Re-measuring and modeling perceived image contrast under different levels of surround illumination

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Abstract

It is established that perceived image contrast depends on viewing conditions, especially the level of surround illumination. In this research, perceived image contrast was re-measured and modeled. The input image was rendered from XYZ values through an image appearance model (iCAM06), in which the default viewing condition is dark surround. The image physical contrast was controlled by an exponential factor in the lightness channel (I) in the IPT space. The paired comparison psychophysical method was used to measure the perceived equivalent image contrast under different levels of surround illumination. The corresponding surround compensation gamma ratio was measured by normalizing all physical gamma values to the one with surround luminance with 100% of image white. The changes in perceived image contrast with different levels of surround illumination were modeled as a power function with different exponent between the perceived lightness and relative physical luminance level in the image. The exponential ratio in this research for average, dim, dark surround is different from the classical result from Bartleson & Breneman or Hunt, CIECAM97s, CIECAM02, and some other research results. An optimal ratio of 1.0:1.10:1.14 was found as opposed to the traditional values of 1.0:1.25:1.50. The results also show that image content plays a very important role when people view an image and judge the perceived image contrast. The results from this research can be used to improve the surround compensation factor in current image and color appearance models.

Introduction

It is well established that the relative luminance level of the surround greatly affects the perceived image contrast. Here, the perceived image contrast is defined as the rate of change of the perceived lightness of image elements as a function of the relative luminance of the original image elements. Bartleson & Breneman's classical results,[1] obtained through matching and scaling experiments, showed that the perceived image contrast increased when the relative luminance level of surround was changed from dark, to dim, to light. Their experimental results also agreed with the historical requirements for optimum image tone reproduction. In order to get the same perceived image contrast, photographic industry found that the tone reproduction of photographic prints viewed in the average surround condition should be greatly different from the tone reproduction of the photographic transparencies projected in the dark room. The relationship between the perceived image contrast and the relative luminance level of the surround was modeled as a psychological function between the perceived lightness and the relative physical luminance of the image elements. This psychological function is a power function with different exponential factor depends on the relative luminance level of the surround. The effect of surround on perceived image contrast is well known; it is also not well understood or quantified.[2] More detail on the exponents can be found in the review of surround effect from Fairchild[2] and Hunt[3] for image reproduction.

Color appearance models such as Hunt's[4], RLAB[5], CIECAM97s[6, 7] and CIECAM02[8] include the predictions of the surround effects on perceived contrast of images. Hunt's model, which is the most complicated and complete color appearance model, uses the different surround effect predictor from other color appearance models, which all use a simple power function to predict surround effect. For this reason, the surround effect predictor in Hunt's model was not compared in this paper.

In RLAB model, the surround effect was modeled as opponent color attributes as a simple power function of tristimulus value under reference viewing condition. This function is shown in Eq. 1.

$$L_R = 100(Y_{ref})^{\sigma} \qquad (1)$$

Where, L_R is the lightness, Y_{ref} is the tristimulus value in reference viewing condition. The exponents σ in the Eq. 1 vary depending on the relative luminance of the surround. For average surround σ = 1/2.3 for dim surround σ = 1/2.9 and for dark surround σ = 1/3.5. In order to compensate the different surround conditions to perceived the same image contrast, the physical image gamma ratios are 1:1.26:1.5 for average, dim and dark surround. These ratios of exponents are close to the classical summary result from Bartleson & Breneman or Hunt. In RLAB model, the surround condition was defined as three category: a dark surround is considered essentially zero luminance, a dim surround is considered a relative luminance less than 20% of white in image, a average surround is considered as a relative luminance equal to or greater than 20% of the image white.

