EOTF Preference for LCD Televisions

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Abstract

Recent commercial LCD (liquid crystal display) televisions are larger and brighter than traditional televisions, which impacts viewing conditions. The adaptation level of the newer viewing conditions may require different electro-optical transfer functions (EOTFs) for the LCD televisions than those in traditional TVs. The research here consisted of a pair of experiments designed to explore how the electro-optical transfer function affected image quality. There were two types of EOTFs tested: a gamma function and the intrinsic function raised to an exponent. The first experiment took place in a darkened room and simulated a range of displays with different transfer functions by using different gamma values and different exponents through image processing of presented images. Paired comparison experiments were used to determine preference. In a second condition the procedure was repeated at a lower luminance level by placing a nominally non-spectrally-selective neutral filter in front of the screen. The results indicated that, in general, a gamma of 1.6 was the most preferred. This preference for 1.6 was more marked at the lower screen luminance level. In the second experiment, the procedure was repeated in a more natural viewing environment by introducing a dim surround that was 10% of the luminance of the display's unfiltered white point. With this surround, the improvement in image preference with change in gamma-functions at both screen luminance levels was more enhanced. The results indicate that image preference for different transfer functions are dependent on the intensity of the displays and that this dependence is maintained under natural viewing conditions with a dim surround.

Introduction

LCD televisions have staked their claim as one of the more popular choices for flat panel displays and their popularity will continue to increase as they become more economical. They hold several advantages over their counterparts including being larger, sharper and having higher luminance levels than other flat panels and traditional displays. Typical flat panel displays have sizes that range from 20" up to 60" and the average size is around 35"-40". Additionally, these televisions have maximum luminance's approaching 600 cd/m^2. Because they are larger and brighter, the viewing conditions associated with these TVs are not the same as with CRTs. The goal of the research is to determine how image quality is affected by the change in viewing conditions brought on by these displays, (as compared to the traditional viewing condition with CRTs) and whether changes should be made to account for the particular viewing condition brought on by these displays.

Changes in the viewing conditions of a display can lead to changes in the perceived contrast of images on the display which is related to the effect of simultaneous contrast. To explore these changes, two electro-optical transfer functions, (EOTFs), were simulated: a traditional gamma-function and an exponential modification to the inherent LUTs used to drive the red, green, and blue channels of the display.

Two historical studies on perceived contrast are Bartelson & Breneman[1] and the Stevens Effect.[2] Bartelson & Breneman showed that as the surround illumination increases, without substantial flare on the screen, the dark regions of the scene appear darker while the light regions remain white. This change in apparent lightness will therefore increase the perceived contrast by increasing the dynamic range in the dark regions of a scene. Similarly, the Stevens Effect shows that as luminance level increases, the whites appear whiter and the darks can appear darker. Again we see that scene contrast can increase due to increased dynamic range in either the dark or light scene regions. Depending on the display characteristics, the increase in contrast may be due to changes in the white point only if the changes in luminance do not affect the black point.

Experimental

Experimental Setup

The experiments were performed using a 30" Sharp AQUOS LC-30HV6U LCD television, with observers seated 3 image heights from the display, approximately 33 inches. Figure 1 below shows a schematic of the experimental layout. The display subtended approximately 42° of visual angle horizontally and 26° vertically. The experiments took place in a specially built room that allowed the surround luminance to change both in lightness and color. The surround was lit behind the LCTV using 12 uniformly distributed high power LED lights.[3] The LED lights illuminated a white semicircle shaped diffusely reflecting screen. The surround filled more than the complete field of view when the observer faced the display. The walls and ceiling of the room were covered in a black material in order to keep flare off the display screen. The LEDs were all situated behind the display so that no direct illumination reached the LCD.

The display was characterized using a 3D-LUT with an average error of 0.36 ΔE_{00} for 2000 random RGB colors, seen in Table 1 below. Because of observed cross-talk between the three primary channels a more simple characterization approach could not be accomplished.[4] Figure 2 shows the native EOTFs for measured red, green, and blue ramps.

