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Considering the Surround in Device-Independent Color Imaging

When viewing images, the relative luminance of the surround has a profound impact on the apparent contrast of the image. For this reason, photographic transparencies intended for projection in a darkened room are produced with an objective contrast substantially higher than that necessary for optimum reproduction as prints viewed in an illuminated surround. The dark surround causes the image elements to appear lighter and this effect is stronger for darker colors resulting in a loss in perceived contrast. This effect is also of great importance in device-independent color imaging since resultant images might be observed in a wide variety of media and viewing conditions. Research on psychophysical scaling of brightness and lightness and the effects of background and surround relative luminance on lightness and chroma is reviewed. The importance of this research for device-independent color imaging systems is described along with the prediction of these effects using the RLAB color-appearance model. Finally, experiments testing the use of RLAB and other color-appearance models in cross-media color reproduction applications are described.

Key words: Color Appearance, Color Reproduction, Brightness and Lightness Scaling.

INTRODUCTION

If the perception of lightness were a function of a single physical variable such as relative luminance, then the tone-scale reproduction of images in various media would be greatly simplified. One would only need to reproduce the relative luminances of the original on the reproduction to assure that the perceived lightness was accurately reproduced. Instead, the perception of lightness depends on several physical variables including the absolute and relative luminances of the stimulus, the background, and the surround (as well as several others). These interactions can be described more simply by stating that lightness depends on the viewing conditions as well as the relative luminance of the stimulus. Thus it becomes necessary to attempt to derive psychophysical relationships between the perception of lightness and this array of physical variables. Such relationships become of critical importance when one attempts to reproduce the lightness scale of an image (or original scene) in a disparate set of viewing conditions.

As an example, consider the comparison of a photographic print viewed in typical illuminated surroundings and a photographic transparency projected in a completely darkened room. If the transparency were produced such that it had the same relative luminances as the print for each image element, then it would appear to be of substantially lower contrast than the print. This is because the dark surround of the projected transparency produces a decrease in perceived contrast. To produce a projected transparency with the same appearance as the print, it becomes necessary to understand the relationship between perceived lightness and the image surround and compensate appropriately. Analogous situations arise in electronic imaging systems. Users view and reproduce images in a wide variety of media and viewing conditions. If these users desire reproductions with similar appearances in all of these media, then proper consideration must be made for changes in the viewing conditions such as the white point, luminance level, and surround. This article concentrates on the effects of surround relative luminance on the lightness contrast and chroma of images. It begins with a review of research on psychophysical scaling of brightness and lightness and the effects of background and surround relative luminance on lightness and chroma. Then the importance of this research for device-independent color imaging systems is described along with the prediction of these effects using the RLAB color-appearance model.

As with any discussion of color-appearance phenomena, it is important that the terms being used are carefully defined and understood. Thus several terms of importance in this article are defined below. The stimulus areas being considered are not universally well defined. The following definitions adapted from Hunt[1] seem to be the most universally agreed upon.

> *Stimulus:* Typically a uniform patch of about 2° angular subtense.
>
> *Background:* The environment of the stimulus being considered, extending typically for about 10° from the edge of the stimulus in all directions.
>
> *Surround:* The field outside the background.

In addition, it is critical to define the physical and perceptual terms used to describe appearance phenomena. The following definitions, from the International Lighting Vocabulary,[2] are used throughout this article.

Brightness: Attribute of a visual sensation according to which an area appears to emit more or less light.

Lightness: The brightness of an area judged relative to the brightness of a similarly illuminated area that appears white or highly transmitting.

Luminance: A physical measure of the stimulus with units of cd / m^2.

It should be carefully noted that the terms brightness and lightness refer to visual perceptions. It is common (and erroneous) practice in the imaging fields to use the terms luminance and brightness interchangeably or to refer to digital values of image elements as "brightnesses." Such practice ignores the complex and nonlinear relationships between luminance and brightness and between digital values and the luminance produced on a given imaging device. Lastly, it is critical to understand the usage of the term contrast. In this article, the following definition of contrast is used.

Contrast: 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.

Often contrast is expressed as the slope of this relationship on log-log coordinates. For example, in photography contrast is defined as the slope of the relationship between density (logarithmically related to reflectance or transmittance) of the reproduction as a function of log exposure (illuminance multiplied by time) and the term gamma is used. A similar use of the term gamma occurs in the description of CRT displays where gamma is used to denote the exponent of a power function relating display luminance to video voltage. (Note that the exponent of a power function is equivalent to its slope on log-log coordinates.) The usage of the term contrast in this article differs from that often used to describe stimuli in visual science. The latter being a measure of the difference between minimum and maximum luminances in a stimulus.

BRIGHTNESS AND LIGHTNESS SCALING

Before examining the effects of background and surround on the perception of brightness and lightness, it is worthwhile to briefly review the general results of brightness and lightness scaling under constant viewing conditions. Two of the most often cited papers on the topic of brightness scaling are those by Stevens[3] and Stevens and Stevens.[4] In the first, entitled "To Honor Fechner and Repeal His Law," Stevens describes the utility of a power function to describe "the correct relation between the apparent magnitude of a sensation and the stimulus that causes it."[3] Stevens presented a table of exponents for the power function relating 22 different perceptions to stimulus magnitude including an exponent of between 0.33 and 0.50 for the perception of brightness. Figure 1a illustrates Stevens' power law relationship between the relative luminance of a stimulus and its relative brightness with an exponent of 0.33. Figure 1b shows the same relationship on log-log coordinates illustrating the convenient feature that a power function becomes a straight line on such a plot. Stevens also showed that the exponent for brightness depended on viewing conditions such as the adaptation level as described below.[4]

The compressive response for lightness (relative brightness) described by Stevens and illustrated in Fig. 1a is pervasive throughout the literature.

An interesting summary of lightness scaling results is presented by Wyszecki and Stiles.[5] They present a plot of lightness scales as a function of relative luminance from 6 different studies. The lightness scale values vary by nearly 30% of the range at some relative luminances. This illustrates that while all of the studies show a compressive response that could be well-modeled with a power function, the precise exponent varies substantially.

One of the most notable lightness scales is the Munsell value scale. It is often cited as a perceptually uniform lightness scale for small patches on a medium gray background. Since the Munsell renotation in 1943,[6] the Munsell value scale has been specified with a 5th-order polynomial that allows reflectance to be calculated as a function of Munsell value. The history of such a complex equation that cannot be inverted is a bit of a scientific curiosity. While Stevens did not make his compelling case for the power law until 1960,[3] a power relationship for Munsell value was suggested much earlier. The original data for the value scale were published in 1933 by Munsell, Sloan, and Godlove.[7] Godlove examined various equations describing the visual data in the second part of that paper, also published in 1933.[8] Godlove evaluated 7 different functions including a power function, referred to as the Plateau-Munsell equation, that described the data extremely well. Here, the original Munsell data are again examined with respect to some recent equations. Figure 2a illustrates the average data[7] along with the adopted 5th-order polynomial.[6] It is clear that the 5th-order function does not describe the visual data as well as might be expected. This is likely due to some adjustments that were made in the renotation.[6] In fact, the CIELAB lightness equation, L*,[9] predicts the original data better than the 5th-order polynomial of the Munsell renotation. This is illustrated by Fig. 2b in which the Munsell value data are plotted as a function of CIELAB L*. Further analyses were completed to evaluate how well such equations fitted the data with respect to visual uncertainty in the original experiments. Figure 3 shows the individual results for each of the 6 observers that took part in the experiment[7] along with the predictions of 3 equations. Each of the 3 equations predict the data well. CIELAB L* predicts the data best with an RMS error of 0.09 in Munsell value. The best-fitting power function (exponent = 0.42) and the modified RLAB L^R equation[10] (also a power function with an exponent of 0.43) have RMS errors of 0.24 and 0.26 respectively. The 5th-order polynomial used in the Munsell renotation has an RMS error of 2.15 value steps with the original data. The conclusion from the various historical data and analyses is that the perception of lightness can be well-described by a power function, but the exponent is highly dependent on the particular viewing conditions involved.

