Journal of Imaging Science and Technology® 52(4): 040905–040905-9, 2008.

Investigation of Large Display Color Image Appearance II: The Influence of Surround Conditions

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Abstract. *The purpose of this work was to quantify the surround effect on the color image appearance of images presented on a large display. The appearance attributes colorfulness, contrast, and naturalness together with image quality were estimated under four surround conditions: Dark, dim, and bright surrounds (all excluding veiling glare), and a typical office environment (including veiling glare). The most interesting visual result was that the three illuminated surrounds caused dark images to have a reduction in all of the image appearances studied, compared with those under dark surrounds. Enhanced contrast, naturalness, and quality were perceived in dark surround conditions, whereas the most colorful appearance was seen with bright surrounds. The most critical attribute affecting image quality in all surrounds was naturalness. Empirical models were developed which took into account the significant visual phenomena revealed in this study to predict the effect of surround on the appearance of color images. © 2008 Society for Imaging Science and Technology.*
[DOI: 10.2352/J.ImagingSci.Technol.(2008)52:4(040905)]

INTRODUCTION

Large displays have recently become popular for a home theater, advertising, information display, and other applications. Images presented on large self-luminous displays are seen under diverse surround conditions. These look different due to changes in the level and color of the illumination in the surrounds. The reason for this phenomenon can be found in our eyes which contain mainly cone-shaped photoreceptor cells in the central 4° of the visual field and rod-shaped cells in the periphery. Cones detect color information whereas rods have monochrome sensitivity. The large number of connections between neighboring rods and cones in the retina can result in the appearance of colors in pictures being affected considerably by surrounds.[1]

In consideration of this aspect of our visual system, quantification of the perceived appearance variation influenced by the change in surround conditions is necessary for consistent image reproduction on displays seen in different environments. Additionally, establishment of the optimum viewing condition which provides enhanced image appearance is valuable for display users. Experiments were devised to achieve these two aims using a large display. In the first article[2] in this series, psychophysical experiments were conducted under a dark surround, in which 22 manipulations using three image parameters were applied to eight test images. Five image appearance attributes contributing to image quality were evaluated in order to reveal which attributes are important in controlling the image quality of a large display. From this preliminary work, colorfulness, contrast, and naturalness were chosen as key attributes affecting image quality.

The foundation of this study lies in many previous studies that attempted to quantify color appearance variations influenced by changes in surround conditions. Observers assessed color appearance attributes such as brightness and colorfulness under different surrounds. The experimental surround conditions investigated were selected based on the locations where the various imaging devices tended to be used.[1] For reflection prints, the average luminance of the surround is similar to that of the picture. For typical television viewing, the surround luminance is only about one tenth of the average picture luminance. For films projected in a darkened room, the surround luminance can be as low as about one hundredth of the average picture luminance. The surround effect on brightness and tone reproduction was well summarized by the Stevens[3,4] and Bartleson-Breneman[5,6] effects. It has been shown that dim (typical TV viewing) and dark surrounds could make the whole picture seem lighter. This effect was greater for dark parts of the picture than for light parts, therefore the dim and dark surrounds tended to reduce the apparent contrast of the picture. As a result, to obtain a picture that appeared to have the same tone reproduction of the scene as the original, dim and dark surrounds accordingly required higher gamma. For the surround effect on colorfulness, the dark surround reduced colorfulness, as discovered by Hunt,[7] Pitt and Winter,[8] and Breneman.[9] Color patches, color mosaics, and achromatic images were used as stimuli in all these past studies, rather than complex color images. It needs to be ascertained whether the same surround effects revealed previously can be applied to complex color images. In reality, what we perceive from color images is not simply colorfulness or brightness alone.

As display development moves towards larger, brighter, and wider color gamut technology, viewing is made practical for outdoor, as well as indoor, conditions. This trend requires that the surround condition, for which luminance is higher than that of the picture on the display, should be

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Received Jan. 22, 2008; accepted for publication Mar. 19, 2008; published online Jul. 17, 2008.
1062-3701/2008/52(4)/040905/9/$20.00.

Table I. Four surround conditions investigated for this study

Name	Surround ratio (S_R)	Veiling glare	Surround white
Dark	—	—	—
Dim	0.17	0%	33 cd m^{-2}, 2610 K
Bright	2.34	0.68%	448 cd m^{-2}, 6020 K
Office	0.30	1.32%	57 cd m^{-2}, 3387 K

studied for its effect on image appearance. Therefore, the current work has attempted to investigate changes in four image appearance attributes influenced by large luminance changes in surround conditions (dark, dim, and bright).

EXPERIMENTAL SETUP

Surround Conditions

The surround conditions used for this study were divided into two groups: Those including and those excluding veiling glare[10] from ambient light sources. Different brightness surrounds were then separated based on the surround ratio, S_R, which was calculated by dividing the luminance of the surround area by that of a reference white shown in the display area.[11] Three surrounds were defined: Average, dim, and dark for $0.2 \leq S_R < 1$, $0 < S_R < 0.2$ and $S_R \approx 0$. All three surrounds were investigated in this study. A bright surround, which was defined as $S_R > 1$, was also added.