In the first experiment a set of images modified to simulate how they would appear on displays with different transfer functions were presented in a dark surround at both the default luminance of the LCD television and at a reduced luminance level. The preferences for the various transfer functions were measured at both screen intensity levels using a paired-comparison experiment. By changing the luminance of the display, the results of the experiment on a more traditional, lower intensity, display were simulated.

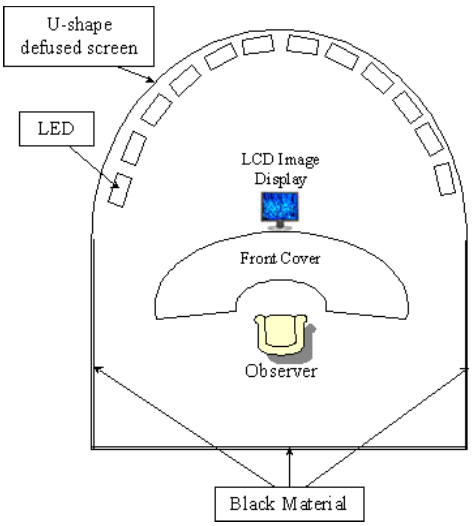

Figure 1. Experimental setup of room

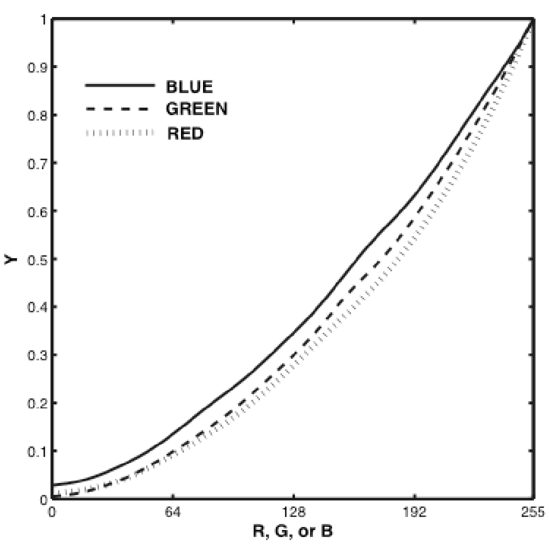

Figure 2. Native EOTFs of primary channels

Table 1: LCTV Characterization Results in Terms of ΔE_{00}

Maximum	1.77
Minimum	0.02
Average	0.36
Standard Dev	0.20

In a second experiment, the LEDs were directed at the U-shaped diffuse screen to raise the surround illumination to the SMPTE's[5] recommended luminance level of 10% of the display's white point, while closely matching the chromaticities, and the procedure from the first experiment was repeated in order to examine the effect of a dim surround on preferences to images shown on displays with different transfer functions. The chromaticites of the ambient illumination and display white for the dim surround are seen in the Table 2.

There were ten images used for the Experiment 1. These images were chosen from a much larger dataset based on their content and characteristics so that they would cover a wide range of images seen on LCD televisions. This set of images included DVD frame grabs, nature scenes, skin tones, and high and low key images. Based on the results from the first experiment, only four of the images from the original set were used in the Experiment 2.

Table 2: Chromaticity of Room at 10% Surround and Display's White Point

	x	y
Ambient Illumination	0.308	0.307
LCD White	0.30	0.26

Table 3: Experimental Settings

	Exp 1 Cond. 1	Exp 1 Cond. 2	Exp 2 Cond. 1	Exp 2 Cond. 2
Surround (cd/m^2)	0	0	40	40
Disp Brightness (cd/m$^{2)}$	400	170	400	170
Number Images	10	10	4	4
Gamma Values (Meth 1)	1.3, 1.6 1.9, 2.2	1.3, 1.6 1.9, 2.2	1.3, 1.45, 1.6, 1.75, 1.9, 2.20	1.3, 1.45 1.6, 1.75, 1.9, 2.20
Exponential Values (Meth 2)	0.75, 0.875, 1.125, 1.25	0.75, 0.875, 1.125, 1.25	--	--