The compressive relationship between relative luminance and perceived lightness has been put to effective use in the development of color spaces. This use has not been limited to just the lightness dimension; the compressive response has been useful in the other two dimensions of color space as well. This was first brought to fruition by Adams in his truly noteworthy paper of 1942.[11] In it, Adams described a color space constructed by plotting differences of CIE tristimulus values Z-Y versus X-Y. Adams further enhanced the space by transforming the tristimulus values through the Munsell value function to construct what he called the chromatic value diagram. Surprisingly, contours of constant Munsell chroma and hue plotted very uniformly in the chromatic value diagram thus indicating that the visual system includes a compressive response for the chromatic mechanisms as well as the lightness mechanism. Adams chromatic value diagram is a direct predecessor of the CIE 1976 L*a*b* color space (CIELAB).[9]

In CIELAB the Munsell value function has been replaced with a modified cube-root power function, which, as illustrated above, actually better describes the original Munsell data. The L* dimension is a cube-root function of relative luminance and the a* and b* dimensions consist of differences in the cube-roots of the X, Y, and Z tristimulus values as envisioned by Adams. Thus the compressive power-function-type response has found great utility in the prediction of hue and chroma, as well as lightness.

The successful uses of a compressive function to model human color perception described above all rely on the assumption that the viewing conditions are constant. For example, CIELAB predicts the appearance of Munsell colors well for a particular luminance level, daylight illumination, and medium gray background and surround. If any of these attributes of the viewing conditions are changed, the accuracy of the CIELAB prediction decreases since the CIELAB equations contain no parameters to account for such changes. As illustrated below, such models can be extended in a straightforward manner to account for changes in viewing conditions. This article concentrates on changes in background and surround with some discussion of luminance-level effects. The effects of chromatic adaptation have been discussed elsewhere.[12,13,14]

BACKGROUND EFFECT ON LIGHTNESS

The effect of changing the relative luminance of the background on the perceived lightness of a stimulus is well known. It can be illustrated by cutting a two small pieces from the same gray paper and placing one on a white background and the other on a black background. The gray paper on a white background will appear significantly darker than the same gray paper on a black background. This effect, often referred to as lightness induction or simultaneous contrast, can also be illustrated by displaying similar stimuli on a computer graphics display.

A second effect of changing background relative luminance, perhaps not as well known, is referred to as crispening. Crispening refers to the observation that the apparent lightness difference between two stimuli will be greater if the stimuli have lightnesses near that of the background than if their lightnesses differ substantially from the background. Semmelroth[15] reviewed some of the data on crispening and proposed equations that predict the effect. Figure 4 illustrates perceived lightness as a function of relative luminance for backgrounds of 3 different relative luminances according to Semmelroth's equations. The significant increase in the slope of the functions about each of their respective background relative-luminance values illustrates the crispening effect. The overall vertical shift of the functions indicates induction.

The background effects of induction and crispening are important for understanding the appearance of simple stimuli on various backgrounds. However, these effects become less important in cross-media image reproduction since the objective is usually to produce a visually equivalent reproduction of the original image and, therefore, the background effects for each image element are constant. Instances in which background effects might become important include applications in which users want to select a color from within an image and reproduce it in a different context and cases in which the size of the image (in angular subtense) changes significantly from original to reproduction.

In related experiments, Stevens and Stevens[4] measured the effects of adaptation on brightness scaling (and lightness through normalization of the scales) by making very large changes in the luminance of the background.

Stevens and Stevens found that the results could be described in the context of the power law. As the adapting background increased in luminance from dark to 97dB, the exponent increased from 0.33 to 0.44. This relationship is illustrated in Fig. 5 where the relative brightness is plotted as a function of relative luminance for each of the 4 adapting backgrounds used by Stevens and Stevens. Stevens and Stevens preferred to use logarithmic dB units for measuring luminance. On their scale 1 cd/m^2 is equal to 65 dB. The results, if applied to images, would indicate that perceived contrast decreases as the luminance of the adapting background decreases. A result similar to that found for surround changes. Stevens and Stevens[4] predicted their results using a variable exponent in a power-function relationship. In a related series of studies, Jameson and Hurvich[16,17] collected similar data. However, their results did not follow the power-law relationship, but were better modeled with an equation that included a subtractive term that increased with increasing background luminance. Given the general agreement in the type of effect and the wide variation in lightness scaling experiments, the differences between the two models is not likely to be of significant importance in device-independent color imaging applications (although it might be critical in understanding the human visual system).

SURROUND EFFECT ON LIGHTNESS

The realization that the psychophysical characteristics of perceived lightness are important for image reproduction dates back to the work of Jones on the theory of photographic tone reproduction.[18,19] Jones developed a graphical technique for the optimization of photographic systems that allowed the desired luminance reproduction characteristics to be achieved. This was outlined in Jones' theory and techniques for objective tone reproduction.[18]

However, Jones also realized the importance of the observer in image reproduction and the necessity to include an understanding of the psychophysical response.[19] Thus, he extended his techniques for objective tone reproduction to those for subjective tone reproduction in which the nonlinear relationships between relative luminance and lightness could be considered and he laid the groundwork for future work that would account for differences in viewing conditions between the original scene and reproduction.

Based on the pioneering work of Jones and others, the photographic industry developed systems that produced images that were optimum reproductions of original scenes well before the perceptual effects that influenced the results were understood, or even measured. The result is that when scenes are reproduced on transparency film, to be projected in a darkened room, the physically-measured contrast, expressed in logarithmic coordinates, must be about 1.5 times higher than the original scene in order to create an optimum reproduction. However, printed images viewed in illuminated surroundings are optimal when their physically-measured contrast is equal to that in the original scene. This result is described in detail by Hunt.[20] Figure 6, adapted from Hunt's text,[20] illustrates the relationships required between the relative luminance of the original scene and optimum reproductions in average, dim, and dark surrounds. It should be noted that both axes in Fig. 6 are logarithmic transformations of relative luminance, thus the changes required are equivalent to changes in the exponent of a power function. Figure 7 illustrates the effect of applying the results described in Fig. 6 to a color image. The image labeled "Print" in Fig. 7 would need to be transformed to the image labeled "Slide" in order to be reproduced with similar appearances when viewed in a dark surround. In other words, the

"Slide" image in a dark surround has the same apparent contrast as the "Print" image in a light surround. Psychophysical results that explain the requirements for optimum image reproduction described above are reviewed in the following paragraphs.

In 1962, Breneman tackled the question: "Why does the objective tone-reproduction curve of an optimum reflection print differ so markedly from that of an optimum transparency?"[21] Breneman addressed this question through a brightness matching experiment in which observers made brightness matches between a previously scaled series of neutral stimuli and various elements of a pictorial image viewed with various levels of luminance and surround luminance. The results showed that the scale of perceived lightness as a function of relative luminance differed for dark and light surrounds. The slope of the curve on log-log coordinates was greater for images viewed in a light surround than those viewed in a dark surround. Breneman's result corresponds exactly with the requirements for optimum image reproduction and did not depend on overall luminance level. Breneman also noted that the effect was greater near the edges of the image (an effect that interestingly helps compensate for lens fall off in projector systems).

Bartleson and Breneman[22] extended Breneman's earlier work[21] in a more extensive study that has become a classic work in the imaging science field. Bartleson and Breneman included a larger number of observers (18) and images (10). The observers completed brightness scaling and matching experiments for various elements of the images. The results indicated significant effects of both overall luminance level and surround relative luminance. In addition, Bartleson and Breneman concluded that the results deviated significantly from the power law relationship found by Stevens and

Stevens[4] (the data were nonlinear on log-log coordinates) and fitted a more complex function that could be adjusted to account for luminance and surround changes. The results again showed that perceived lightness contrast of images is higher in an illuminated surround than in a dark surround.