In the revision of CIECAM97s, the surround effect was modeled as a power function applied on the achromatic opponent channel, which is shown in Eq. 2

$$J = 100(A/A_W)^{cz} \qquad (2)$$

Where J is the lightness, and A is the achromatic response in the opponent dimension, z is the base nonlinear factor, and c is the surround dependent parameter. A_W is the achromatic response of white. For average surround c = 0.69, for dim surround c = 0.59, for dark surround c = 0.525. In order to compensate the different surround conditions to perceived the same image contrast, the physical image gamma ratios are 1:1.17:1.31 for average, dim and dark surround. The intermediate (or more extreme) values of c and N_c (a surround related chromatic induction factor) in the revised CIECAM97s will be obtained by linear interpolation (or extrapolation). The average, dim and dark surround in CIECAM97s revision are defined as same as the definition in RLAB, thus it is still hard to determine the precise intermediate surround parameter c from these categorical surrounds.

CIECAM02 is a simplified version of CIECAM97s with some changes in the chromatic adaptation part. But both models use the same parameter setting and equation for surround compensation. In CIECAM02, the surround parameter c is set to the same value as the one in CIECAM97s. The surround compensate image gamma ratios are 1:1.17:1.31 for average, dim and dark surround in CIECAM02.

In the image appearance model, it has the functional module of surround effect. In iCAM[9] this module was not complete yet. In iCAM06,[10] the surround predictor was implemented in the achromatic channel (I) in IPT space[11] with a simple power function, which was shown in Eq. 3. The default surround parameter γ was set to 1:1.25:1.5 for average, dim and dark surround.

$$I_a = I^{\gamma} \tag{3}$$

For the last several decades, some researchers have tried to measure the perceived image contrast under varied surround illuminant conditions using different methods and different testing medium. Bartleson & Breneman's experiment use matching and lightness scaling method. Their result shows that the ratios of the physical gamma value are 1:1.25:1.5 for average, dim and dark surround condition in order to perceived same image contrast. Some research works indicate that Bartleson's gamma ratio for compensating the average, dim and dark surround (1:1.25:1.5) was over predicted when applied in the image. Daniels el at.[12] designed an experiment with match the lightness contrast of image among three different surround-viewing conditions: dark, average and light surround which is 100% of image white. Their experimental result showed that Bartleson & Breneman's result was over predicted. The physical gamma for compensate surround effect should be 1:1.09:1.16 for light, average and dark surround conditions. In this experiment, the light surround referred to 100% paper white. Their experiment was performed on reflectance prints. Liu[13] designed a contradict experiment on LCD display by using adjustment method. This experiment measured the required color and luminance of the surround to achieve the same perceived image contrast. The results in this experiment do not get the direct gamma ratio for average, dim and dark surround. But their result trend shows that Bartleson's result was less predicted.

The surround parameters in color appearance models and the experiment results show the different values. But all the researches above agree on the over all trend of Bartleson's result, that the increased surround luminance will increase the perceived image contrast and vice versa. So the appropriate and continuous surround parameter values in the color appearance model need to be determined. Thus, there is need to further explore the effect of surround on perceived image contrast to determine the appropriate model parameter values in the color appearance model and image appearance model.

This research tries to find a robust way to measure the perceived image contrast under various surround conditions rather than only average, dim and dark. The optimum surround compensation exponent ratios for those surround conditions will be measured. For intermediate or more extreme surround conditions, the surround compensation exponent will be obtained from linear interpolation or extrapolation.

Experiment

This research was a directly continuation of previous research[13] and used the same experimental setup. The experimental method was inspired from Laird's[14] preferred EOTF research. The OETF refers to Electro-optical Transfer Function. In his experiment, the preferred EOTF curve of LCD TV was measured under dark and dim viewing condition. The surround effect was shown in their experimental result.

This research was based on the assumption that the observer holds a preferred image contrast in mind for a given scene, and this reference preferred image contrast does not change when surround changes. This assumption was ensured by being specified in the experimental instruction. Under various surround conditions, the observer matched the reference preferred image contrast by selecting among images with modified gamma values on their lightness channel. An interval scale was formed where the image closest in appearance to the reference preferred contrast would have the highest value, while other gamma values will be perceived as either too high or too low contrast for the observer. As result, those images will have lower value on the scale.

