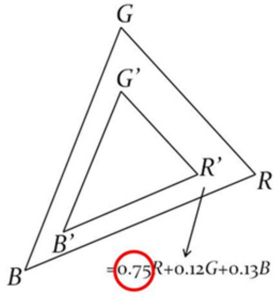


Figure 2: Desaturation of primaries shown on the CIEXYZ chromaticity diagram. *R*, *G*, and *B* are the original primaries at DDL=255. *R'*, *G'*, and *B'* are the desaturated primaries at a lower DDL=*k*. *R'* can be mixed by *R*, *G*, and *B* with a unique ratio. Then the normalized ratio coefficient for *R* is defined as the primary stability for the red channel at DDL=*k*.

Consider the CIEXYZ tristimulus values of the red, green, and blue primaries of an 8-bit display driven at DDL=$k, 0 \leq k \leq 255$:

$$R^k \equiv Tristimulus(k,0,0) \equiv [R_X^k \; R_Y^k \; R_Z^k]$$

$$G^k \equiv Tristimulus(0,k,0) = [G_X^k \; G_Y^k \; G_Z^k]$$

$$B^k \equiv Tristimulus(0,0,k) = [B_X^k \; B_Y^k \; B_Z^k]$$

Based on the principle of trichromactic generalization, a color Q within the color gamut of the display can be reproduced by mixing the original primaries R^{255}, G^{255}, and B^{255} with scaling factors w_R, w_G, and w_R, respectively. Equating the tristimulus values of Q to those of the mixed primaries, we get

$$\begin{bmatrix} R_X^{255} & G_X^{255} & B_X^{255} \\ R_Y^{255} & G_Y^{255} & B_Y^{255} \\ R_Z^{255} & G_Z^{255} & B_Z^{255} \end{bmatrix} * \begin{bmatrix} w_R(Q) \\ w_G(Q) \\ w_B(Q) \end{bmatrix} = \begin{bmatrix} Q_X \\ Q_Y \\ Q_Z \end{bmatrix} .$$

The scaling factors can then be calculated by

$$\begin{bmatrix} w_R(Q) \\ w_G(Q) \\ w_B(Q) \end{bmatrix} = \begin{bmatrix} R_X^{255} & G_X^{255} & B_X^{255} \\ R_Y^{255} & G_Y^{255} & B_Y^{255} \\ R_Z^{255} & G_Z^{255} & B_Z^{255} \end{bmatrix}^{-1} * \begin{bmatrix} Q_X \\ Q_Y \\ Q_Z \end{bmatrix} .$$

Usually the scaling factors are between 0 and 1. A negative or greater-than-one scaling factor implies an out-of-gamut color, which, in the case of an LCD, is caused by the primary hue shift.

Now substitute Q with any desaturated primary (i.e., R^k, G^k, or B^k, $0 \leq k < 255$) in order to obtain its scaling factors. For example, the scaling factors for the red primary R^k are

$$\begin{bmatrix} w_R(R^k) \\ w_G(R^k) \\ w_B(R^k) \end{bmatrix} = \begin{bmatrix} R_X^{255} & G_X^{255} & B_X^{255} \\ R_Y^{255} & G_Y^{255} & B_Y^{255} \\ R_Z^{255} & G_Z^{255} & B_Z^{255} \end{bmatrix}^{-1} * \begin{bmatrix} R_X^k \\ R_Y^k \\ R_Z^k \end{bmatrix} .$$

Likewise, the scaling factors for the green primary G^k and blue primary B^k are respectively

$$\begin{bmatrix} w_R(G^k) \\ w_G(G^k) \\ w_B(G^k) \end{bmatrix} = \begin{bmatrix} R_X^{255} & G_X^{255} & B_X^{255} \\ R_Y^{255} & G_Y^{255} & B_Y^{255} \\ R_Z^{255} & G_Z^{255} & B_Z^{255} \end{bmatrix}^{-1} * \begin{bmatrix} G_X^k \\ G_Y^k \\ G_Z^k \end{bmatrix} \quad \text{and}$$

$$\begin{bmatrix} w_R(B^k) \\ w_G(B^k) \\ w_B(B^k) \end{bmatrix} = \begin{bmatrix} R_X^{255} & G_X^{255} & B_X^{255} \\ R_Y^{255} & G_Y^{255} & B_Y^{255} \\ R_Z^{255} & G_Z^{255} & B_Z^{255} \end{bmatrix}^{-1} * \begin{bmatrix} B_X^k \\ B_Y^k \\ B_Z^k \end{bmatrix} .$$