The four viewing conditions investigated are summarized in Table I. The luminance of the display's reference white was 174 cd m^{-2}. The luminance and Correlated Color Temperature of the surround white were determined by measuring white paper at several positions around the display. Two tungsten lamps for the dim surround and 16 D65-simulator lamps for the bright surround were positioned behind the display facing the back wall. The color images reproduced on the display were not affected by the light sources due to there being little glare, however observers could perceive brightness variations in the surround. The three surrounds, "Dark," "Dim" and "Bright," belong to the condition excluding glare and their S_R values were 0, 0.17, and 2.34 respectively. A typical office environment was used for the surround condition which included glare and was named "Office." Three ceiling mounted fluorescent lamps were used but these were not directly above the display. Their combined S_R value was 0.3 corresponding to average conditions. The veiling glare was calculated by measuring the reference white of the display with and without ambient light, giving 1.32% in the Office condition and 0.68% in the Bright condition due to reflection from surrounding room walls.

Psychophysical Experimental Setting

In the first article of this research,[2] eight test images and their manipulations (22 versions per original image) were used as stimuli presented to observers for assessing their perception of the six image appearance attributes under the dark surround. To investigate the surround effect on image appearance, five images and 14 methods were chosen from the possible eight test images and 22 image manipulation methods. The five images were: *Fruits, Pier, Seashore, Park*, and *Kids*. The 14 image manipulation methods are summarized in Table II. Each method was labeled as follows: First, the image parameter controlled; second, the type of the manipulating function; and third, the amount of variation given to the original image. For example, SHFE1/5 is a sharpness manipulation (*S*) using a high-frequency emphasis filter (HFE) with a 1/5 cutoff frequency parameter. All of these images were displayed on a 42 in. Plasma Display Panel (Samsung, PPM42H3) at a resolution of 1024×768 pixels and viewed from a distance of 2 m. The reference white of this display was 174 cd m^{-2} with a correlated color temperature of 8940 K.

The three image appearance attributes (contrast, colorfulness, and naturalness) were found to be responsible for controlling image quality under the dark surround conditions.[2] Therefore, changes in these three attributes and image quality due to changes in the surround were measured in this study. The categorical judgment method with a nine-point category scale was applied to assess these four attributes. Thurston's Law of Comparative Judgment, Case V, was used to convert the observers' data into equal-interval scale values. Each image was assessed by 9–14 observers. Individual session contained 150 assessments (5 images $\times$ 15 manipulations $\times$ 2 image appearance attributes) and lasted for approximately 15 min. A total of 53,700 observations was completed.

RESULTS AND DISCUSSION

Observer Variations

The coefficient of variation (CV), which is a statistical measure to represent the agreement between two data sets, was used to compute inter- and intra-observer agreement. For the dark surround,[2] it was shown that observers performed similarly in terms of intra- and inter-observer agreement (i.e., within an observer and between observers) for colorfulness, contrast, and image quality. Table III compares the inter-observer agreements for the four attributes assessed under the four surround conditions. The smallest differences between the CV values of two different surrounds are found for contrast, whereas the largest differences were for naturalness. Overall, smaller CV values are seen in colorfulness and contrast than in naturalness and image quality for the dark, dim, and bright surrounds. It can therefore be presumed that naturalness and image quality were more difficult for observers to scale than colorfulness and contrast.

Optimum Surround Conditions for Image Appearance

To establish which surround conditions yielded the best image appearance (in terms of colorfulness, contrast, naturalness, and image quality), a paired samples *t*-test was conducted. A comparison was made of the observed differences between the mean of all the observers' results for any two surround scale values. This was done for each of the five

Table II. Image manipulations used to render each of the five test images to determine changes in perception of contrast, colorfulness, naturalness, and image quality under the four different surround conditions.

Lightness		Chroma		Sharpness	
Effect due to image manipulatons					
Decreasing lightness linearly	LL09 LL08	Decreasing chroma linearly	CL08 CL06	Sharpening using *CSF*[a]	SCSF
Increasing lightness contrast	LSS LSL	Increasing chroma contrast	CS	Sharpening using *HFEF*[a]	SHFE 1/5 SHFE 1/11
Decreasing lightness contrast	LISS LISL	Decreasing chroma contrast	CIS		
Dark pixel into lighter and light pixel into darker by *LCC*[a]	LLCC				

[a]*LCC*: Local Color Correction method, *CSF*: Contrast Sensitivity Function, *HFEF*: High Frequency Emphasis Filter.

Table III. Inter-observer agreements in terms of mean CV values (across all observers) for each of the four attributes assessed under the four surround conditions.

Inter-observer agreement	Dark	Dim	Bright	Office
Colorfulness	17	17	19	21
Contrast	18	18	19	19
Naturalness	25	19	24	21
Image quality	22	20	23	21

Table IV. Comparison of the four image-appearance attributes between two different surrounds in terms of *p* value. The surround shown inside a bracket provided enhanced image appearance.

