Measuring the Relationship between Perceived Image Contrast and Surround Illumination

Changmeng Liu and Mark D. Fairchild
Munsell Color Science Laboratory
Rochester Institute of Technology, USA

Abstract

While an image's relative surround luminance increases from dark to light, the perceived contrast of the image will increase. For this reason, projected transparencies are made with higher physical contrast than reflection prints, which are intended to be viewed in an illuminated environment. Previous research shows that the surround effect is important for color appearance and device-independent imaging. An experiment was designed to investigate the effects of surround color and luminance on apparent image contrast. An LED illuminated lab was built to perform this experiment. Within the RGB 24-bit gamut of the LEDs, the surround color and luminance in this lab can be freely adjusted. The method of adjustment was used in this experiment. Results show general agreement with previous tone reproduction and lightness scaling research. However the surround effect on image contrast is not obvious for non-expert observers. Because the perceived image contrast not only depends on the image luminance but also upon image spatial structure and the observer's cognitive system, non-expert observers might not notice the contrast changes caused by the surround effect when the images have complicated spatial structure and "flat" contrast.

Introduction

Tracing back to the 1930's and 1940's, people working on tone reproduction began to realize the nonlinear relationships between the physical luminance and perceived lightness. Based on Jones' work,[1,2] the photographic industry optimized the characteristic curve of the tone reproduction for projected transparencies and reflection prints to obtain optimal perceptual appearance. Different characteristic curves were optimal for projected transparencies to be shown in dark surround and reflection prints to be shown in the light surround. The physically measured contrast or the slope of the characteristic curve in logarithmic coordinates for transparencies was typically 1.5 times higher than the contrast of reflection prints for equal apparent contrast.

In order to understand the reason why there exists this obvious difference between the optimized tone reproduction characteristic curves for dark and light surrounds, brightness and lightness scaling must be considered.

Brightness is defined as the attribute of a visual sensation according to which an area appears to emit more or less light. Lightness is the brightness of an area relative to the brightness of a similarly illuminated area that appears white or highly transmitting. Luminance is a physical measure of the stimulus with units of cd/m^2. All the definitions above are adopted from the International Lighting Vocabulary.[3] Both brightness and lightness are perceptual attributes. There exists nonlinear relationships between the perceptual attribute brightness and the physical attribute luminance.

Another very important concept for this paper is contrast. There are two different definitions for contrast. The following definitions are adopted from Fairchild.[4] One definition for contrast, which is used in tone reproduction, is the rate of change of the relative luminance of image elements of a reproduction as a function of the relative luminance of the same image elements of the original image. On log-log coordinates, the contrast is the slope of the relationship between the reproduction and original. The contrast defined in this way is an attribute of the system transfer function.

Another definition for contrast, which is used in visual science, is the difference between minimum and maximum luminances in an image. This contrast is an attribute of the image. The perceived image contrast is the perceived lightness difference between dark part and the light part of an image.

According to the classic psychophysical brightness scaling experiment from Stevens,[5] perceived brightness could be expressed as power function of physical luminance. If this power relationship is plotted in log-log coordinates, it becomes a straight line. From the further research by Stevens and Stevens,[6] the slope of the straight line in log-log coordinate (or the exponent of the power function) is different for different adapting illumination levels (similar to a surround change). The results showed that the dark surround has lower slope, and light surround has higher slope. If the illuminance of the surround changed from light to dark, the light area of the image looks a little bit brighter, while the dark area looks much brighter; as result, the perceived image contrast is decreased.

Bartleson and Breneman[7] extended brightness scaling to more complicated fields, black and white images, deriving a modified logarithmic form equation to predict perceived image brightness. In 1975, Bartleson[8] published a simplified equation from their previous research. The simplified equation has been widely used in the imaging industry.

Both Stevens and Bartleson used the lightness magnitude estimation method in their research. The perceived image contrast not only depends on the luminance of the image, but also upon the content or spatial structure of the image. Some color appearance phenomena,[9] such as simultaneous contrast, crispening and spreading, are related to the perceived image contrast. And our cognitive system will also play a very important role in the perceived lightness. Some phenomena related to perceived contrast have been discussed.[10–13] The human cognitive system participates in high-level perception. The perceptual contrast after interpretation of the human cognitive system relies on the spatial structure of the image and our knowledge of the world.