Now we can define the primary stability function, s, for the red, green, and blue primaries:

$$s(R^k) \equiv \frac{w_R(R^k)}{w_R(R^k)+w_G(R^k)+w_B(R^k)}$$

$$s(G^k) \equiv \frac{w_G(G^k)}{w_R(G^k)+w_G(G^k)+w_B(G^k)}$$

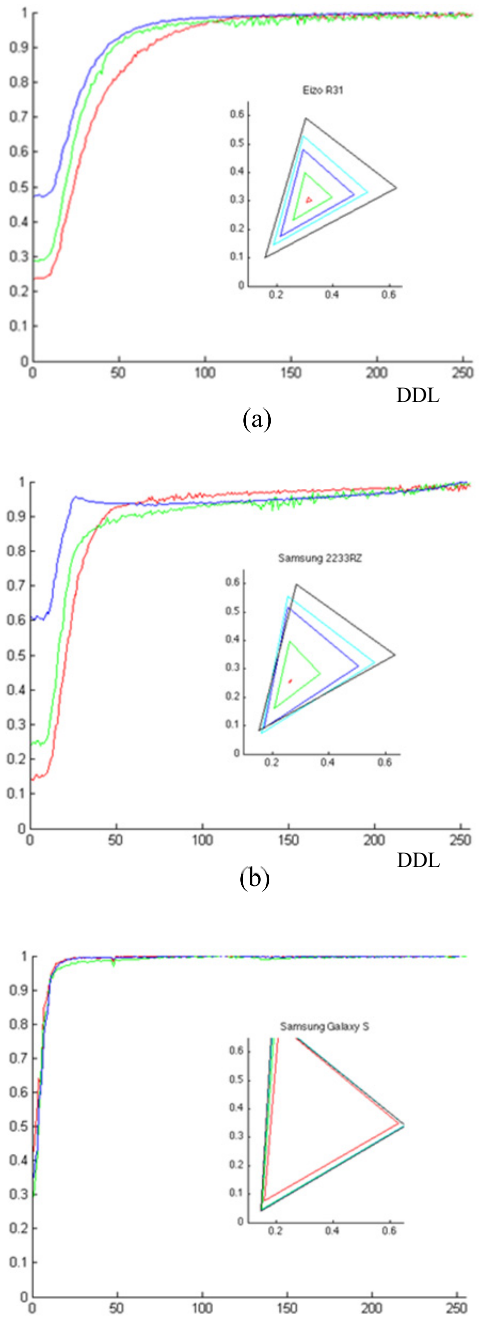
$$s(B^k) \equiv \frac{w_B(B^k)}{w_R(B^k)+w_G(B^k)+w_B(B^k)} .$$

Intuitively, the primary stability function represents the “relative purity” of the desaturated primaries. The stability of the original primaries is always 1. For an ideal display, $s(R^k)$= $s(G^k)$= $s(B^k)$=1 for any k between 0 and 255. For a real display, as the DDL decreases, the primary stability always decreases because the primaries become desaturated.

Figure 3 shows the primary stability functions of 3 displays. In Figure 3a, a medical display, the 3 curves start to separate from each other below DDL=120, and the blue curve is above the green and red ones. So we can infer that the gray shades start to shift toward blue once the DDL goes below 120. In Figure 3b, a consumer-grade 3D display, the primaries are less desaturated compared with Figure 3a. However, the gray balance is poor across the whole DDL range and shifts toward either red or blue. Figure 3c, an OLED mobile display, shows minimal chroma reduction and gray imbalance.

Compared with the traditional two-dimensional triangular color gamut representation on the chromaticity diagram, the one-dimensional primary stability curves contain more information about the relative properties of the display. The absolute color coordinates, however, are not indicated by the primary stability curves.

Notice that the primary stability is defined with ratio in the CIEXYZ color space, because the concept is based on the color mixing theory. Although CIEXYZ is not perceptually uniform, it does not affect the effecacy of the primary stability.



(a)

(b)

(c)

Figure 3: The RGB primary stability functions of 3 displays. The x-axis is the DDL, k, and the y-axis is the primary stability. The red, green, and blue curves represent the primary stability functions of the red, green, and blue channel, respectively -- $s(R^k)$, $s(G^k)$, and $s(B^k)$. (a) A medical LCD with typical color gamut shrinkage and gray imbalance. (b) A gaming-oriented LCD with less color gamut shrinkage but pronounced gray imbalance. (c) A mobile OLED display with minimal color gamut shrinkage and gray imbalance. The insets show color gamut at DDL=255, 40, 30, 20, and 10 on the CIEXYZ chromaticity diagram for reference.

Applications

The primary stability function can be immediately generalized to measure other display properties.

Measuring Gray Imbalance

The quality of gray balance is revealed by the difference between the three stability curves. If the three stability curves overlap completely, the gray balance is perfect and there is no color shift for the gray shades. Otherwise, the area difference between the three stability curves represents the degree of gray imbalance.