In a second study published the same year,[23] Bartleson and Breneman used their brightness scaling results to analyze optimum tone reproduction in photographic systems. They extended Jones' techniques[18] to include functions that related the relative luminance in the scene to the relative brightness of elements of the scene and the relative luminance of the reproduction to the relative brightness of the reproduction in its viewing conditions. This allowed them to make predictions across disparate viewing conditions. They were able to conclude that optimum image reproduction is achieved when there is a one-to-one reproduction of relative brightness (lightness) between original and reproduction and that in order to achieve this when the image is viewed in a dark surround, an increase in contrast on log-log coordinates of 1.5 is required. This is equivalent to saying an increase in the exponent of a power function by a factor of 1.5 is required. An additional study was published by Clark[24] in the same year in which observers were asked to scale the quality of photographic images and the optimum reproductions were found to follow the concept of one-to-one reproduction of lightness. Clark, however, did find a small systematic deviation from this criterion when the luminance level changed. In addition, Clark was able to show that the results were equally well predicted using either the power functions of Stevens and Stevens[4] or the Bartleson and Breneman[22] equations.

Bartleson later published a set of simplified equations for the prediction of lightness of various surround relative luminances.[25] These functions were of forms similar to the CIELAB L* function with different exponents for different surrounds. The exponents used by Bartleson were 0.33 for dark surrounds, and 0.41 and 0.50 for dim and light surrounds respectively. These exponents are almost exactly in the ratio of 1.50:1.25:1.00 suggested by Hunt[20] to be optimal as illustrated in Fig. 6. While Bartleson's functions, called L**, are not simple power functions, they are very close approximations as illustrated in Fig. 8 which shows the lightness in dim and dark surrounds as a function of the lightness in a light surround for a given stimulus relative luminance as calculated by Bartleson's equations. Figure 8 can be thought of as a plot of the lightness changes that occur when the surround changes. A given stimulus appears lighter in a dark surround and the overall lightness contrast decreases. While the Bartleson equations predict the changes in image reproduction necessary to account for changes in surround, they have one minor problem for practical applications; for some values of relative luminance, the calculated L** values are negative.

The prediction of lightness as a function of stimulus and surround relative luminance levels continues to be an issue of interest due to the increasing number of imaging media and display technologies. Evidence of this is given in a recent study by Choi[26] in which the relationship between the Bartleson and Breneman equations[22] and the Stevens Power Law is examined and differences between the two are rectified by illustrating that the surround effect in Bartleson and Breneman's results can be modeled as an exponential decay from a power function that is itself a power function of the surround luminance.

SURROUND EFFECT ON CHROMA

The studies described above were carried out using black-and-white photographic systems. While such systems remain important in many applications, color imaging systems are becoming more prevalent — often to the exclusion of gray-scale systems. It seems safe to assume that the effect of surround on the lightness contrast of black-and-white images would also hold for the lightness contrast of color images. However, there is a second question to address: Does the relative luminance of the surround have any effect on the perceived chroma of color images? This issue has become more important recently since digital imaging systems make it much easier to manipulate the lightness and chromatic information in images independently.

Hunt[27] studied the relationship between light adaptation and color appearance for simple patch stimuli. He had observers make haploscopic color matches with one eye dark adapted and the other eye adapted to either daylight or tungsten illumination. The results illustrated that substantially greater colorimetric purity was required to match a colored stimulus when dark-adapted than when light adapted. In addition, Hunt arranged to eliminate the influence of simultaneous contrast by assuring that the stimulus and adapting background were not viewed simultaneously. This result indicates that dark surrounds might result in a loss of perceived chroma along with the decrease in lightness contrast. Hunt's results are analogous to the Stevens and Stevens[4] results that examined the influence of adaptation on relative brightness in that neither experiment was directly measuring a surround effect, although the results are similar.

Pitt and Winter[28] examined the effect of surround relative luminance on chroma with both simple stimuli and a slightly more complex mosaic of 6 colored stimuli viewed simultaneously. The experiment was carried out using a successive binocular viewing technique that required short-term memory matches. In both cases they found that increased colorimetric purity was required in a dark surround to match a given color in a light surround. This result is consistent with that reported by Hunt.[27] However, the area varied in the Pitt and Winter experiment was immediately adjacent to the colored stimuli and should more properly be considered the background rather than the surround. Pitt and Winter concluded that it was likely that "the increased system contrast necessary to obtain correct tone reproduction in dark surrounds, although it causes the colors to increase in purity, may not result in any increase in (perceived) saturation." In photographic systems, the two are inseparable since the system contrast for lightness is controlled by three color processes that must be balanced to properly reproduce the gray scale. If the gray-scale contrast is increased, all three processes must have increased contrast, resulting in an increase in chromatic contrast and therefore the chroma of colored image areas.

Breneman[29] examined the effect of surround on perceived chroma by constructing a target consisting of a mosaic of achromatic samples with a test color patch near the center. The surround was varied in relative luminance and separated by approximately 6° angular subtense from the test stimulus. Breneman also equated the lightness of the samples in the light and dark surrounds prior to asking observers to scale the perceived saturation ratios between stimuli viewed in the two surrounds using successive-binocular viewing. In eliminating all of the other variables, Breneman was also able to almost completely eliminate the effect of surround on perceived chroma. Breneman concluded that the surround had no significant effect on chroma. However, examination of the results indicates that there was a small effect for each color investigated and the tendency was for a dark surround to decrease perceived chroma. Thus, there was a small, but significant, surround effect. The small magnitude of the effect was probably caused by the large distance between the surround and the test stimulus. This agrees with Breneman's earlier results on lightness scaling that indicate that the surround effect is larger near the edge of the image than in the center.[21] Perhaps a similar effect would be found if full-color images were used. A decrease in the perceived chroma of image elements near the edge of a dark-surrounded display might somehow propagate through the image to give an overall perception of decreased chroma. Apparently, the recently obtained ability to manipulate luminance and chromatic contrast independently using digital imaging systems has not been put to use in a psychophysical experiment to provide a more definitive answer to this question.

Hunt, Pitt, and Ward[30] examined the relationship between optimum tone reproduction in color photographic materials and surround. They found that printed color images require a one-to-one reproduction of relative luminance when viewed in illuminated surrounds while color transparencies projected in a darkened room require a contrast increased by a factor of 1.5 on log-log coordinates. They also illustrated why photographic transparency materials are manufactured with an objective contrast that is roughly a factor of 2 greater than that of the original scene on log-log coordinates. This is due to camera and projector flare that reduce the objective contrast of the viewed image to the required contrast factor of 1.5. Hunt, Pitt, and Ward also concluded that the increase in colorimetric purity of images produced with a higher lightness contrast for viewing in a dark surround "may not result in an equivalent, or even any, increase in apparent saturation."[30]

While the influence of surround relative luminance on perceived chroma in images is a question that remains to be definitively answered, Hunt[31] has observed another interesting effect. Hunt pointed out that as the background becomes darker, chroma decreases for light colors and increases for dark colors. Thus the surround effect might not be a simple increase or decrease in chroma with surround relative luminance and there might be different effects for background and surround.

DEVICE-INDEPENDENT COLOR IMAGING

Figure 9 shows a flow chart of the process of color reproduction in device-independent imaging systems. The first step is a transformation from the color coordinates of the input device to a device-independent color space, such as CIELAB, through colorimetric characterization of the input device. Then the viewing conditions of the original image are accounted for using chromatic-adaptation and color-appearance models to transform to a "viewing-conditions-independent space" that describes the image elements in terms of perceptual variables such as lightness, chroma, and hue. This is the transformation stage that can be used to include the effects of surround on the appearance of an image. At this stage the image can be edited for color preference and processes such as gamut mapping can be effectively applied. Then the process is inverted for the viewing conditions of the reproduction and the device on which the reproduction is produced. Changes in the viewing conditions result in the production of a physically different image with color appearances identical to the original to the degree physically possible.