	Between dark and each of the three illuminated surrounds			Between any two of the three illuminated surrounds		
	Dark and			Dim and		Bright and
	Dim	Bright	Office	Bright	Office	Office
Colorfulness	0.29	**0.00** (Bright)	0.44	**0.00** (Bright)	0.16	**0.00** (Bright)
Contrast	**0.00** (Dark)	0.31	**0.01** (Dark)	**0.00** (Bright)	0.29	**0.00** (Bright)
Naturalness	**0.00** (Dark)	0.15	**0.00** (Dark)	**0.00** (Bright)	0.33	**0.00** (Bright)
Image Quality	**0.00** (Dark)	**0.00** (Dark)	**0.00** (Dark)	**0.00** (Bright)	**0.00** (Office)	**0.00** (Bright)

original images and their 14 manipulations. Table IV summarizes the resulting *p* values at 0.05 significance level. In this analysis if the *p* value does not exceed 0.05, the image in one surround condition was perceived to have enhanced appearance over the other surround. The second to fourth columns show results comparing image appearances between the dark and each of three illuminated surrounds. The fifth to seventh columns report the results between two of the three illuminated surrounds. The *p* value in bold and the surround condition inside brackets indicate that a significantly enhanced image appearance was perceived under that surround than under the other being compared.

The dark surround provided more perceived contrast, naturalness, and image quality than any illuminated surround, whereas the bright surround proved to be the best environment for increased colorfulness. Enhanced appear-

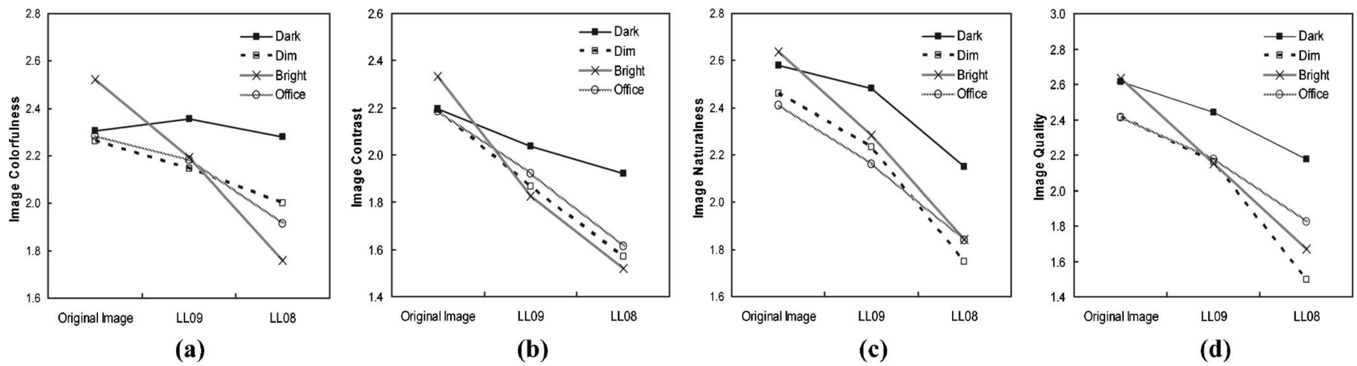

Figure 1. Changes in (a) image colorfulness, (b) image contrast, (c) image naturalness, and (d) image quality for the original and two darkened images against dark, dim, bright, and office surrounds.

ance in each of the four attributes was perceived for the bright surround, when comparing both the bright and dim surrounds and the bright and office surrounds. The reason for this visual effect in the dim and office surrounds can be explained by the desaturating effect of the illuminated surround. As a result of this effect, the preferred skin color presented on a television display viewed in dim tungsten ambient light requires higher purity than for a reflection print viewed in daylight.[12] The correlated color temperatures of the dim, office, and bright surrounds investigated were 2610, 3387, and 6020 K, respectively. Observers were adapted to dim and office surrounds which had low color temperatures, so the images seen on the display might look slightly bluish, and therefore have degraded image appearance. There was almost no difference between the dim and office surrounds in the perception of image appearance.

In summary, the dark surround is the viewing condition preferred by most observers in terms of contrast, naturalness, and image quality. If, however, observers want to experience a more colorful image appearance, the bright surround is recommended. The dim surround may inhibit observers from perceiving enhanced image appearance.

Significant Psychophysical Phenomena

This section discusses the particular manipulated images that were perceived to have significantly degraded or enhanced image appearance under each of the three illuminated surrounds as compared with those under the dark surround. To this end, a paired samples t-test was carried out by observing differences between two mean scale values (again for all observers). These comparisons, between the dark surround and each of the dim, bright, and office surrounds, were done for all manipulated variants of each of the five test images. The main results will be described in terms of three visual phenomena.