Define the *area-between-curve* (ABC) measure of a given display as the normalized area enclosed by the three stability curves:

$$ABC \equiv \frac{1}{256}\sum_{k=0}^{255} MAX\left(s(R^k), s(G^k), s(B^k)\right) - MIN\left(s(R^k), s(G^k), s(B^k)\right).$$

As an example, Figure 4 shows the RGB primary stability functions and the corresponding ABC for the display in Figure 3a.

The ABC metric indicates the stability deviation among the primaries and therefore the degree of gray imbalance. For an ideal display, the ABC measure is always zero. A greater ABC indicates a worse gray balance.

Measuring Color Gamut Shrinkage

The *area-under-curve* (AUC) function is defined as the area under the lowest stability of the three primaries:

$$AUC \equiv \frac{1}{256}\sum_{k=0}^{255} MIN\left(s(R^k), s(G^k), s(B^k)\right) .$$

As an example, Figure 5 shows the RGB primary stability funtions and the corresponding AUC for the display in Figure 3a.

The AUC measure represents the reduction in the color gamut size caused by color shift of the primaries. The magnitude indicates how much gamut size can be preserved compared with an ideal display, which has an AUC equal to 1.

Experimental Results

The primary stability curves, AUC and ABC of 9 displays are shown in Figure 6. By looking at the curves, two OLED displays can be easily identified by their larger AUC. Three medical displays can also be recognized by their smaller ABC.

Figure 7 compares the 9 displays on the ABC-AUC plane. On the lower right corner (high AUC, low ABC), display (f) delivers the best performance in terms of color gamut preservation and gray balance. In contrast, display (a) performs the worst. Symmetrical to the diagonal, display (d) has less color gamut shrikage but greater gray imbalance, while display (i) has the opposite properties.

Conclusions

In this work we developed a quantitative method for evaluating the color shift characteristics of a display. The primary stability is a performance metric for describing desaturation of primaries. The chart of RGB primary stability curves is a powerful tool for visualizing the color shift characteristics of a display compared with the traditional triangular color gamut representation on the chromaticity diagram. Based on the primary stability function, the area-between-curves and area-under-curve metrics were derived for measuring the gray balance and color gamut reduction of a display, respectively. These two metrics help the users choose the optimal display according to their requirements.

For future work, we will use the primary stability metrics to optimize the workflow of a color calibration kit.

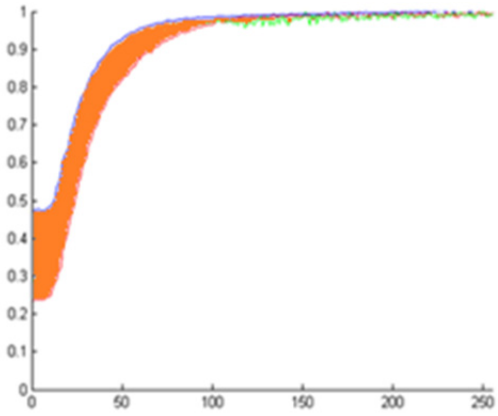


Figure 4: The orange area indicates the ABC of the display in Figure 3a.

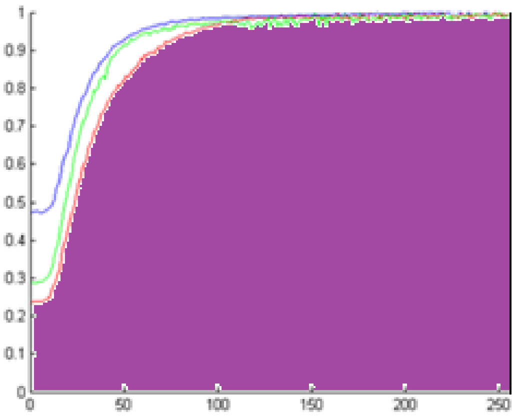


Figure 5: The purple area indicates the AUC of the display in Figure 3a.