One color-appearance model that has been proposed for device independent color imaging applications is the RLAB color space.[10,12] Figure

10 is a flow chart of the application of the RLAB color space to image reproduction. The first step is a transformation to tristimulus values in a reference viewing condition using a previously described chromatic adaptation model.[13] The tristimulus values in the reference viewing conditions are then transformed into CIELAB-type coordinates using the CIELAB equations with exponents that depend on the surround relative luminance. At this point predictors of lightness, chroma, and hue for each image element can be obtained. Again the process is reversed for the viewing conditions of the reproduction. Recently,[10] the RLAB equations have been reduced to simple power functions and the chromatic-adaptation model has been slightly simplified. The predictive power of the equations is unaffected, as illustrated in Fig. 3, while the computational complexity (an important issue in imaging applications) is significantly reduced. Sève[32] has also proposed a simplified set of equations for CIELAB that eliminate the need for separate equations for low luminance levels and might prove useful. Additional work is planned on the refinement of the RLAB equations.

The simplified (power function) transformation from reference tristimulus values to RLAB coordinates is given by Eqs. 1-3.

$$L^R = 100(Y_{ref}/100.00)^{\sigma} \tag{1}$$

$$a^R = 430[(X_{ref}/95.05)^{\sigma} - (Y_{ref}/100.00)^{\sigma}] \tag{2}$$

$$b^R = 170[(Y_{ref}/100.00)^{\sigma} - (Z_{ref}/108.88)^{\sigma}] \tag{3}$$

The σ values in Eqs. 1-3 are 1/2.3 for average surrounds, 1/2.9 for dim surrounds, and 1/3.5 for dark surrounds. Like Bartleson's equations,[25] these exponents are almost exactly in the ratio of 1.50:1.25:1.00 suggested by Hunt[20] to be optimal. However the exponents themselves are different than Bartleson's. The exponents have also been applied to all three dimensions of color space. This means that the RLAB color model predicts that a dark surround will result in a decrease in perceived chromatic as well as lightness contrast. This feature has been included since it agrees with the successful optimal color reproduction in photographic systems. Since the visual data are somewhat equivocal on this point, adjustments might be necessary as additional visual data become available. To date, using variable exponents on all three dimensions has proven appropriate. A simple adjustment can be made if it is desired to eliminate the chroma effects. The exponents in the a^R and b^R equations would be made constant and only the L^R exponent would be allowed to vary.

It is of interest to examine images produced with the two different hypotheses regarding the effect of surround on chroma. Such images are illustrated in Fig. 11. The image labeled "Print" is the same as in Fig. 7. The center image in Fig. 11 has been adjusted for viewing in a dark surround by manipulating only the luminance contrast. The rightmost image in Fig. 11 has been adjusted for a dark surround along all three dimensions. Fig. 11 is only of utility for illustrating the differences between the techniques and it clearly illustrates that there is an interaction between apparent lightness contrast and chromatic contrast. While no quantitative psychophysics has been completed, both of the adjusted images produce good reproductions in a dark surround and they become difficult to distinguish when viewed one at a time. However, the image with all three dimensions adjusted appears to be a slightly more accurate reproduction in a dark surround.

Psychophysical tests of the RLAB model in comparison with other color-appearance models and chromatic-adaptation transforms as applied to cross-media color reproduction have been completed. In an experiment comparing printed images with CRT displays,[33] the RLAB model performed better than CIELAB, a von Kries model, the Hunt model,[31] and the model of

Nayatani *et al.*[34] This experiment did not directly address the surround issue since the images in both media were viewed in a dark surround. A second experiment was completed in which CRT images viewed in a dim surround were reproduced as projected slides viewed in a dark surround.[35] In this experiment, the RLAB model again performed better than the other models thus lending some support to its application of variable exponents on all three dimensions of color space.

CONCLUSIONS

A wide variety of functions have been proposed to predict the perception of lightness as a function of relative luminance. Figure 12 illustrates 3 functions that also include the effect of surround relative luminance. The 3 functions, illustrated in Fig. 12 for a dark surround, are significantly different. As illustrated by Wyszecki and Stiles,[5] this might not be of significant concern since the functions can be significantly altered by small changes in experimental design. All of the functions agree in the general compressive shape and can be modeled either exactly or approximately with a power function.

There is greater agreement between the 3 models that include surround effects when the changes due to surround are examined. This is illustrated in Fig. 13, a plot of the predicted lightness in a dim or dark surround as a function of the predicted lightness in an average surround for any given relative luminance. Figure 13 illustrates the adjustments necessary to compensate for surround changes in image reproduction. It is clear in Fig 13. that the Bartleson equations, L^{**},[25] and the RLAB equations, L^R,[10] predict exactly the same surround effect. Hunt's model[31] predicts an effect approximately one half as large. This is likely due to the fact that the Hunt model is designed to predict a large number of other color-appearance phenomena resulting in a diminution in its ability to predict any single phenomenon. Also, it should be noted that the functions for the Hunt model were calculated for the luminance level of a typical computer graphics display (about 60 cd/m^2) and that the predicted effect increases with luminance level according to the model.[1]

While the effect of surround has been of great interest for decades in the photographic industry, it is now possible to apply the knowledge gained through that research to modern electronic imaging systems. The RLAB color space provides one mechanism for such applications. Another tool is the ICC Profile Format[36] that could potentially become an international standard for the exchange of color image data and transforms. Version 3.0 of the ICC format includes a data structure called "viewingConditionsTag" that includes floating-point values for the absolute XYZ tristimulus values in cd/m^2 of the illuminant and the surround. If these data are put to appropriate use, users will experience greatly improved color reproduction across a variety of media and displays.

One last hurdle to overcome in applying color-appearance models to cross-media color reproduction is the practical definition of background and surround in image displays. Such a definition will become necessary for the efficient implementation of color-reproduction algorithms and the exchange of image data. A recent experiment by Berns and Choh[37] suggests that the surround of a computer CRT display has less influence than expected on the contrast of images. This might be due to the way observers view the display, essentially neglecting the remainder of the visual environment, thus making a practical definition of surround for such a display equivalent to the display itself.

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FIGURE CAPTIONS

Figure 1. Plot of the Stevens Power Law relationship between stimulus relative luminance and relative brightness with an exponent of 0.33 on (a) linear and (b) logarithmic coordinates. Note that a power function transforms into a straight line on log-log coordinates.

Figure 2. (a) Average visual results from the 1933 experiments to derive the Munsell value scale[7] (symbols) and the 5th-order polynomial used to define the renotation of Munsell value[6] (line). (b) The same Munsell value scale data (symbols) plotted as a function of CIELAB L*/10. The solid line has a slope of 1.0 illustrating the accuracy of the CIELAB L* equation in predicting Munsell value.

Figure 3. Results for each observer in the 1933 Munsell experiments[7] (symbols) and predictions of 3 lightness functions: an optimum power function with exponent = 1/2.39 (dotted line), the CIELAB L* equation (solid line),[9] and the revised RLAB L^R equation (dashed line).[10]

Figure 4. Lightness as a function of relative luminance for backgrounds with relative luminances of 0.15, 0.45, and 0.75 illustrating the crispening effect according to the equations of Semmelroth.[15]

Figure 5. Relative brightness as a function of relative luminance (log-log coordinates) for various adapting luminance levels according to the results of Stevens and Stevens.[4] The results follow a power function with the exponent increasing as a function of adapting luminance.

Figure 6. Optimum tone-scale reproduction for images viewed in average, dim, and dark surrounds adapted from Hunt.[20] Since density is related to relative luminance logarithmically, these curves represent power functions with increasing exponents as surround luminance decrease. This is necessary to offset the perceived decrease in contrast with decreasing surround relative luminance.

Figure 7. An illustration of the transformation required to reproduce a printed image (labeled "Print") as a transparency viewed in a dark surround (labeled "Slide"). Due to the perceptual effects of surround relative luminance, the "Slide" image viewed in a dark surround would look similar to the "Print" image in this illuminated surround. These images illustrate the magnitude of the visual effect of surround luminance on image contrast although the printed image lacks the luminance range necessary for optimal dark-surround viewing.

Figure 8. Predicted lightness in dim and dark surrounds as a function of predicted lightness in an average surround for equivalent relative luminances on log-log coordinates according to Bartleson's equations for optimum image reproduction.[25] The thin solid line represents one-to-one lightness reproduction.