Appropriate experimental settings are seen in Table 3. The labels across the top of the table describe the particular experimental design. Condition 1 is the default luminance of the display and condition 2 is the lowered luminance of the display. The background of the LCTV for all conditions in both experiments was set to 20% of the white point of the display. In Condition 2 of both experiments the overall luminance of the display was reduced by placing a neutral filter over the entire display. While not a perfect neutral-density filter, it effectively reduced the luminance with a minimal shift in color. The average ΔE_{00} shift in color was 0.98 for white, black and the three primaries. Spectral transmittance for the filter was highly nonselective so that the curve shapes of the spectral radiances were only slightly affected. With the filter in place the luminance of white was reduced approximately 57% from 400 cd/m^2 to 170 cd/m^2. It is interesting to note that when it was in place over the display observers were unaware that a filter was covering the screen.

Experimental Design

Gamma Method

Two methods were used to compute images that simulated their appearance as if shown on a display with a different tone-mapping function. In Method 1, which is referred to as the Gamma method, the raw RGB image values were translated to RGB image values that correspond to a particular display. The raw RGB values are translated to scalars through the gain, offset, and gamma (GOG) formula (Berns[6]) in Equation 1 using a gamma value that corresponds to the simulated display. There are similar equations for green and blue. See Table 3 for the gamma values used in the experiment.

$$R_{Scalar} = \left(gain_r \left(\frac{dc_r}{dc_{r,\max}} \right) + offset_r \right)^{gamma_r} \qquad (1)$$

The *gain* and the *offset* values were based on best fits to the native EOTFs of the display (see Figure 2). The "*dc*" in each equation above is the input digital count between 0 and 255. For a well behaved, additive display, the normal process when using the GOG method is to then multiply the R,G, or B scalars by a 3x3 matrix, which has elements corresponding to the maximum values of the primary channels. This transforms the scalars to XYZ values using Equation 3, except that there is a 3x3 multiplied by a 3x1.

However, since there was significant cross-talk between the primary channels in the display used here, a more complicated method, which took into account this interdependence of the channels, was used to estimate the tristimulus values for the modulated images. A 3x11 matrix multiplied by an 11x *n* vector transform was used to convert the scalars for each image of the n image pixels to tristimulus values. The vector accounted for channel interdependence by modeling some of the possible interactions, as seen in Equation 2. The 3x11 matrix is a transform matrix whose elements were found through optimization and converts the RGB scalars to XYZ.

$$\begin{bmatrix} R_{scalar} \\ G_{scalar} \\ B_{scalar} \\ R_{scalar}^2 \\ G_{scalar}^2 \\ B_{scalar}^2 \\ R_{scalar} * G_{scalar} \\ R_{scalar} * B_{scalar} \\ G_{scalar} * B_{scalar} \\ R_{scalar} * G_{scalar} * B_{scalar} \\ 1 \end{bmatrix} \qquad (2)$$

Therefore, the method used to obtain XYZ for each pixel in the newly modulated image was

$$\begin{bmatrix} X_{pixel} \\ Y_{pixel} \\ Z_{pixel} \end{bmatrix} = [3x11][11xn] \qquad (3)$$

These XYZ values are converted to CIELAB units and sent through the inverse 3D LUT. The inverse 3D-LUT was then used to get the RGB values for the new image. The inverse 3D LUT was derived from the characterization performed on the LCTV. The output of these steps is then converted RGB values that correspond to a simulated display.

Figure 3 below shows an example of the three primary ramps and a neutral ramp for the display using the two extreme gamma values (1.3 and 2.2) in the experiment. The ordinate for this graph is absolute Y value and because of this the curves do not fall on top of each other. The intrinsic functions of the display for each primary had a different gamma value, as seen in Figure 2, but for the process used in Method 1, each primary channel was forced to have the same gamma value. Figure 3 shows the resulting transfer function for each primary and a neutral ramp for two gamma values. Table 3 shows the gamma values used in the experiment.