Surround also affects the chroma of stimuli. In tone reproduction, color images in dark surround need higher contrast than the images in light surround. It is similar in the lightness perception. In Fairchild's review[4] of surround there is more detail about the surround effect on perceived colorfulness. "While the influence of surround relative luminance on perceived chroma in images is a question that remains to definitively answered."[4]

Experimental

1. Building the Surround Lab Using LED Illumination

In order to investigate the surround effect on perceived image contrast, an LED illuminated lab was built. The color and luminance of the surround in this lab can be adjusted within the gamut of the LEDs.

A computer controlled LCD, which is used to display the image, is placed in the center of this lab. This computer also controls the color of surround. Behind the LCD display, 12 uniformly distributed high power LED lights (Color Kinetics ColorBlast 12) are used to irradiate a white semicircle shaped diffusively reflective screen. Each LED light contains three primary LEDs, red, green and blue. The intensity of each LED primary can be controlled with 8-bits of precision. The semicircle background reflective screen simulates an integrating sphere that covers the whole viewing field of the observer. The ceiling and the wall in front of the LCD display (behind the observer) are covered by black material to absorb the diffused light and avoid flare on the LCD display. Underneath the LCD display, white paper is used to block direct view of the LED light. It prevents observers from seeing the LED directly, and thus avoids unwanted cognitive interpretation of the scene. Figure 1 shows the demo of this lab under two different surround conditions. Figure 2 is a schematic top view of the lab.

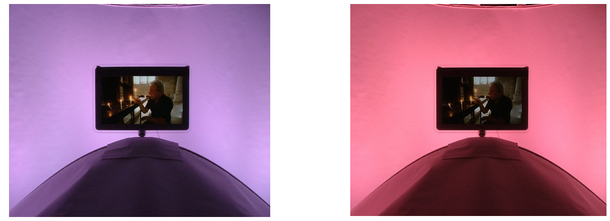


Figure 1. Demos for surround lab. Image is shown in different surround condition.

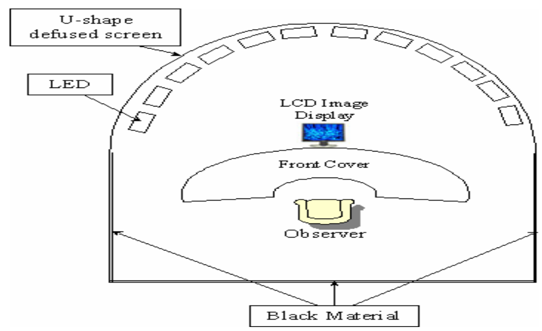


Figure 2. Schematic top view of the lab.

2. Eliminating Physical Viewing Flare

Viewing flare will lower physical image contrast. Viewing flare has more perceptual effect on dark parts of the image. Light surrounds often have more flare therefore cause low-perceived image contrast; dark surround has less flare therefore cause high-perceived image contrast. So surround and flare have opposite effects on perceived image contrast. It is very important to eliminate viewing flare when investigating the surround effect on image contrast.

The ceiling and wall in front of the LCD display were covered with black material to absorb the light from the surround and minimize flare. Some flare on the LCD screen is unavoidable given an illuminated surround. After adjusting the angle of the paper underneath the LCD, the measured maximum flare is less than 0.4% of the LCD maximum luminance. This is small enough to neglect the effect of flare during the experiment.

3. Surround LED Characterization

The peak wavelengths of three LEDs used in this experiment are 470 nm, 520 nm, and 640 nm. The corresponding bandwidths (half height) of these LEDs are approximately 20 nm, 30 nm and 20 nm. The LED is an additive color mixing system with three primaries. The chromaticity coordinates and maximum luminance of three LED primaries are shown in Table 1.