Figures 1(a)–1(d) plot three mean scale values (across five test images) against the original and two images darkened by 10% (LL09) and 20% (LL08) for the four surrounds in terms of colorfulness, contrast, naturalness, and image quality, respectively. The four surrounds are expressed using different symbols and lines so that variations in image appearance against the four surrounds caused by changes in image lightness can be compared. Results of the paired samples t-test are also summarized in Table V using p values at 0.05 significance level. Values written in bold indicate that there was a statistical image appearance difference between the dark and each of the dim, bright, and office surrounds.

The first unique visual phenomenon was that there was a clear surround effect on the darkened images resulting in them appearing to be less colorful, less natural, and to have lower contrast and image quality under the illuminated surrounds than under the dark surround. Note that all the p values in the image darkened by 20% (LL08) are equal to or smaller than 0.05 for all four attributes.

In Fig. 1(a), colorfulness is not affected by lightness reduction (LL09 and LL08) for the dark surround, however, a lowering in the colorfulness for the three illuminated surrounds can be clearly seen. In Fig. 1(b), image contrast decreases when the overall lightness of an image is decreased by 20%, and this can also be seen more distinctly for the dim, bright, and office surrounds than for the dark surround. The decreased lightness image is viewed as being darker and less colorful, as seen in Fig. 1(a). Hence, it may be that the lower perceived image contrast was due to the image appearing darker and less colorful. The decreased contrast seen in the decreased lightness images is supported by the Stevens effect,[4] which states that when looking at a darkened image a decrease in the brightness of whites and an increase in the brightness of blacks are observed, resulting in lower perceived contrast. Fig. 1(c) again demonstrates the trend in lowering naturalness with decreasing lightness more apparently for the dim, bright, and office surrounds. Fig. 1(d) shows that as lightness decreases linearly, image quality degrades gradually for all the surrounds; however, it is again more obvious for the dim, bright, and office surrounds. This tendency is due to the decreases found in the three perceptual appearances forming image quality. It is believed that the darkened image was perceived to have a poorer appearance for the dim, bright, and office surrounds was because observers perceive a much darker image for these illuminated surrounds than for the dark surround.

The second visual phenomenon can also be found in Fig. 1(a): the original image is perceived to be more colorful for the bright surround than for the dark surround. This

Table V. Resulting p values of paired samples t-test in the comparisons between under the dark surround and each of the dim, bright, and office surrounds for the four image-appearance attributes.

	Image colorfulness			Image contrast			Image naturalness			Image quality		
	Orig.	LL09	LL08	Orig.	LL09	LL08	Orig.	LL09	LL08	Orig.	LL09	LL08
Dark and Dim	0.28	0.07	**0.01**	0.49	0.16	**0.02**	**0.01**	**0.03**	**0.00**	0.06	**0.03**	**0.01**
Dark and Bright	**0.01**	0.10	**0.00**	0.13	0.05	**0.01**	0.17	0.06	**0.01**	0.42	**0.00**	**0.00**
Dark and Office	0.38	0.11	**0.03**	0.47	0.21	**0.05**	**0.00**	**0.00**	**0.04**	**0.04**	**0.02**	**0.02**

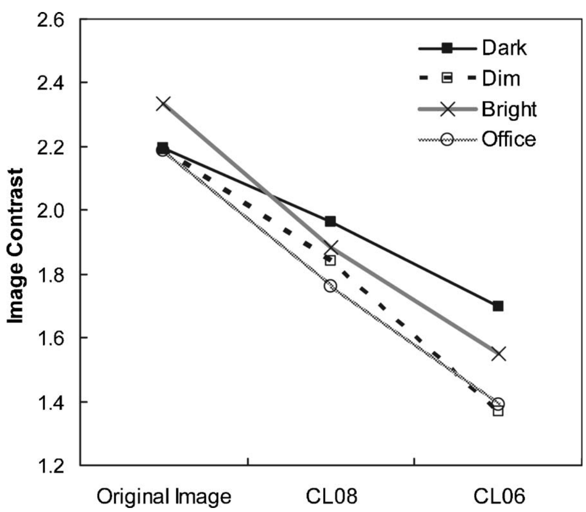

Figure 2. Change of image contrast in the original and two darkened images for each of the dark, dim, bright, and office surrounds.

result is consistent with the findings of Hunt,[7] Pitt and Winter,[8] and Breneman.[9]

Figure 2 illustrates the third visual phenomenon by plotting the mean scale values of image contrast for the four surrounds against both the original and two images having chroma decreased by 20% (CL08) and 40% (CL06). The four surrounds are depicted using different symbols and lines. The results of the paired samples t-test are also summarized using p value at 0.05 significance level in Table V. As chroma is decreased linearly, perceived contrast becomes lower for all surrounds as shown in Fig. 2. This result can be explained by the Helmholtz-Kohlrausch effect[13] by which more colorful colors look brighter, and by the Stevens effect[4] by which brightness (or lightness) contrast increases with increasing luminance. A set of images with decreasing colorfulness can therefore appear to get gradually darker and also to have lower contrast. This phenomenon is more apparent for the dim and office surrounds, as evidenced by the p values being less than 0.05 for the CL06 image in Table VI.