Table I, Surround luminance levels and gamma values for compensate surround effect (Y_{LCDwp} = 140 cd/m^2)

Absolute surround luminance levels (cd/m^2)	0, 35, 70, 105, 140, 175
Relative surround luminance levels (relative to the LCD white point)	0, 25%, 50%, 75%, 100%, 125%
Gamma value to compensate surround effect	0.50, 0.67, 0.75, 0.80, 0.85, 0.90, 0.95, 1.00, 1.05, 1.10, 1.20

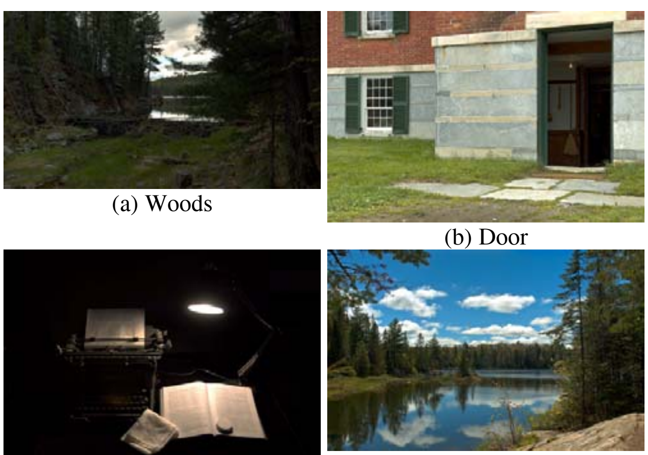
In this research, a paired comparison experiment was designed to measure perceived image contrast under six different surround conditions with relative luminance levels from totally dark to 125% of image white. Eleven different surround compensation gamma values were selected from a preliminary experiment and applied to the achromatic channel (I) in IPT space. Previous research[15] showed that the surround color affects color perception in the central display. The color of the surround was set to make the central display looks neutral instead of being set to be the same tristimulus values as the LCD display's white point. The observer could change the color for each surround condition during the experiment if they found the LCD display white point no longer appeared neutral in the new surround luminance level. But the luminance level of the surround was kept the same during the adjustment of color of surround. Table I shows the details of the surround luminance levels and surround effect compensation gamma values. A pair of images with different physical gamma values was displayed on the LCD display. The observers selected the image, closest to their reference preferred image contrast.

The viewing distance was 60 cm from the LCD display. This viewing distance is about double of the general viewing distance when watching the computer display screen in order to maximize the surround area. The viewing angle of LCD display was approximately 31° (horizontal) by 16° (vertical). The experiments were run on an Apple Cinema HD LCD Display with the maximum luminance of 140 cd/m^2 with and approximate D65 white point. This 23-inch LCD display has a 1920 by 1200 resolution. The display was characterized using the colorimetric characterization model by Day[16]. The LCD display was set in a surround lab. More details about surround configuration can be found in the previous research[13], 12 uniformly distributed high power LED SETS lights (Color Kinetics ColorBlast 12) were used to irradiate a white semicircle shaped diffusively reflective screen. The surround area covered 180° in horizontal. A total of 17 observers participated in this experiment.

Input images

In the experiment, the input images were rendered from high dynamic range images encoded in XYZ tristimulus values. iCAM06 [10] was used to render the HDR image to low dynamic range RGB image (8bit/channel) with the corresponding LCD color characterization model. The surround effect compensation factor γ in iCAM06 was chosen as gamma values listed in Table I to control the physical contrast of the image. The IPT image was transformed back to RGB image using inverse IPT transform and LCD color characterization model.

Four different scenes were used in this experiment: Woods, Door, Desk and Lake (Figure 1). The input images were selected from HDR images because their high overall contrast make it relative easy for observers to perceive the image contrast changes.