Table 1. LED Primaries

Primary	Red	Green	Blue	White
x	0.703	0.179	0.124	0.273
y	0.294	0.725	0.09	0.269
Y (cd/m^2)	80.5	171	61.6	313

After testing on 11-equal step color ramp for each primary range from 0 to 255, it was found that the chromaticity coefficients for each primary are very stable. A nonlinear relationship between the digital count and luminance was also found. There is no black flare for the LED since there is no light output when LED digital count is set to 0. Therefore, the LED colorimetric characterization can be separated into two steps. The first step is linear model, and second step is the nonlinear model. The linear model can be described as equation (1).

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

where (Xr,max, Yr,max, Zr,max) is the tristimulus values for maximum red primary output. The (R, G, B) is the additivity coefficient (relative linear luminance).

The nonlinear part is implemented by one-dimensional LUT (look-up table) for each primary. Base on the reverse of equation 1 and the chromaticity coefficients of color ramp data, we can build a LUT for each primary.

$$R=LUT(d_r),\ G=LUT(d_g),\ B=LUT(d_b),\ 0 \le R,G,B \le 1 \quad (2)$$

where, (d_r, d_g, d_b) is the digital count for each primary.

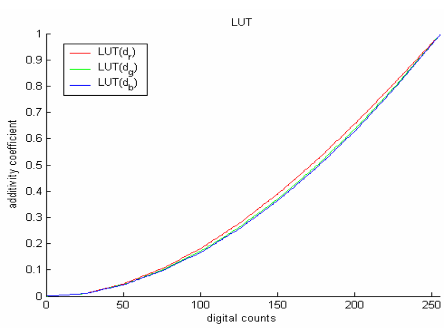


Figure 3. The LUT for three primaries of LED.

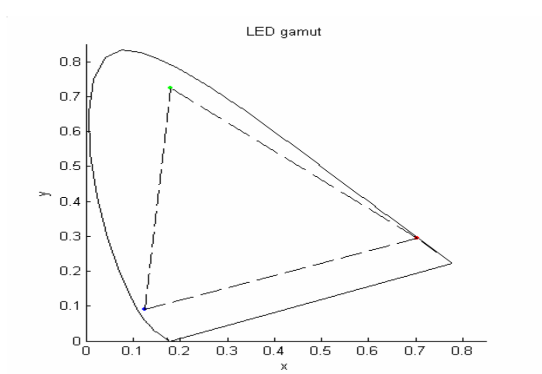


Figure 4. The gamut of LED plotted in CIE chromaticity diagram

The LUTs for each of the three primaries are plotted in Figure 3. It shows that the nonlinear relationship is similar to a power function. 292 different colors were used to test the characterization model; the average color difference between measurement and prediction for these 292 colors is 1.17 CIE DE2000. Figure 4 shows the gamut of the LED in a CIE chromaticity diagram. The surround luminance range for LED is 0 to 313 cd/m^2 (near the LCD display).

In this experiment, the reverse LED model is used. The input tristimulus values for the LEDs are set by observer. The reverse version of equation 1 is used to calculate the additive coefficient (R, G, B). Then from the reverse LUT, we can get the digital counts (d_r, d_g, d_b) for the LEDs.

4. Psychophysical Experiment Procedure

The method of adjustment was used in this psychophysical experiment. Seventeen observers performed the experiment. During the experiment, the image is displayed over the entire LCD screen. Observers were asked to adjust the color and brightness of the surround until the apparent image contrast was most preferred. The color of the surround was adjusted by changing u' and v' chromaticity coordinates, and brightness of the surround was adjusted by changing the relative luminance.

In order to make the surround effect on the image more obvious, the viewing distance is 5 times the image width. The image viewing angle is about 10°. The surround filled approximately 180° horizontally and 90° vertically. Because the image occupied the whole LCD screen and the frame of LCD is narrow and transparent, the background (as opposed to surround) effect on the image should be minimized.

In order to assure maximum observer adaptation to the adjusted surround, observers were given 30 seconds to adjust the surround followed by 15 seconds of adaptation time. During the adaptation time, the image disappeared, and the LCD displayed a similar color as the surround in order to make observer have better adaptation. This 30-seconds controllable and 15-seconds adaptation time cycle repeated until the observer was satisfied with the surround setting. A confirmation of the decision was made after a final 15-second adaptation period.