Modeling the Surround Effect

The main visual phenomena having statistical significance within the scope of the psychophysical experiments conducted under the four surround conditions are summarized below.

Table VI. Resulting p values in the comparisons between dark and each of the dim, bright, and office surrounds for image contrast.

	Image contrast		
	Orig.	CL08	CL06
Dark and Dim	0.49	0.08	**0.01**
Dark and Bright	0.13	0.21	0.08
Dark and Office	0.47	**0.02**	**0.01**

(1) The darkened images looked less colorful, less natural and to have lower contrast, resulting in a lower image quality under the dim, bright, and office surrounds than under the dark surround.
(2) Images appeared more colorful under the bright surround than under the dark, dim, and office surrounds.
(3) Images having decreased chroma looked to have less contrast under the dim and office surrounds than under the dark surround.

Surround effects on the four image appearance attributes (colorfulness, contrast, naturalness, and quality) will be modeled in order to take into account these three results. Therefore, the model developed in the current work is not complete in the sense that it is unable to predict more diverse surround effects on image appearance beyond the scope of this work.

Surround Effect on Image Appearance for Darkened Images

The developed model predicts the degree of reduction in the four image appearance attributes. This reduction occurs when darkened images are viewed under the illuminated surrounds, as compared to those seen against the dark surround. The amount of the reduction is dependent not only on the surround condition, but also on the lightness reduction ratio of an image. For all surrounds, the mean scale values of both the original and the two images that were darkened by 10% and 20% were all normalized using the mean scale value of the original image in the dark surround. Consequently, the variations in the four attributes affected by changes both in surround conditions and image lightness can be determined with reference to the original image viewed under the dark surround.

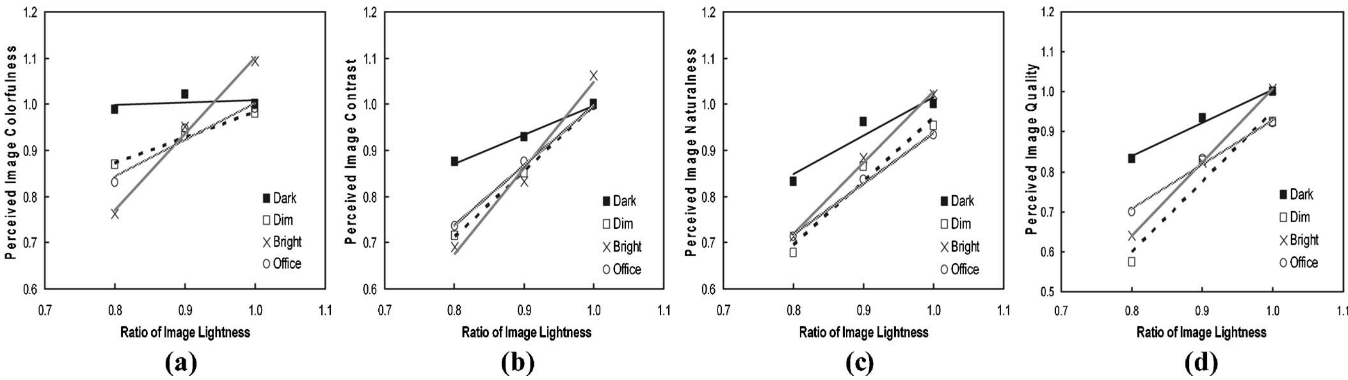

Figure 3. Normalized scale values of (a) image colorfulness, (b) image contrast, (c) image naturalness, and (d) image quality against image-lightness ratios (0.8, 0.9 and 1) for the dark, dim, bright, and office surrounds.

Table VII. Slope and intercepts of the four models for predicting the surround effect on each of colorfulness, contrast, naturalness, and image quality for darkened images.

Each of the four image-appearance attributes = aximage − lightness ratio + b

	Colorfulness		Contrast		Naturalness		Image quality	
Surround	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
Dark	0.06	0.95	0.62	0.37	0.84	0.18	0.84	0.17
Dim	0.56	0.42	1.42	−0.42	1.38	−0.41	1.75	−0.80
Bright	1.65	−0.55	1.86	−0.81	1.54	−0.51	1.84	−0.83
Office	0.80	0.20	1.31	−0.31	1.11	−0.17	1.12	−0.19

Table VIII. Slopes and intercepts of the four models for predicting the surround effect on contrast for images having decreased chroma.

Surround	*a*	*b*
Dark	0.57	0.43
Dim	0.94	0.07
Bright	0.89	0.16
Office	0.90	0.09

The normalized scale values of the four surrounds are plotted against the image lightness ratios (1, 0.9, and 0.8) for colorfulness, contrast, naturalness, and image quality in Figures 3(a)–3(d) respectively. The images having lightness ratios 0.9 and 0.8 correspond to the images darkened by 10% and 20%, respectively. The best-fit lines in each of the four surrounds are shown; their slopes and intercepts are summarized in Table VII.