(a) Woods (b) Door

(c) Desk (d) Lake

Figure 1. Four test scenes in the experiment.

The default viewing condition of iCAM06 is dark surround viewing condition. For surround effect compensation, the surround parameter γ was set to 1 for dark viewing condition. Therefore, a γ value less than 1 is needed to compensate the surround effect under lighter surround luminance levels in order to perceive the same image contrast as the one in the dark surround. The replaced surround effect compensation factor γ used in this experiment was ranged from 0.5 to 1.2. A preliminary experiment was performed to ensure the selected images had gamma values that showed off contrast differences among the images. No extremely high or low contrast images were used in the experiment to reduce the number of pair comparison.

Results and Discussion

For this paired comparison experiment, Thurstone's Law of Comparative Judgments, Case V, was used to analyze the results. The proportional observer data were converted into an interval scale of the degree of preferred image contrast. In order to deal with the zero-one proportion results in the experimental data, which caused the unanimous judgments problems, Morrisey's incomplete matrix solution [17]], a linear regression technique to fill in the incomplete z-scale value matrix, was used in the data analysis to account for this problem.

Experimental Results

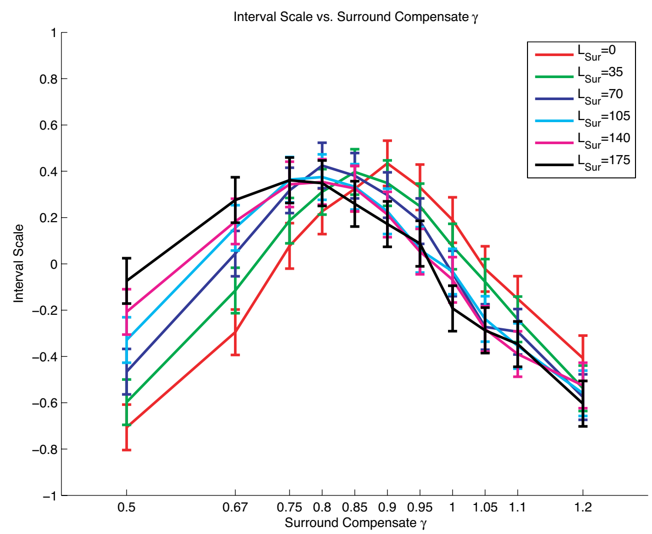


Figure 2. Interval scale vs. surround compensate γ under 6 different surround conditions.

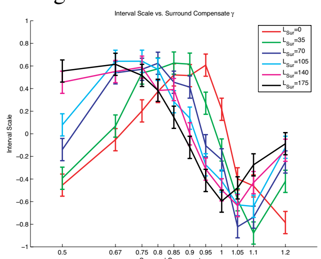
Figure 2 shows the interval scale along with 95% confidence limits for overall result average over four different scenes. In Figure 2, six different color-coded curves represent the results under different surround luminance conditions. The results clearly show that the observers most preferred the γ = 0.9 for the dark surround condition. The interval scales of either higher or lower than this γ value were gradually decreased. This suggests that if the iCAM06 was applied in preference reproduction, surround parameters can be set to 0.9. Figure 2 also shows that the shape of the curves for each surround condition is similar. They are all with single peak Gaussian like shape. In experimental instruction and assumption, the observer had in mind a reference-preferred image contrast and picked the image more close to it. This result indicated that the perceived image contrast with the peak valued γ is most similar to the reference preferred image contrast under each surround condition. The reference preferred image contrast is not changed over different surround conditions, therefore the perceived image contrast of the images with these peak γ under their corresponding surround conditions have same contrast appearance. The peak for each curve is shifted from higher valued γ to lower valued γ. This proved the Bartleson and Breneman's surround effect.