Figure 9. Flow chart of the process of device-independent color imaging.

Figure 10. Flow chart of the procedure for applying the RLAB color space[10,12] to cross-media color image reproduction.

Figure 11. Similar to Fig. 7, but illustrating the difference between making the contrast adjustment to compensate for the surround change on just the luminance information (center image) and making adjustments on both the luminance and chromatic information (rightmost image).

Figure 12. Predicted lightness as a function of relative luminance in a dark surround according to the Bartleson equations (L**),[25] RLAB (L^R),[10] and Hunt's color-appearance model.[31]

Figure 13. Relationship of predicted lightness in dim and dark surrounds with predicted lightness in an average surround for equivalent relative luminances according to the Bartleson equations (L**),[25] RLAB (L^R),[10] and Hunt's color-appearance model.[31]

Figure 1.

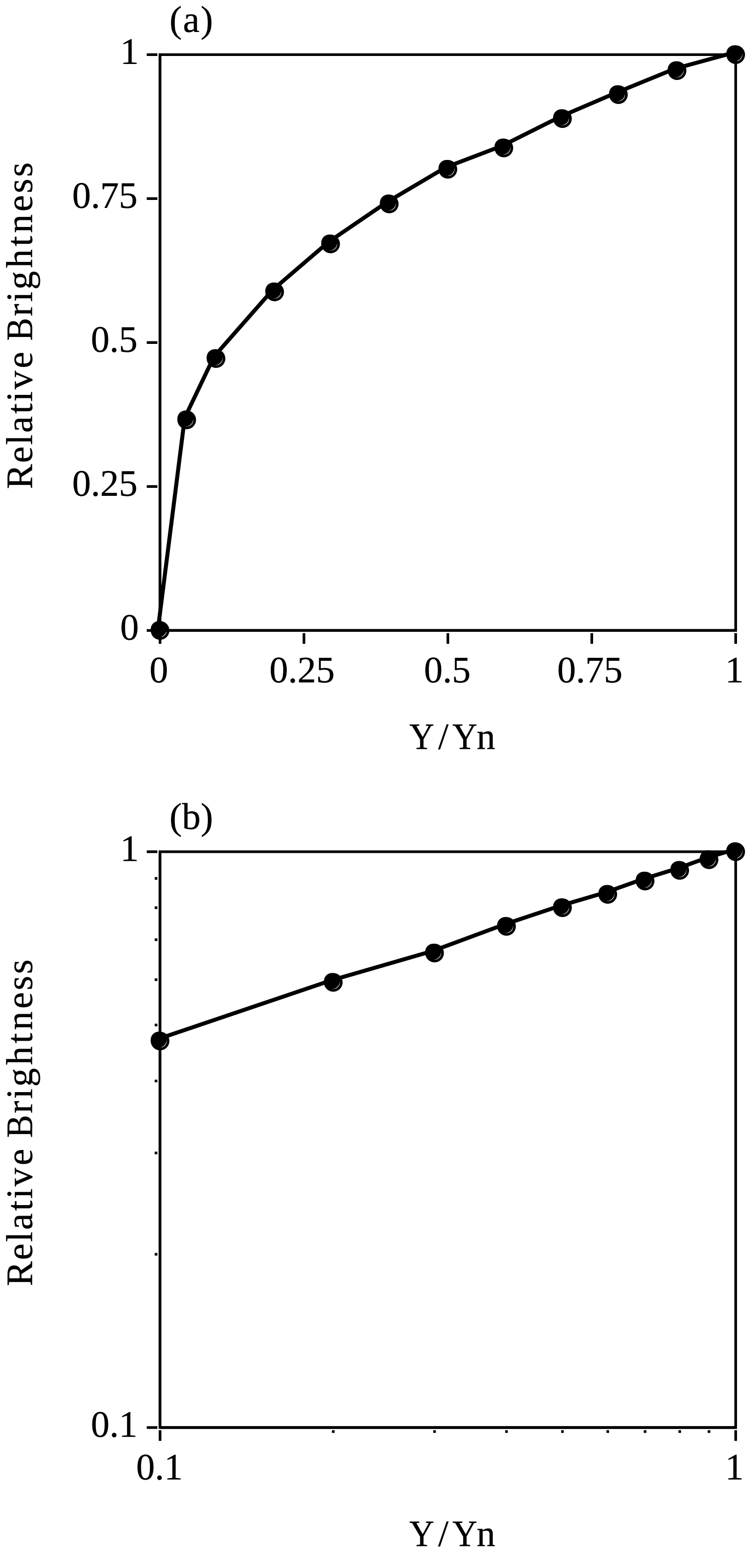
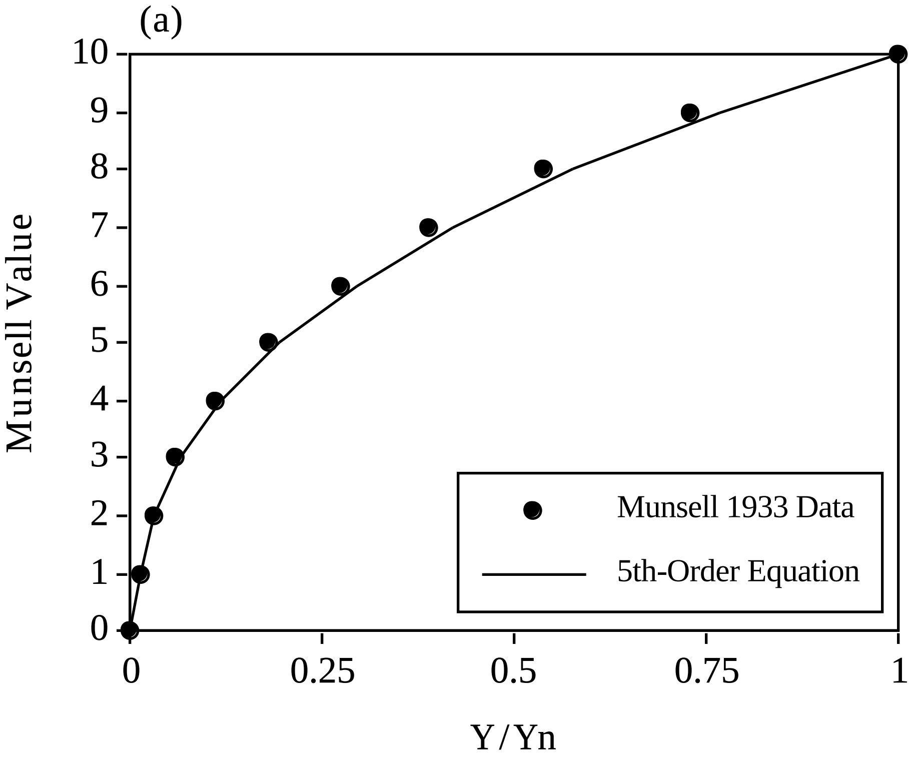
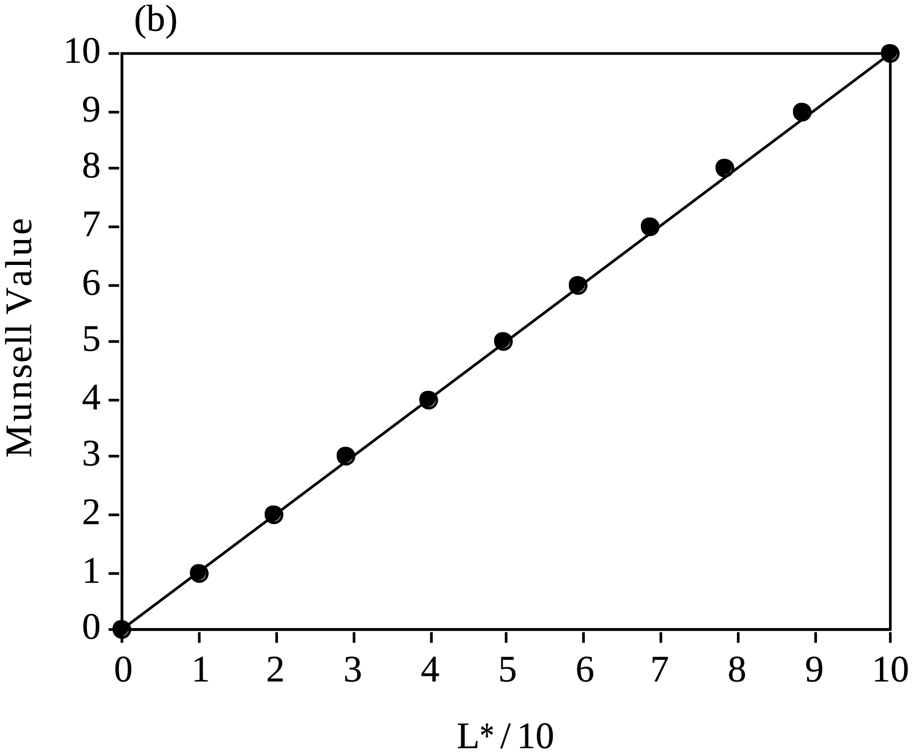