The influence of different surround conditions on colorfulness, contrast, naturalness, and image quality can be predicted using the four equations given in Table VII for images varying in the lightness domain. For example, any test image seen under a dark surround may be considered to be a reference. This reference image may appear 10% more colorful under a bright surround than under a dark, dim, or office surround, which indicates that under the bright surround the increase in image colorfulness can be predicted by the model. The image darkened by 20% may appear 13% less colorful under the dim surround and 23% less colorful under the bright surround than under the original dark surround condition. Also, this darkened image may appear 15% less natural under the dark surround and 30% less natural under the dim, bright, or office surround.

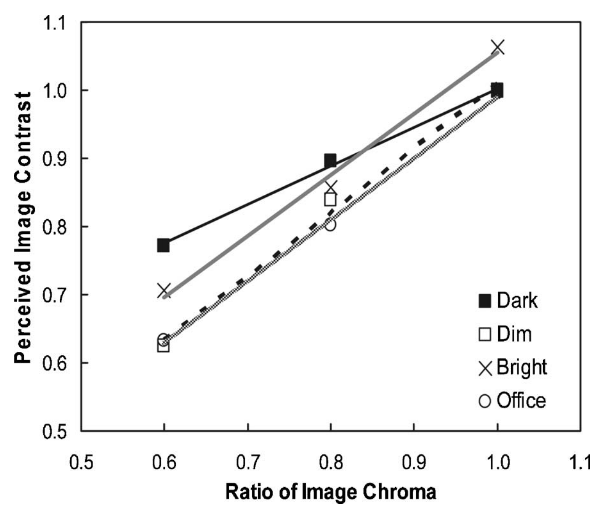

Figure 4. Normalized scale values of image contrast against image-chroma ratios (0.6, 0.8, and 1) for the dark, dim, bright, and office surrounds.

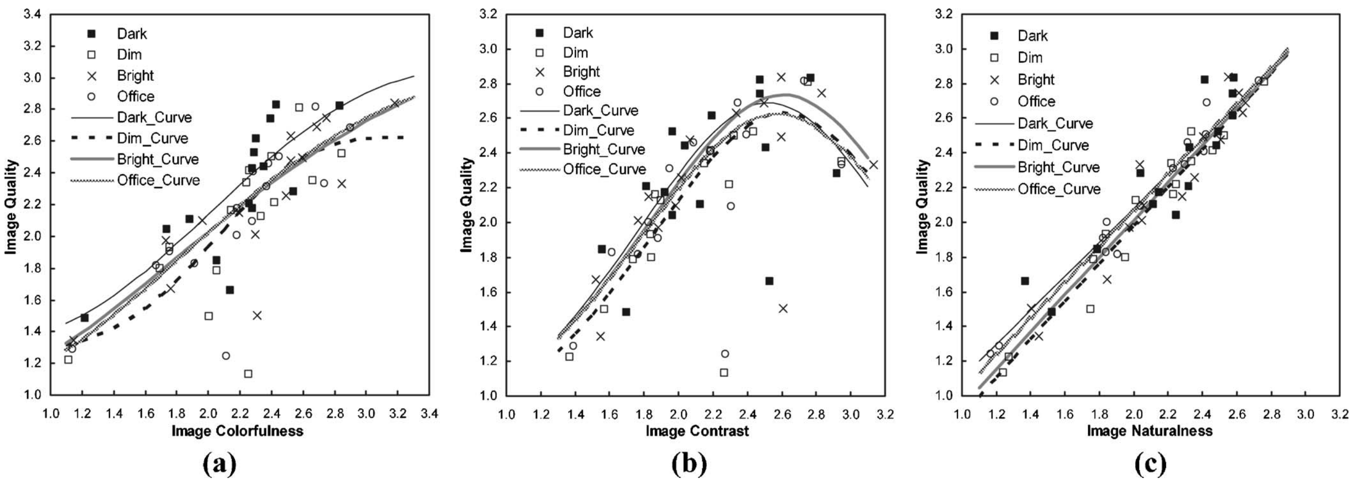

Figure 5. Mean scale values (across five test images) for image quality vs mean scale-values for (a) image colorfulness, (b) image contrast, and (c) image naturalness. The data are viewed separately with respect to each of the dark, dim, bright, and office surrounds. Also shown are suitable data-fitting curves.

Surround Effect on Image Contrast for Images Having Decreased Chroma

The model developed in this section will take into account the following visual phenomenon: Images having their chroma decreased by 20–40% had a tendency to appear to have reduced image contrast under dim, bright, and office surrounds than they appeared to have under the dark surround.

Image contrast was altered both by different surround conditions and by chroma reduction ratio in an image. For all surrounds, the mean scale values of both the original and the two images that had chroma reduced by 20% and 40% were all normalized using the mean scale value of the original image in the dark surround. The normalized contrast scale values in the four surrounds are plotted against the image chroma ratios (1, 0.8, and 0.6) in Figure 4. Images having chroma ratios of 0.8 and 0.6 correspond to a reduction in chroma by 20% and 40%. The best-fit lines in each of the four surrounds are shown; their slopes and intercepts are summarized in Table VIII.