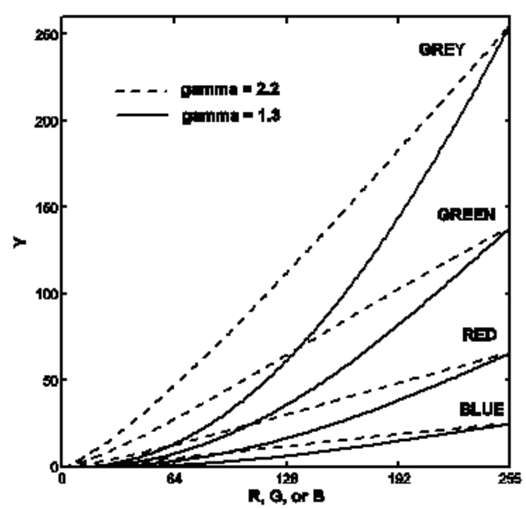

Figure 3. Primary & neutral ramps modified using 2 gammas

Exponential Method

The second method was entitled the Exponential method and was a much simpler approach for simulating different displays. The native transfer functions, seen in Figure 2, were raised to values seen in Table 3. This method tested whether keeping the same relation and shape of each primary channel, yet changing gamma values would impact image preference. Figure 4 shows an example of the primary ramps and a neutral ramp using this method for the extreme values of 0.75 and 1.25.

The first step in this process was to simply scale the digital RGB values in an image between 0 and 1 and then raise the values to an exponent. These values were then rescaled between 0 and 255 to create the new image RGB values. This approach uses the intrinsic gamma of the image and serves only as a "gamma-boost" or "gamma-reduction".

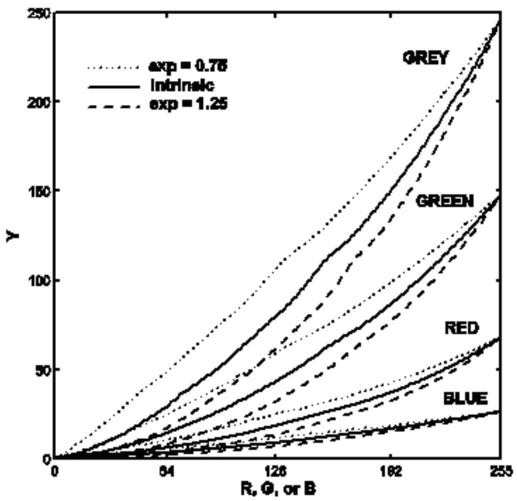

Figure 4. Primary & neutral ramps modified using 2 exponential values

In both conditions for Experiments 1 and 2, a paired-comparison experiment was performed in which each image, including the original unprocessed image, was presented with all the others. The observers' task was to choose which of the two images in the pair they preferred based on overall image quality. The observers could toggle between the two images and select their choice by hitting the "Return" key while the preferred image was displayed. There were a total of 360 trials in Experiment 1, (10 images with 9 variations each) and in Experiment 2 there were 84 trials, (4 images with 7 variations each). The data was analyzed using Thurstone's Law,[7] Case V, which produces interval scale values of image preference. Additionally, the 95% error bars for curves in all the below graphs were created using a method based on Monte Carlo simulation.[8] There were 26 observers for Experiment 1, ranging in age from 22-49. For Experiment 2 there were 20 observers in the same age range.

Results

Experiment 1: Dark Surround

Figure 5 shows the average results for all 10 images for Experiment 1. The interval scale values from Condition 1 (bright display – solid line) and Condition 2 (lower luminance display – dashed line) were shifted by an additive constant so that the scale value of the original image (far left value) was 1. This allows the trends for both sets of data to be compared relative to the original. As a result, the scale values between conditions cannot be compared but the trends relative to the original can be.

The curves on the left of the vertical line represent the Gamma method and there are several noticeable trends. Overall, a gamma of 1.6 produced images that are preferred over the original. At the lower luminance level (dashed line) the curve appears wider, thus suggesting less selectivity for different gamma values. Conversely the higher luminance levels (solid line) result in a narrower curve, suggesting that gamma values are more critical and that higher values are more objectionable. In other words, for brighter displays the choice for gamma becomes more constrained. The images from Method 2, the Exponential Method, to the right of the vertical line, on average, are not preferred to the original tone functions. (An exponent of 1 would produce images identical to the original).