In this experimental setup, the 0 cd/m^2 surround condition is equivalent to dark surround in CIECAM models. While, the surround condition from 35cd/m^2 to 175cd/m^2 are matched to average surround in CIECAM models, which is greater than 20% of image white. Figure 2 shows the peak interval scale for 35 cd/m$_2$ corresponding to γ = 0.85. It shows that the surround effect is measurable in this experiment. But the result is different from Bartleson & Breneman's or Hunt's classical result and CIECAM models, it shows that Bartleson & Breneman's and CIECAM models are over predict the surround effect.

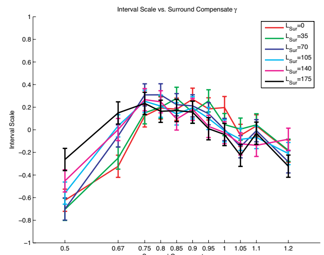
The surround setting in this experiment is much higher than CIECAM's average surround because the surround setting for current image display application is usually in lighter surround rather than dim or average. Results in Figure 2 show that the curve shape is more flat around the peak for high surround luminance levels (greater than 50% of image white). That means that the perceived image contrast changes caused by surround changes is visually equivalent for observers, and it also indicated that measuring surround effect would be more difficult under these light surround conditions.

Image dependence

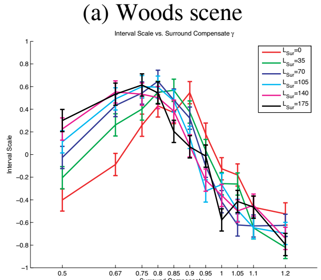
Figure 3 shows the interval scale along with 95% confidence limits for each scene. The results in Figure 3 show great difference among different scenes.



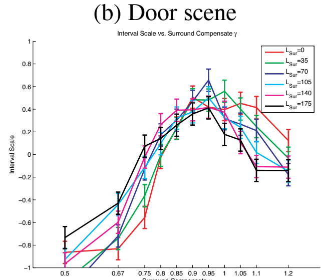
(a) Woods scene



(b) Door scene



(c) Desk scene



(d) Lake scene

Figure 3. Interval scale vs. surround compensate γ for each scene.

Figure 3 shows that the peak of the curve trend toward the lower γ value when the surround luminance increases. This result agrees with the results in Figure 2. But Fig. 3 shows each scene has its own peak values and curve shape. This indicates that the image content plays a very important rule in perceiving the image contrast. For example, in Fig. 3a the most high contrast image with γ = 1.2 is more preferred than γ = 1. The possible reason is that all detail in woods will be too dark to see when γ > 0.9, but the bright cloudy sky in the image will be the dominant object in the image in that case. Therefore, the observers will pick the cloudy sky to judge the contrast and find the image with γ = 1.2 is more preferable than the image with γ = 0.9.

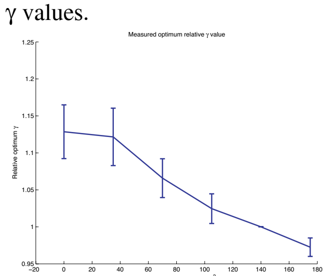
Another example is the "Door" scene in Fig. 3b. The curves are relative flat compare to other scene. This indicates that the perceived image contrast for this scene is visually equivalent for the observers. The possible reason about this confusion is the dominant part is the building and grass, which is the lighter part of the image, but not the dark door. The surround effect occurs because the dark area appears lighter while having little effect on the light area. When the dominant part in the image is the lighter part, the observers will find trouble to see the contrast changes when surround changes.

In Fig. 3d the curves are overlapped to each other. The possible reason for this overlapping is the dominant object is blue sky. When γ value changes the achromatic channel in IPT space, the perceived saturation of color will be changed at the same time. For some observers, the saturation of blue sky is the induction factor when judging the perceived image contrast.