The four equations given in Table VIII can be used to predict the change in perceived image contrast resulting from the change in surround conditions for the images manipulated in chroma domain. For example, any test image seen under a dark surround can be considered to be a reference image. An image having a 30% decrease in chroma compared with the reference image may appear to have a 17% lower image contrast under the dark surround, a 30% lower image contrast under the dim and office surrounds, and a 20% lower image contrast under the bright surround.

MODELS FOR IMAGE QUALITY

Relationships between Image Quality and Other Image Appearance Attributes

Psychophysical relationships are generated between image quality and each of the perceived colorfulness, contrast, and naturalness for each of the four surrounds in Figures 5(a)–5(c), by plotting the mean scale values (across five test images) for image quality respectively against those for colorfulness, contrast, and naturalness. The data points in the figures represent the original image and its 14 manipulations. To clearly demonstrate how the variations of colorfulness, contrast, and naturalness influence image quality, the appropriate functions were fitted to the data points for each of the four surrounds. These fitted curves are also shown in the figures.

Generally, changes in image quality affected by changes in each of colorfulness, contrast, and naturalness are not likely to be perturbed by different surround conditions. The image quality-colorfulness relationship in Fig. 5(a) has a tendency for image quality first to rise and then reach a peak as colorfulness increases. The maximum image quality occurs for a specific contrast in Fig. 5(b). A similar trend can be found in work elsewhere.[14] As naturalness increases, image quality increases linearly as shown in Fig. 5(c).

Key Image Appearance Attributes Affecting Quality

Perceived colorfulness, contrast, and naturalness were important image appearance attributes for determining image quality under dark surrounds.[2] Multiple regression analysis was conducted in order to examine whether these three key attributes are also still significant in predicting image quality under the three illuminated surround conditions studied here. Table IX introduces the coefficient for each independent variable (colorfulness, contrast, and naturalness) and the multiple correlation coefficient for each empirical image quality model against each of the four surrounds. The coefficient for each independent variable written in bold is statistically significant. The image quality model, which is given in the last row, were derived using all visual data for the four surround conditions.

The psychophysical relationships between image quality and each of colorfulness, contrast, and naturalness were not likely to be affected by the change in surround conditions, as was explained in the previous section. Thus, the derived image quality model for the dark surround (second row) was applied to predict the image quality for the three illuminated surrounds. Multiple regression coefficients were then com-

Table IX. The empirical image quality models for the dark, dim, bright, and office surrounds using three independent variables (naturalness, contrast, and colorfulness).

Image Quality = a × Naturalness + b × Contrast + c × Colorfulness + d					Multiple regression coefficients		
	a	*b*	*c*	*d*	By the model developed using the data for individual surrounds	By the model developed using the data for all surrounds	By the model developed using the data for the dark surrounds
Dark	**0.78**	**0.27**	**0.16**	**−0.38**	0.94 (7)	0.93 (8)	0.94 (7)
Dim	**1.07**			−0.15	0.94 (9)	0.93 (10)	0.92 (11)
Bright	**0.79**	**0.16**	**0.18**	**−0.29**	0.97 (6)	0.96 (6)	0.96 (7)
Office	**0.84**		**0.19**	−0.02	0.94 (8)	0.94 (8)	0.93 (9)
All	**0.84**	**0.16**	**0.12**	**−0.24**	0.94 (8)	0.94 (8)	0.93 (8)

puted between the predictions made by the model for the dark surround and the observer-judged image quality data for each of the dim, bright, and office surrounds; these are given in the rightmost column. The model derived using the data collected for all surrounds (bottom row) was used to predict image quality for each of the four surrounds. Multiple regression coefficients were then computed between the predictions made by this model and the observer-judged quality data for each of the dark, dim, bright and office surrounds; these are shown in the second column from the right in Table IX. The coefficient of variation (CV) was calculated to evaluate the agreement between the observer-judged quality data and the predicted data from the derived empirical image quality models. The calculated CV values are given inside brackets in the table.

In the determination of image quality, naturalness itself is a sufficient independent variable for the dim surround; naturalness and colorfulness are sufficient for the office surround. All three attributes are required for the dark and bright surrounds. Therefore, naturalness may be the most critical image appearance attribute affecting image quality for all surrounds, followed by colorfulness. The office surround includes veiling glare that is added to the displayed images. This leads to a reduced dynamic range due to decreased lightness in highlight areas, and a loss of dark detail in images.[15] These effects can be compensated for by increasing colorfulness rather than by enhancing contrast for the office surround. This is because more colorful images appear brighter and so seem to have increased dynamic range and enhanced shadow-detail reproduction. Thus, aside from naturalness, colorfulness may be a more important factor in image quality than contrast for typical office environments.