(a)
1
0.75
0.5
0.25
0
Relative Brightness
0
0.25
0.5
0.75
1
Y/Yn
(b)
1
0.1
Relative Brightness
0.1
1
Y/Yn

Figure 2.



(a)
Munsell Value
10
9
8
7
6
5
4
3
2
1
0
0
0.25
0.5
0.75
1
Y / Yn
● Munsell 1933 Data
5th-Order Equation



(b)
Munsell Value
10
9
8
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
L* / 10

Figure 3.

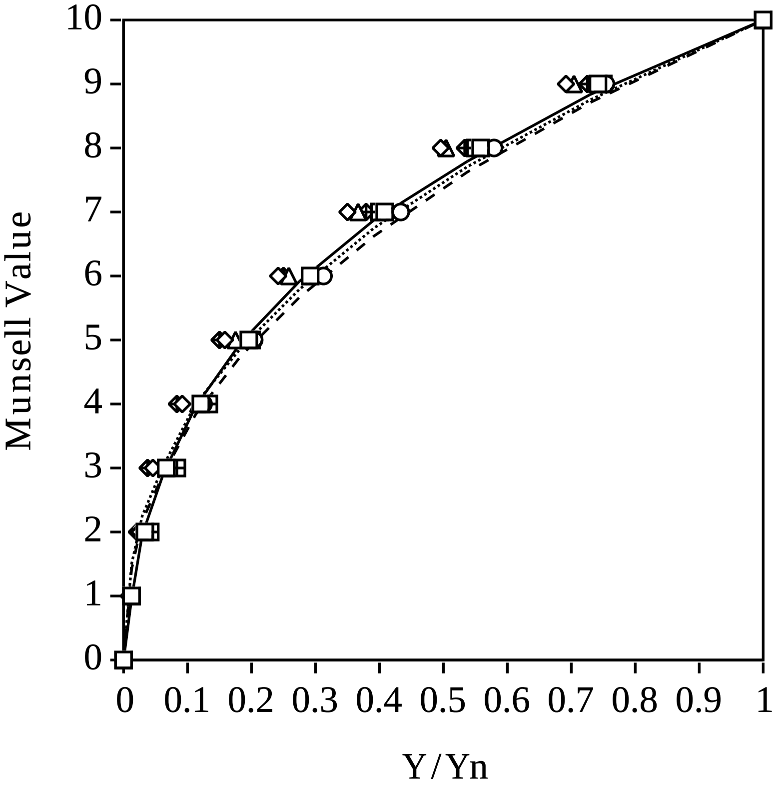


Figure 4.

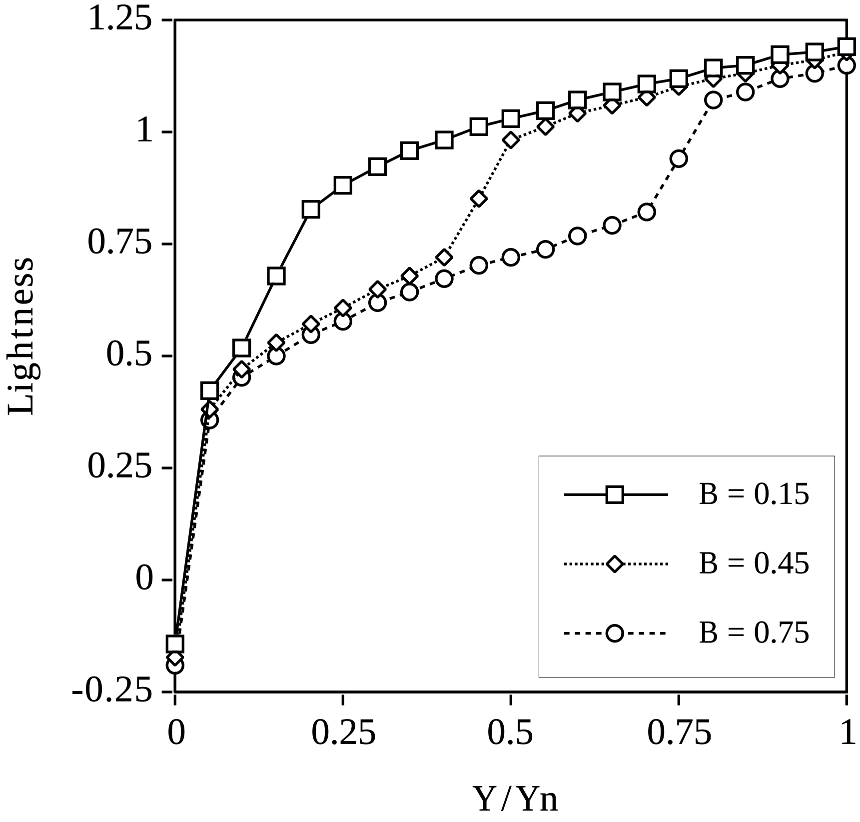

1.25
1
0.75
0.5
0.25
0
-0.25
Lightness
0
0.25
0.5
0.75
1
Y/Yn
B = 0.15
B = 0.45
B = 0.75

Figure 5.

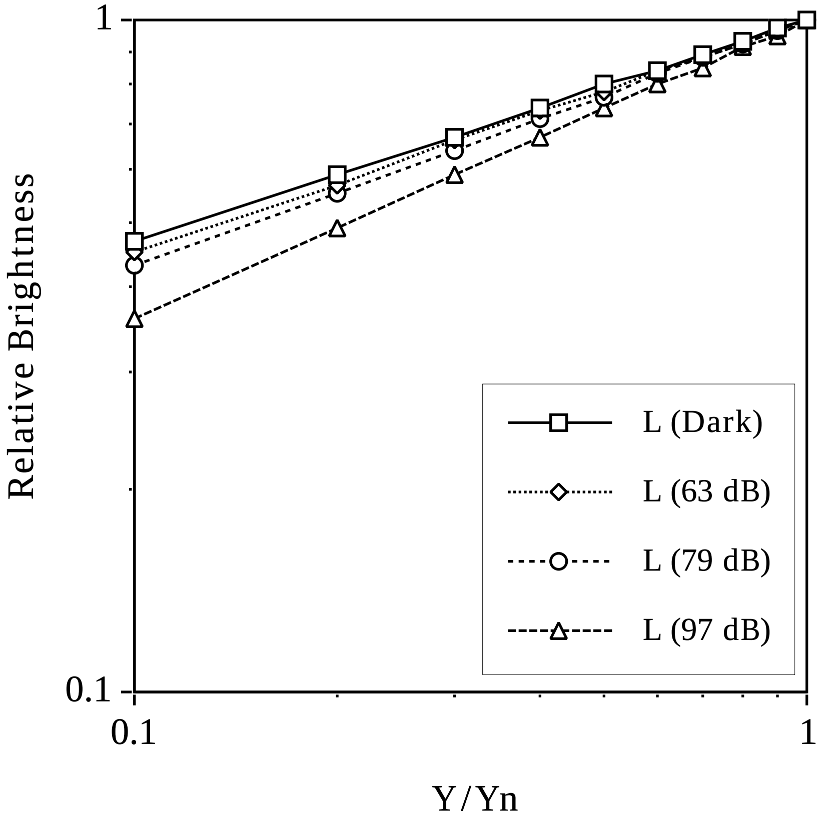


Figure 6.