Figure 6 shows results for four images that are representative of the trends observed in the other six images. These four images are used later in Experiment 2. The graphs in Figure 6 show that there is a great deal of image dependence in terms of the absolute preference relative to the original. However the trends within each type of image manipulation are quite similar for both brightness levels.

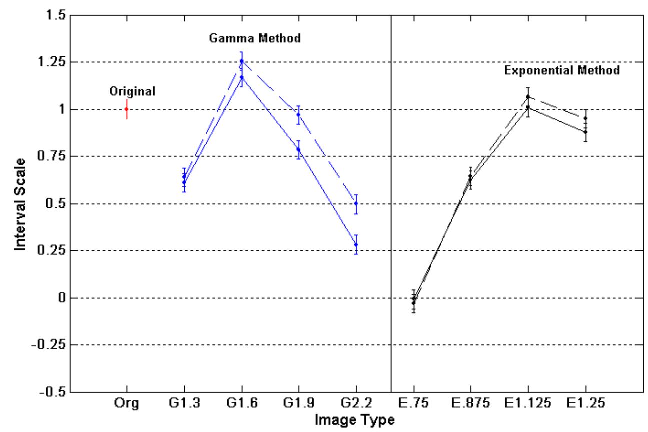

Figure 5. Average of all images for dark surround. Solid line is default brightness, dashed is lowered

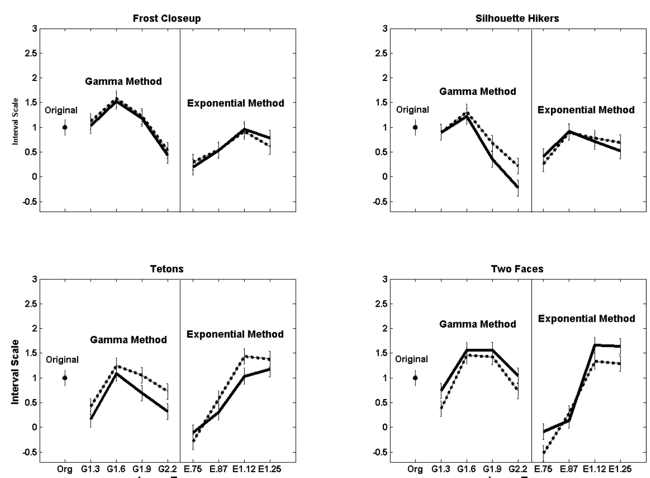

Figure 6. Results of individual images for dark surround. Solid line is default brightness, dashed is lowered.

It is seen that there is a small effect of display brightness on the preferred tone function. Furthermore, the preferred tone mapping of 1.6 gamma does not change for the two screen intensities tested. However, at the higher brightness, it appears that obtaining this optimal gamma is more critical. Additionally, it is clear that the intrinsic tone- mapping of the display can be improved because of scale values greater than that of the Original.

Experiment 2: Dim Surround

The images used in Experiment 2 had two additional gamma values added in order to better determine the optimal gamma. The Exponent Method was dropped from this experiment based on the results from Experiment 1, which showed that the intrinsic tone function was optimal for curves of this shape (i.e. boosting or reducing the intrinsic tone function did not improve performance).

Figure 7 shows the average results from all four images. At the higher brightness, (solid line), the gamma value of 1.6 is clearly preferred but at the lower brightness it is either 1.6 or 1.75. Figures 9 and 10 show the differences between the dim and dark surround, comparing the trends seen in Experiments 1 and 2. Figure 8 shows the differences at the default brightness of the display and Figure 9 shows the differences at the lowered brightness. For the dim surround level there was a greater range between least and most preferred compared to the original. This trend holds true for all images except the "silhouette hikers."