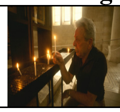
For each image, observers performed three replicate trails. At the end of the experiment, observers were asked to make a final choice from their three selected and one average surround colors for each image.

5. Image Selection and Contrast Adjustment

Because this experiment is a preference detecting experiment, the test images should vary as much as possible. Based on this constraint, images with variance in contrast, dominant hue, and theme were utilized.

Four images were selected based on these considerations. Table 2 shows the makeup of these four images. Note the contrast is based on the histogram of the luminance channel of the image. The high contrast image has two peaks in the histogram separated in both light part and dark part of luminance range. While the low contrast image has the only one peak in the middle of the histogram plot. In order to compare color with black/white images, the portrait image was also included a black/white version in the experiment.

Table 2 The Variance of the Images

				
Contrast	Medium	High	Low	Low
Dominant hue	Grayish	Black/ white	Greenish	Yellowish
Theme	Building	Portrait	Landscape	Indoor

Since it is known that surround mainly affects image contrast, a more quantitative control of image contrast is required. Applying different gamma transforms on the image data is one good way to adjust image contrast. Gamma adjustment can be expressed as the following function: $V'(x,y) = [V(x,y)/255]^{\gamma}$. Where V(x,y) is the original pixel value of the image, V'(x,y) is the gamma adjusted image pixel value. For color images, this equation is applied on R, G, and B channels individually. Since the luminance of the image is a linear combination of R, G, and B channels, the luminance contrast of the image will be changed with gamma adjustment. When $\gamma > 1$, the image contrast will be increased because the dark pixel will be darker relative to the white point. Contrarily, when $\gamma < 1$, the image contrast will be decreased. In this experiment, three different γ were applied on the test images, $\gamma = 1.3$, $\gamma = 1$, and $\gamma = 1/1.3$. Therefore, there are three different contrast versions for each test image, one is an increased contrast image, one is the original image, and one is a decreased contrast image.

Results and Discussion

1. Analyzing the Surround and Perceived Image Contrast for All Observers

Seventeen observers performed this experiment. Five of them are expert or experienced observers who have background knowledge about the surround effect. The other 12 observers have no such experience.

From the experimental data, the average and standard deviation of the relative surround luminance for each scene are calculated. Figure 5 shows the relationship between the surround luminance and the image contrast (different gamma adjustment). Each column represents the relationship for each scene. The first row shows the image of the scene. The second row shows the relationship between the average surround luminance (relative to the maximum LCD luminance) of 17 observers and gamma (or image contrast) for each scene. The last row represents the same relationship as row two, but the relative luminance is normalized to the average luminance of the three different contrast versions of the scene.

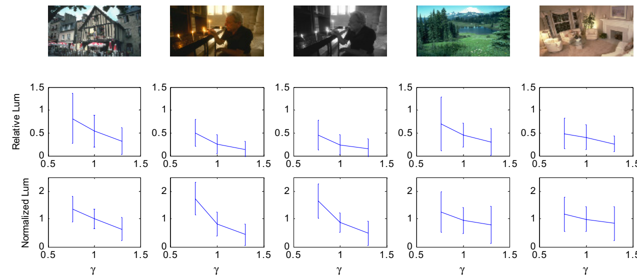


Figure 5, Relationship between the average surround luminance and image contrast. Each column shows the plot for each scene. The first row shows the scene; the second row shows the average surround luminance (relative to maximum LCD luminance) vs. gamma for each scene; in the last row, the relative surround luminance is normalized to the average luminance of three different gammas (γ= 1/1.3, γ= 1, and γ= 1.3) for each scene.

From previous research, it is known that the perceived image contrast will decrease as surround luminance decreases. Suppose the observer has constant criteria when he judges the perceived image contrast for each scene, then the observer will tend to increase the surround luminance when viewing the low physical contrast version (γ = 1/1.3) of the scene. Vice versa, he will decrease the surround luminance when viewing the high contrast version (γ = 1.3) of the scene.

Figure 5 shows a bit of this negative trend for each scene. However the standard deviations are too big to say this negative trend exists for all observers. Figure 5 also shows the high contrast images (scene 2 and 3) have a more clearly defined negative trend.