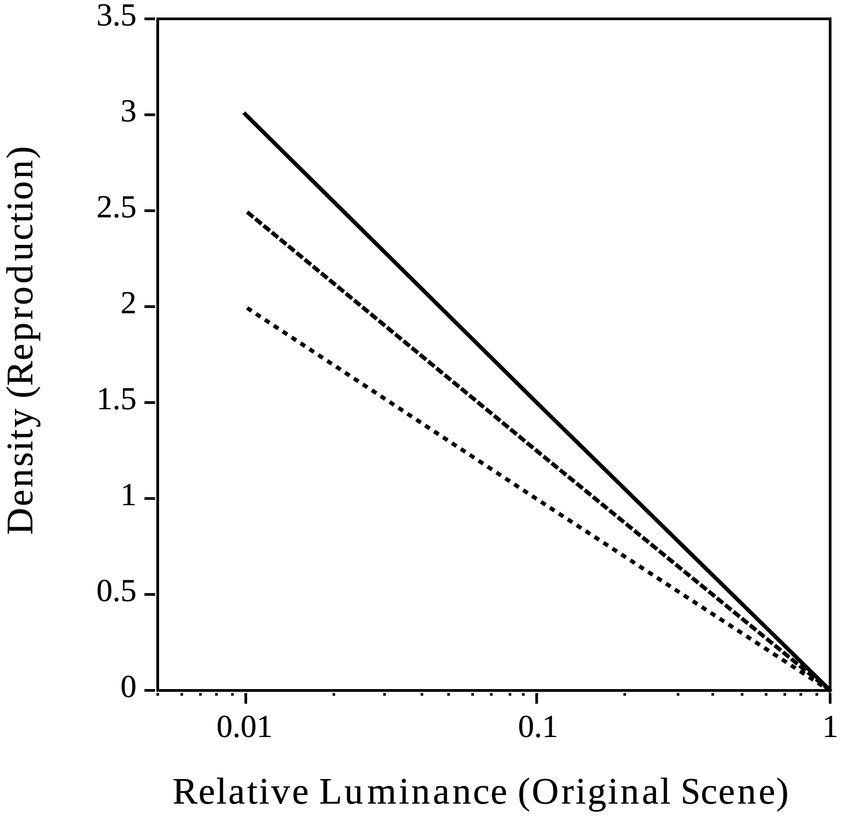

3.5
3
2.5
2
1.5
1
0.5
0
0.01
0.1
1
Density (Reproduction)
Relative Luminance (Original Scene)

Figure 7.

2 Versions of Sierra

Figure 8.

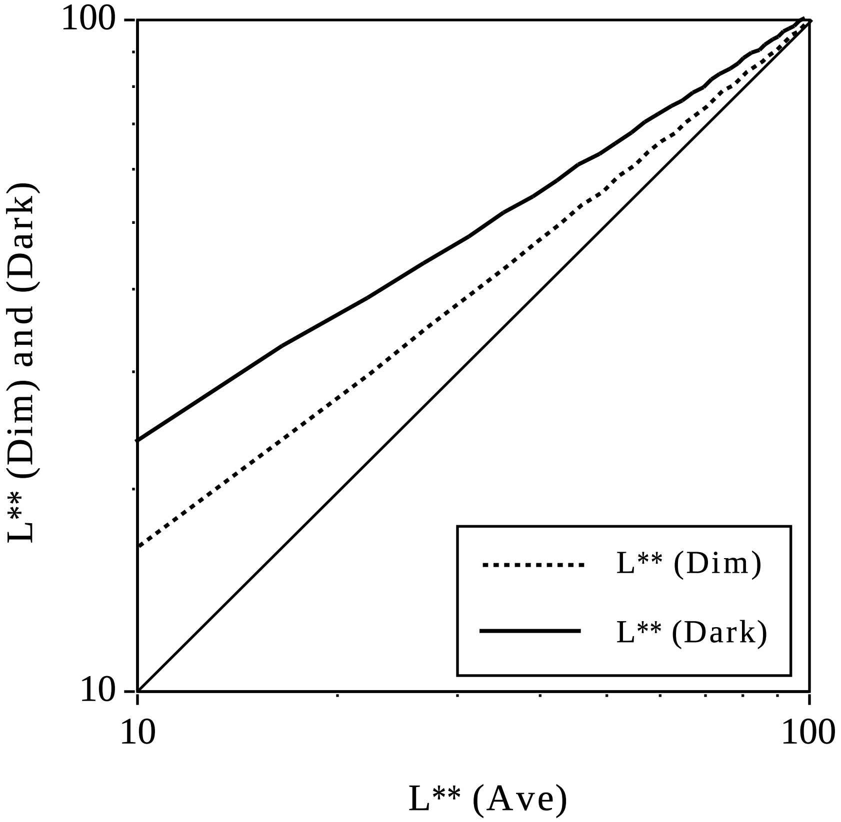


Figure 9.

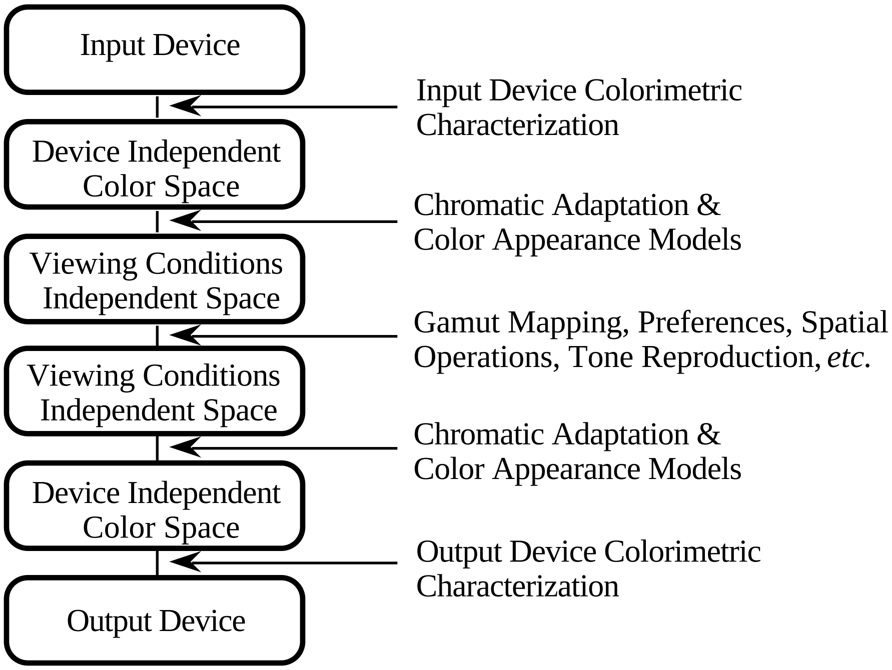

Input Device
Input Device Colorimetric Characterization
Device Independent Color Space
Chromatic Adaptation & Color Appearance Models
Viewing Conditions Independent Space
Gamut Mapping, Preferences, Spatial Operations, Tone Reproduction, *etc.*
Viewing Conditions Independent Space
Chromatic Adaptation & Color Appearance Models
Device Independent Color Space
Output Device Colorimetric Characterization
Output Device

Figure 10.