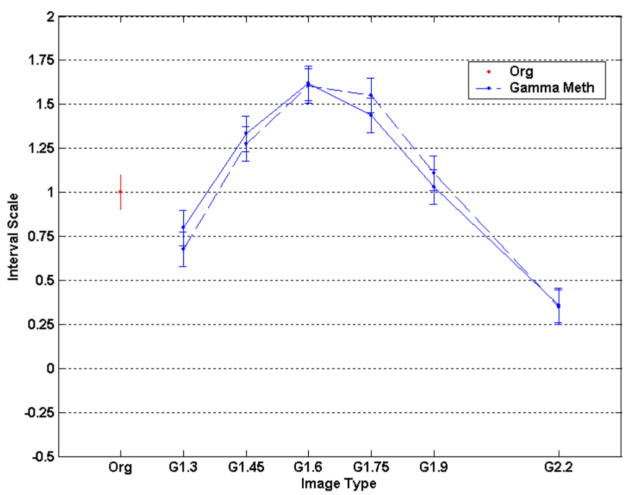

Figure 7. Average of four images for dim surround. Solid line is default brightness and dashed is lowered

In general, the optimal gamma value was even more preferred when there was a dim surround present than when the surround was dark. Therefore, under more natural viewing conditions with a surround recommended by SMPTE,[5] greater improvement in image preference is seen when using a traditional gamma tone function as compared to the intrinsic tone curves.

Discussion

Based on the Steven's Effect, at the default luminance of the display there is a higher perceived contrast than at the at the lower luminance level with the overlayed filter. Based on the Bartelson & Breneman effect, the dark surround will have a lower perceived contrast than the dim surround. With newer, brighter TVs the perceived contrast of the display is higher; therefore adjustments may need to be made in the tone mapping of images in order to compensate for these changes. The prediction is that when the luminance of the display is increased, a lower gamma value is preferred due to the increased contrast produced by the brighter display.

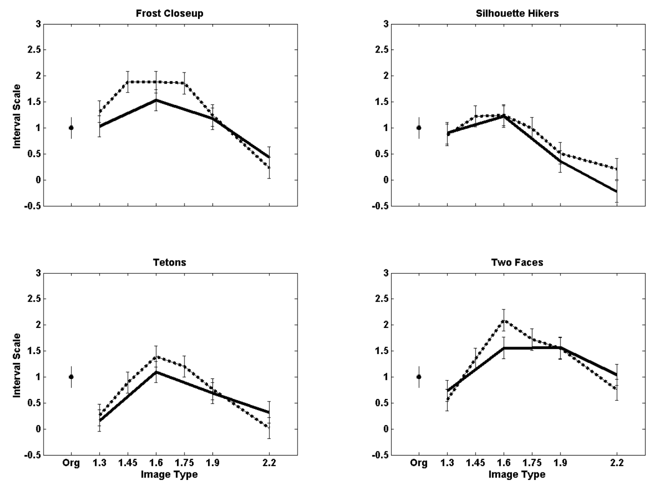

Figure 8. Comparing surround at default brightness. Dashed line is dim surround and solid is dark surround

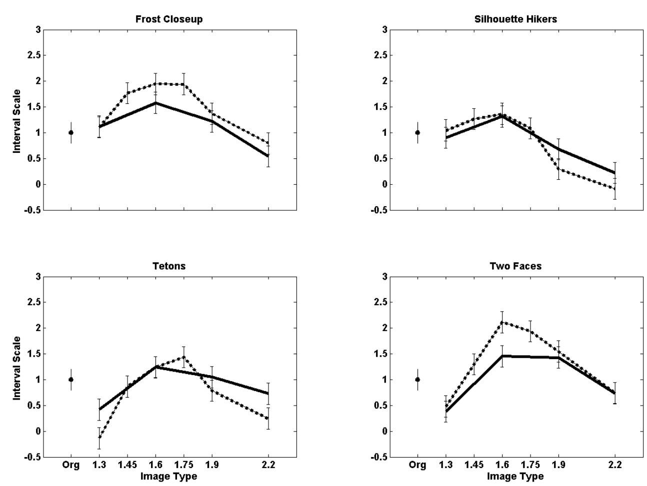

Figure 9. Comparing surround for lowered brightness. Dashed line is dim surround and solid is dark surround

The effects of the surround and the intensity of the display can have profound effects on the appearance of a scene (see Fairchild[9] for a discussion of these effects). Bartleson and Breneman[1] found that if the surround illumination around a display is increased, without causing substantial flare, the white point remains stable but the blacks appear darker thus increasing the perceived contrast. This effect generally enhances the appearance of an image but it is noted that the effect depends on the image whether it enhances or makes the appearance worse.