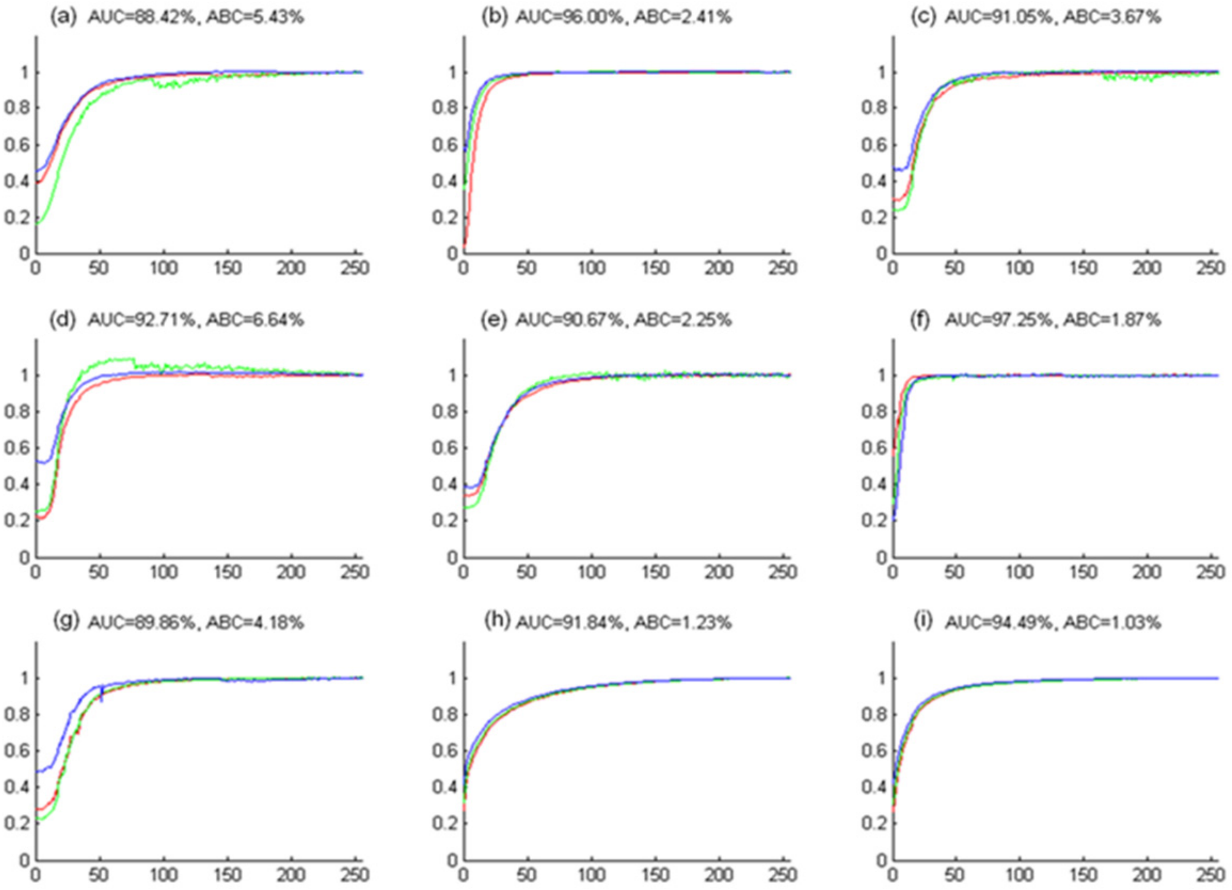


Figure 6: The RGB primary stability functions of 9 displays with their AUC and ABC calculated. For each display, the AUC, which is the area under the minimum of the three curves, and the ABC, which is the area between the minimum and the maximum of the three curves, are shown in the subfigure title. Among the 9 displays, (b) and (f) are OLED displays (Sony PVM2551MD and Samsung Galaxy S) showing minimal color gamut reduction. (e), (h), and (i) are medical displays (Eizo R31, Barco 6130 DICOM, and Barco 6130 sRGB) and exhibit better gray balance. The rest are consumer-grade displays (CMO 56QFHD, Dell 1907FP, Apple Cinema 30" HD, and Apple iPhone 4). Notice that some primary stability exceeds 1.0 because the desaturated primary is out of the original color gamut.

References

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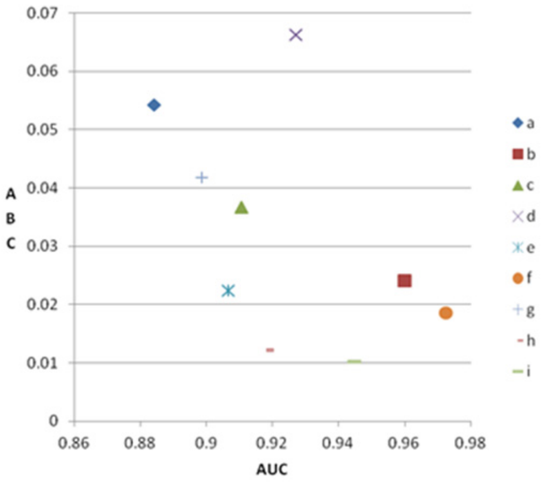

Figure 7: Nine displays located on the ABC-AUC plane. The lower right corner indicates the best performance. The upper right corner trades gray balance for color gamut, while the lower left corner the other way around.