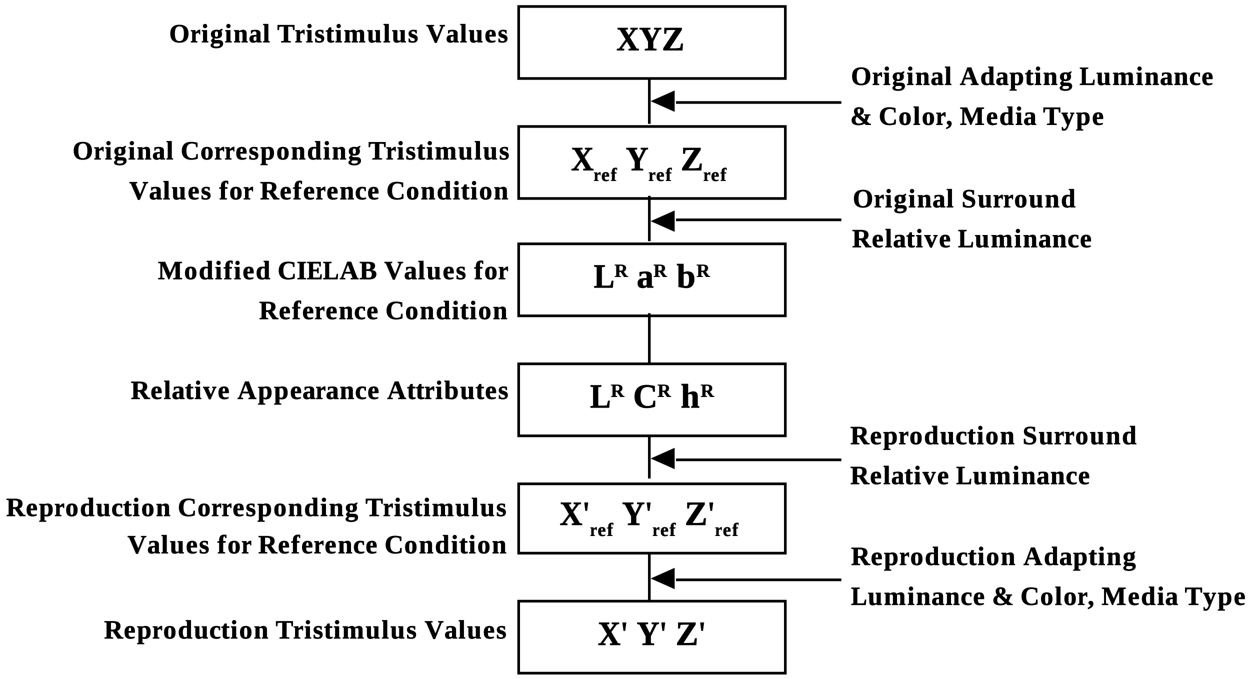
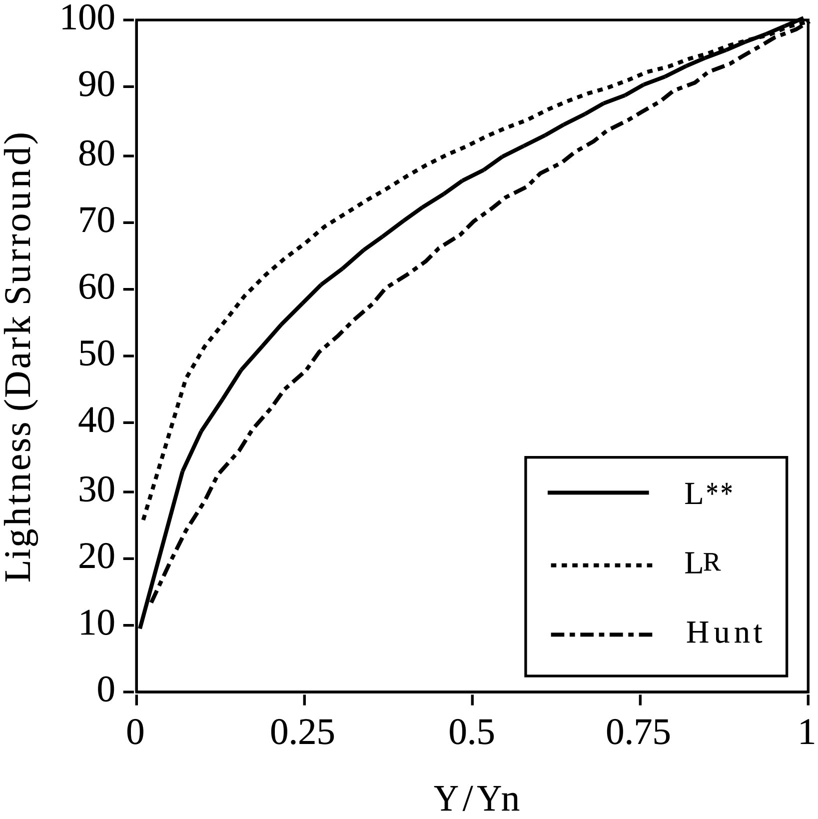

Original Tristimulus Values
XYZ
Original Adapting Luminance & Color, Media Type
Original Corresponding Tristimulus Values for Reference Condition
X_{ref} Y_{ref} Z_{ref}
Original Surround Relative Luminance
Modified CIELAB Values for Reference Condition
L^R a^R b^R
Relative Appearance Attributes
L^R C^R h^R
Reproduction Surround Relative Luminance
Reproduction Corresponding Tristimulus Values for Reference Condition
X'_{ref} Y'_{ref} Z'_{ref}
Reproduction Adapting Luminance & Color, Media Type
Reproduction Tristimulus Values
X' Y' Z'

Figure 11.

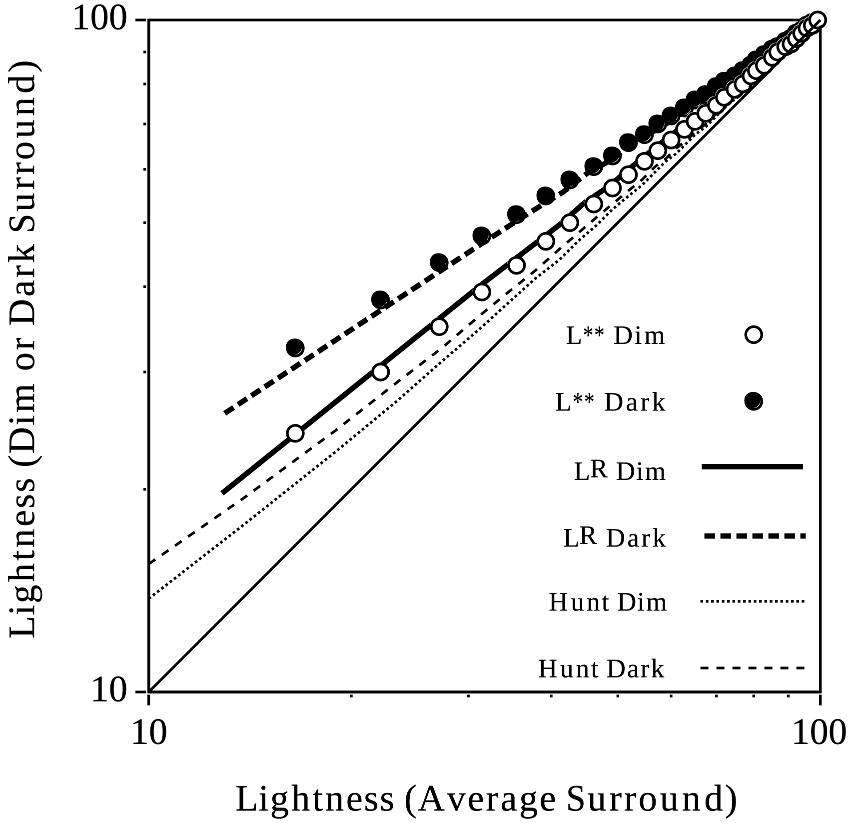
3 Versions of Sierra

Figure 12.



100
90
80
70
60
50
40
30
20
10
0
Lightness (Dark Surround)
0
0.25
0.5
0.75
1
Y/Yn
L**
LR
Hunt

Figure 13.


100
10
10
100
Lightness (Dim or Dark Surround)
Lightness (Average Surround)
L** Dim ○
L** Dark ●
LR Dim
LR Dark
Hunt Dim
Hunt Dark