Conversely, by reducing the default LCD luminance through a filter both the white point and absolute black were reduced, resulting in a change in preference with the lower luminance. The Stevens Effect[2] describes the decrease in perceived contrast with reduced luminance. As the luminance level decreases the bright areas of an image do not appear very white and the dark areas do not appear very dark, thus the perceived contrast has decreased. This would account for the fact that at lower luminance levels the overall luminance decreased thus decreasing contrast and causing observers to choose images with higher gamma values.

It is noted that the Bartleson-Breneman Effect explains the shift in preference between the two surround conditions while the Stevens Effect explains the change in preference between the display's luminance levels. While it might seem that these two effects might balance each other the results indicate that surround conditions chosen here had a larger impact on observer preference than display luminance at the levels tested. In other words, changing display luminance had less of an effect on preference than changing surround. Figures 9 and 10 show that as surround illumination is increased observer preference decreased for higher gamma value images. This result is directly in line with the Bartleson-Breneman Effect because observers already perceived a higher contrast so therefore objected more persistently to images with high gamma values.

Conclusion

The results indicate that at the default luminance of the 30" LCD television observers preferred a gamma of 1.6 in each channel over the intrinsic EOTFs of the display. At the lower luminance there was more tolerance in the absolute choice for preferred gamma but on average, observers still preferred a gamma of 1.6 for the dark surround and either 1.6 or 1.75 for the dim surround. Again, the end result is that for higher luminance displays viewed in a dim surround the choice of gamma in a display becomes critical.

It is also clear that these effects are dependent on image content. The change in color due to the uniform gamma curves relative to the intrinsic curves, which are different in each channel, may also have contributed to these results. Further experimentation is needed to explore both the effect of these color changes on preference and determine whether a completely different tone-mapping function would produce even better results. From the results found in this study what can be said is that manufactures of these display types need to choose the particular gamma value carefully and using similar values for each channel should be considered. It is clear that using the traditional value of 2.2 would not be optimal.

Further studies are required in order to quantify the effect of different luminance levels and backgrounds on image preference. In addition, these experiments only tested two forms of the EOTF: a gamma function and the intrinsic LUTs built into the display hardware. The results showed that modifying the shape of the intrinsic EOTFs by an exponent did not improve image quality. However, the use of a more traditional gamma function did improve image quality. The change in the images was not confined to changes in lightness and contrast with the use of the gamma function because the intrinsic LUTs of each of the display primaries are slightly different. Therefore, the use of the gamma functions also leads to color shifts. It is possible that other shaped curves, such as sigmoids, may produce even better results.

The method of simulating different gamma functions is susceptible to image artifacts due to quantization and loss of image detail in the dark regions due to the implementation of the algorithm to recompute the images. Despite these artifacts, the image manipulations did lead to improvement in image quality.

Besides changes in display intensity and surround conditions, the next generation of televisions are also larger and sharper than older CRTs. Both of these factors may also produce changes in image quality. As display technology improves and displays become brighter and larger, it is possible that the effect of the display luminance may necessitate different tone mapping due to local adaptation to the display. However, it seems that those limits have not quite been reached yet. Further study is needed to determine how these factors should be accounted for in image processing with these displays.

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Justin Laird received his B.S. degree in Imaging and Photographic Technology from Rochester Institute of Technology in 2003 and will have his M.S. in Color Science from RIT in 2005. He has interned at various companies while in school such as Gretag Imaging and Harley Davidson. His professional interest includes exploring new ideas pertaining to display technology and different approaches to showing images. He recently accepted a position at Philips Research.