Figure 6 shows the selected surround chromaticity vector from the white point of the LCD for all observers. In Figure 5, the surround chromaticity vector is plotted in the CIE u' v' chromaticity diagram. Each column represents different scene; each row represents the different image contrast (gamma). From Figure 6 no consistent relationship is evident between the surround chromaticity and the image contrast or the different scene.

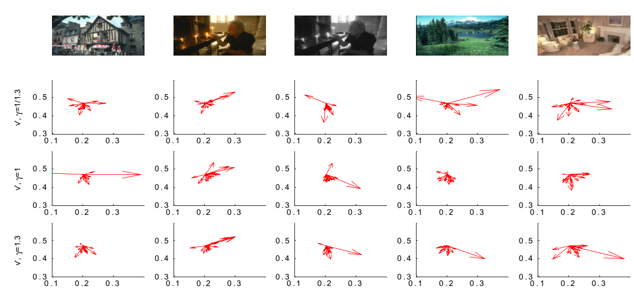


Figure 6, the surround chromaticity vector (from the white point of LCD) for each scene. Each vector represent for different observer's selected surround chromaticity from the white point of LCD.

2. Analyzing Observer Variance Using Analysis of Variance (ANOVA)

From the experimental data of all 17 observers, the surround effect is not very clear. Statistical analysis is needed to find the observer variance. Analysis of Variance (ANOVA) for each observer on the luminance setting was performed. The gamma and content of the scene are two factors in the ANOVA.

Table 3 shows the result of ANOVA result for 17 observers. Based on the p value of the gamma factor, the observers can be classified to two groups. The p values of gamma factor for Group One are less than 5%. The p values of gamma factor for Group Two are greater than 5%. This indicates that the observers' settings in Group One depend on the image contrast (gamma) when they adjust the surround luminance. Observers in Group Two do not depend on the image contrast when they select the surround luminance. The result of ANOVA also shows that all experts are in Group One. That means all expert observers depend on the image contrast when they select the surround luminance.

Table 3. ANOVA Result for 17 Observer

Observer	P_Gamma	P_contant	Group	Expert
1	0.51	0.00	2	N
2	0.98	0.01	2	N
3	0.79	0.10	2	N
4	0.01	0.01	1 *	N
5	0.00	0.01	1	E
6	0.00	0.00	1 *	N
7	0.06	0.21	2	N
8	0.00	0.00	1	E
9	0.00	0.06	1	E
10	0.80	0.04	2	N
11	0.00	0.00	1	E
12	0.25	0.00	2	N
13	0.46	0.85	2	N
14	0.00	0.00	1	E
15	0.45	0.01	2	N
16	0.11	0.03	2	N
17	0.00	0.00	1	N
* observer moved to group 2				

After carefully checking the experiment data, two observers in Group One are identified that have random selected surround luminance for different scenes. Their tendency is totally different for different images, and there is no dominant trend for these five scenes. They were moved to Group Two due to their random, though significant results. These two observers are marked with * in Table 3.

The p value of the image content factor shows that 14 of 17 observers have image dependency (based on the 5% threshold). That means the selected surround luminance depends on different image scene for most observers.

3. Relative Surround Luminance vs. Perceived Image Contrast

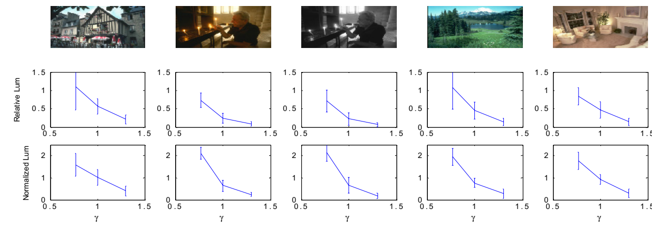


Figure 7. The relationship between average surround luminance and image contrast for Group One.

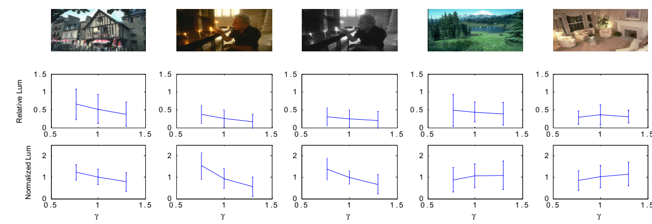


Figure 8. The relationship between average surround luminance and image contrast for Group Two.