The multiple regression coefficient and CV value for each of the four surrounds are almost identical to those computed between the experimental data and those predicted by the model developed using either the data for the dark surround (in the rightmost column of Table IX), or the data for all surrounds (in the second column from the right). This suggests that the two models—which have three independent variables (colorfulness, contrast, and naturalness), whether derived using the data for the dark surround or for all the surrounds—are applicable to all surround conditions. However, there are exceptions that are incompatible with the developed model, and these cases were modeled in the section Modeling the Surround Effect.

We conclude that the model derived using the collected data for the dark surround can be applied to illuminated surrounds. An image quality model will therefore be developed using the experimental data accumulated for the dark surround and reported in a future paper in this series.

Miscellaneous Psychophysical Phenomena in Image Contrast

Bartleson and Breneman[5] showed that a bright surround caused dark areas in an image to appear darker than when seen under a dark surround, whereas the perceived lightness of light areas remained constant. This effect leads to a higher perceived image contrast for bright surrounds compared to dark surrounds, however, it was only demonstrated for achromatic images. To examine whether this effect can also be found for color images, Figure 6 compares the perceived contrast between the bright and dark surrounds for the original image and two images manipulated by lightness-based sigmoid (LSL) and inverse-sigmoid (LISL) functions. The data points are mean scale values of the five test images and error bars are 95% confidence intervals of the mean scale values. The LSL made dark areas of the original image darker and light areas lighter, while the LISL generated the opposite effect.

There is no significant image-contrast difference between the dark and bright surrounds, as shown in Fig. 6 by similar mean scale values and error bars for the original, LSL, and LISL images. Note that there was, however, significant image contrast difference between the dark and bright surrounds for the image darkened by an overall 20%. Therefore, it may be said that the Bartleson–Breneman effect is not maintained when only some parts of the color image appear darker. The reason for this result may be that the image size

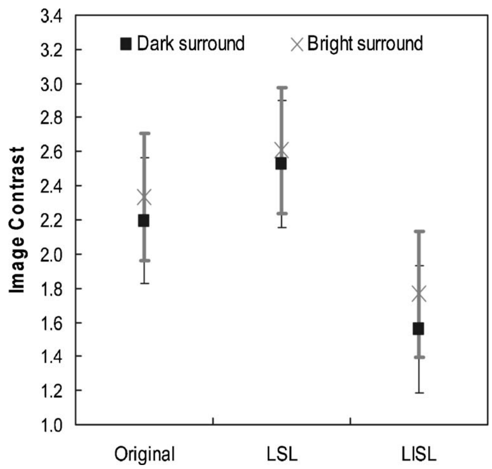

Figure 6. Comparison of image contrast between the dark and bright surrounds for the original, LSL, and LISL images.

in the present study (42 in.) was relatively large, so that observers may not have noticed the variation in perceived lightness that occurred for dark and light areas within an image due to changes in the surround luminance.

CONCLUSIONS

The present work follows on from the first paper in this series which determined the image appearance attributes significantly influencing the image quality of a large display viewed under a dark surround. The three key attributes revealed were: Colorfulness, naturalness, and contrast. In the current work, these were again evaluated under three illuminated surround conditions together with image quality so as to quantify the surround effect on color image appearance. The experimental surround conditions were categorized into two groups: Viewing environments with and without veiling glare. The surround luminance was changed from dark to dim to bright for the environment without glare. A typical office viewing condition was used for the environment with glare. Among the four surround conditions studied, the dark surround provided superior contrast, naturalness, and image quality, over the illuminated surrounds, whereas the bright surround could offer the most colorful appearance.

Three main visual phenomena were identified: (1) darkened images appeared to be less colorful, less natural, and to have lower contrast and quality under the dim, office, and bright surrounds than under the dark surround; (2) images looked more colorful under the bright surround than under the dark surround; and (3) images having decreased chroma were perceived to have less contrast under the dim and office surrounds than the dark surround.

These distinct surround effects were modeled. To represent the first and second phenomena, four models for the dark, dim, bright, and office surrounds were developed using image lightness ratio as an independent variable. The amount of degradation or enhancement of the four perceptual attributes could be determined for images viewed under any of the illuminated surrounds compared with those under the dark surround. For example, images under a bright surround may be perceived to be 10% more colorful than those under a dark surround. Four models for the four surrounds were made to account for the third phenomenon using image chroma ratio as an independent variable.

Image quality models were developed for the four surround conditions using multiple regression analysis. For all surround conditions, the most important perceptual attribute was naturalness, followed by colorfulness, and contrast. The psychophysical relationships between image quality and each of colorfulness, contrast, and naturalness were not influenced by changes in surround conditions. The result also demonstrated that the image quality model, which had been derived using the data for the dark surround and which had three independent variables (colorfulness, contrast and naturalness), should be applicable to all surrounds except those cases having significant, unique surround effects, as were summarized earlier. Therefore, in future work we will develop image appearance models capable of predicting colorfulness, contrast, naturalness, and image quality using color appearance attributes such as lightness and colorfulness.

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