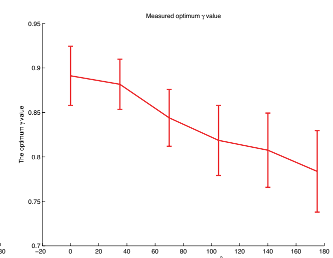
All those individual scenes have their own curve shape and characteristic. This confirms that the image content is very important on judging the image contrast.

Measuring the Compensate γ ratio for different surrounds

Although the interval scale in Fig. 2 shows the peak of the interval scale curve shifts when surround luminance level changes, it is not sufficient to get the optimum γ value from the peak γ on the curve for a given surround luminance level. The optimum γ value for a given surround may lie between two adjacent sampled γ values.



(a) optimum relative γ values

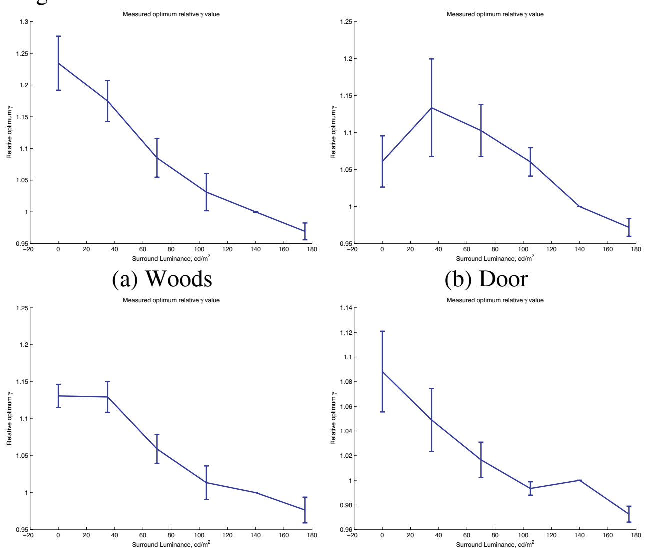


(b) optimum γ values

Figure 4. Measured optimum γ values and relative γ values. The error bar represent the standard deviation.

In order to measured the optimum γ value for each surround conditions; the observer's data was individually counted instead of making a frequency matrix. For a given surround condition, the single observer's data was counted to get which γ value is the most preferred. After all six preferred γ values for six surround conditions were got from this method, the average observer γ ratios over six surround conditions can be obtained. Furthermore, this ratio can be normalized to one surround condition before taking the observer average. The result of this measured γ ratio is shown in Fig. 4. Figure 5 shows the measured γ for each individual scene.

Figure 4a shows a linear relationship between the surround luminance levels and the optimum surround compensation γ values except the dark surround. Compare the result from Fig. 5b, the bias from the line in the dark surround was most contributed from the "Door" scene. This is an additional evident showing that the image content is very important factor to affect the perceived image contrast.



(a) Woods (b) Door

(c) Desk (d) Lake

Figure 5. Measured optimum γ values and relative γ values for each scene.

A simple linear model can be used in predicting the surround compensate factor γ value as defined in equation [4].

$$\gamma = -0.1356 * L_s + 1.137 \quad [4]$$

Where the L_s is the proportion of luminance of surround to the image white, γ is the exponent factor in achromatic channel in IPT space, see equation [3]. By this equation, the ratio of the light surround (100% of image white), average surround and dim surround is 1.0:1.10:1.14. This result is very close to the result from Daniels el at.. Their result was obtained from hard copy prints and the corresponding γ ratios are 1.0:1.09:1.16.

Conclusions

In this research, the surround effect on perceived image contrast and its application on color and image appearance models are reviewed. A paired comparison experiment was designed to measure the perceived image contrast under different surround conditions. A linear model to predict the surround compensation exponent factor was created from the experimental result. The optimum ratio of the light surround, average surround and dim surround is 1.0:1.10:1.14. The results confirm the Bartleson & Breneman's surround effect. It also confirms that the Bartleson & Breneman's or Hunt's and CIECAM models' surround compensation is over predicted. And the image content has very huge effect on the image contrast perception.

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