After classifying the observers into two groups, the relationship between surround luminance and image contrast is plotted separately for these two groups. Figure 7 and Figure 8 is similar to Figure 5, except showing data from different groups. Figure 7 shows the surround luminance vs. the image contrast for Group One. It clearly shows the negative trend. This matches the previous result very well in both magnitude and direction. The observers in Group One tend to decrease the surround luminance to compensate the high image contrast. Vice versa, they will increase the surround luminance to compensate the low image contrast.

Figure 8 shows the same plot for Group Two. It shows that the observers in Group Two have no clearly negative trend and the variance is very large. That indicates the observers have not noticed the image contrast changes when they adjusted the surround color and luminance. Their preferred surround setting is image-content dependent, but not image-contrast dependent.

Figure 9 shows the relationship between overall absolute surround luminance and image gamma. The overall absolute luminance is calculated from the surround luminance setting in Group One for all test scenes. In Figure 9, the experimental data are compared with the classical summary result from Bartleson & Breneman or Hunt. Those results suggest the ratio of physical gamma is (1:1.25:1.5) for average, dim, and dark surrounds. The ratio of the luminance is approximated as (40:10:0) for average, dim, and dark surrounds. In Figure 9 the typical luminance level for dim surround is converted to same luminance level as the luminance in our experiment with $\gamma = 1$.

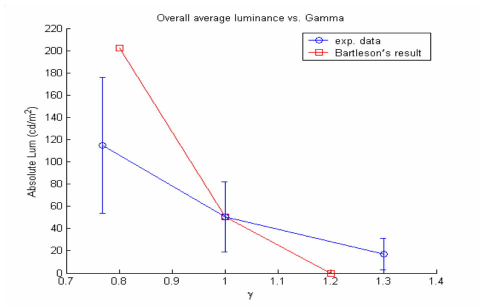


Figure 9. Overall average surround absolute luminance vs. gamma.

Figure 9 shows general agreement between this experiment and Bartleson's result. Both of two results show the same negative trend. The standard deviation in this experiment is caused by the image content dependency. It also shows that the image content dependency for high gamma image is small.

4. Surround Chromaticity vs. Perceived Image Contrast

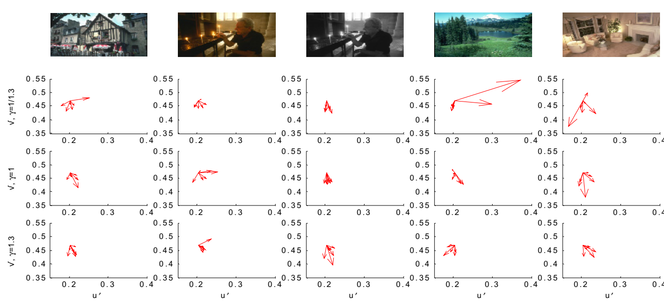


Figure 10. The surround chromaticity vector (from the white point of LCD) for Group One.

Figure 10 shows the chromaticity vector for Group One. It shows most observers tend to make the surround neutral color when viewing images with less colorfulness, such as the Scenes 1 to 3. When the images have more colorfulness, the preferred surround color will have more variance based on different observers' preference. Further experiments will be needed to prove the surround color effect with respect to the image contrast or content.

For Group Two, the observers have much more variance in the surround color selection. Most of the variance in Figure 5 is caused by the observers in Group Two. The probable reason for the big variance for observers in Group Two is that they tended to randomly select the surround color and luminance if they cannot see the image contrast changes when they adjust the surround.

5. Why Non-Expert Observers Have Trouble Finding the Surround Effect on Image Contrast?

The results clearly show that expert observers (Group One) can easily find the surround effect on the image contrast, whereas the non-expert observers have difficulty recognizing the image contrast changes when they adjust the surround color and luminance.

The survey after the experiment shows that the expert observers tended to focus on both the darkest and the lightest part of the image when they judged perceived image contrast. On the other hand, the non-expert observers don't focus on the darkest part of the image; instead they tended to focus on the part of the image in which they were most interested.

Figure 8 shows the observers in Group Two can find some surround effect on the high contrast image (scene 1, 2 and 3). But they can't find this effect on the low contrast scenes (scene 4 and 5).

From previous research, the reason for the surround effect on the perceived image contrast is that the perceived lightness changes in dark areas is more than the changes in light areas for different adapted surround condition. But the non-expert observers don't focus on the dark part of the image, the perceived image contrast changes caused by surround is not big enough to be noticed when they focus on the middle luminance range of the image. Therefore, they cannot observe the contrast changes caused by surround changes.

Another probable reason is that the spatial structure and human cognitive system will affect the perceived image contrast. When the image contains more complicated spatial structure, observers will feel it more difficult to judge image contrast. Also observers will tend to focus on the most interesting objects in the image based on their real world knowledge through the cognitive system. So the spatial structure effect and cognitive effect will act as "noise", when people judge the lightness of the physical luminance.

Conclusion

An LED controlled surround lab was built to investigate the surround effect on perceived image contrast. The method of adjustment was used in this experiment. The experiment result shows that expert observers can detect the surround effect on the image contrast much easier than the non-expert observers. Expert observers tended to lower the surround luminance when they perceive the contrast of the image is too high. This result matches previous results from the tone reproduction optimization and lightness scaling. Expert observers also tended to adjust the surround to neutral color. When the image is more colorful, the preferred surround might tend to more saturated color, but this needs more experimentation to prove. The non-expert observers have more difficulty finding the surround effect. One reason is that they don't focus on the dark part of the image. Another reason is the human cognitive system will affect the perceived image contrast when the image has more complicated spatial structural. Further experiments will be designed and implemented to use this facility to better understand the importance of surround in image appearance modeling and reproduction.

References

1. L.A. Jones, On the Theory of Tone Reproduction, with a Graphical Method for the Solution of Problems, J.S.M.P.E. 16, 568-599 (1931).
2. L.A. Jones, Psychophysics and Photography, J. Opt. Soc. Am. 34, 66-88 (1944).
3. International Lighting Vocabulary, CIE Pub. No. 17.4, Central Bureau of the CEI, Geneva, 1987.
4. M.D. Fairchild, "Considering the Surround in Device Independent Color Imaging," *Color Research and Application, 20* 352-363 (1995).
5. S.S. Stevens, To Honor Fechner and Repeal His Law, Science 133, 80-86 (1961).
6. J.C. Stevens and S.S. Stevens, Brightness Function: Effects of Adaptation, J. Opt. Soc. Am. 53, 375-385 (1963).
7. C. J. Bartleson and E. J. Breneman, "Brightness perception in complex fields," J.Opt. Soc. Am. 57, 953-957 (1967).
8. C. J. Bartleson, "Optimum Image Tone Reproduction," J. SMPTE 84, 613-618 (1975).
9. M.D. Fairchild, Color Appearance Models, Addison-Wesley, Reading, 1998.
10. P. Oskoui & E. Pirrotta, Influence of Background Characteristics on Adapted White Points of CRTs, *IS&T/SID 6th Color Imaging Conference*, 22-26 (1998).
11. R.O. Brown & D.I.A. MacLeod, Color Appearance Depends on the Variance of Surround Colors, *Current Biology 7*, 844-849 (1997).
12. B. Spehar, J.S. DeBonet & Q. Zaidi, Brightness Induction from Uniform and Complex Surrounds: A General Model, *Vision Res. 36*, 1893-1906 (1996).
13. E.H. Adelson, Lightness Perception and Lightness Illusions, in the Cognitive Neurosciences 2nd Ed., MIT Press (1999).

Biography

Changmeng Liu received his B.S. degree in Electronic Engineering Department from TianJin University (China) in 1996 and M.S. degree in Computer Science Department from the Rochester Institute of Technology in 2002. He is a Ph.D. candidate in the Munsell Color Science Laboratory at the Chester F. Carlson Center for Imaging Science at the Rochester Institute of Technology. His current interests include color appearance, image quality, color management, and digital Halftoning.