A COMPARISON OF ALGORITHMS FOR MAPPING COLOR BETWEEN MEDIA OF DIFFERING LUMINANCE RANGES

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One of the problems faced in reproducing an image in a different medium is that the luminance ranges of the original and reproduction are often quite different. While the preferred mapping of the luminance / lightness component is well understood for most images, the mapping of the chromatic components of color images is not. In this paper we examine several alternative mappings, both analytically and experimentally.

In the analytical phase of this investigation we postulated that a color reversal transparency was to serve as the original image, and four-color process printing on uncoated paper was to serve as the reproduction medium. We considered several color spaces (XYZ, xyY, and CIELab) and performed compression on the luminance / lightness component while holding the other two coordinates constant. This created three different ways in which to map a color in the original into a color in the reproduction. In addition, we examined the case of compressing the X and Z tristimulus values using the same compression used for Y, which yielded a fourth mapping. Finally, a fifth mapping, with a user-selectable Chroma Compression Ratio (CCR), was examined. We then examined the effects of these five mappings on hue, chroma, saturation, and gray balance.

The results of our experiments are summarized as follows: Holding X and Z constant while compressing Y resulted in undesirable translation towards yellowish green. The effect is greatest for darker colors. Holding the chromaticity coordinates constant caused an increase in Chroma, while maintaining gray balance and hue. Again, the effect is greatest for darker colors. This is undesirable, because media with limited luminance ranges are typically limited also in Chroma. The remaining three techniques are all related; the last is shown to be a generalization of the other two. They differ in their treatment of Chroma. One leaves Chroma unchanged; it uses a CCR of unity. Another uses a CCR which is the ratio of the L* range of the reproduction to that of the original. The final technique allows the user to set the level of CCR. All three of these methods preserve hue and gray balance.

For most originals, the mapping of color coordinates from one domain to another reduces to a problem of determining the CCR. Our experimental evidence indicates a value midway between unity and the L* range ratios of the two media.

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INTRODUCTION

In his excellent discussion of the objectives of color reproduction systems, Hunt offers a series of reproduction ideals. In one of these, Colorimetric, the aim is for each color in the reproduction to have the same chromaticity and relative luminance as in the original. Equivalent color reproduction, another reproduction ideal, involves making each point in the reproduction match the appearance of the corresponding point in the original. [1] How could one argue with so noble a goal as matching the color or appearance of an original?

There are several facets to the problem of working with images in different media. On one hand, differences in viewing conditions, highlight luminance and chromaticity, and other appearance-related factors must be considered. On the other hand, it may be impossible to produce an appearance match between an original and its reproduction in a different medium. For example, a photographic transparency is often considered the "original" in publishing, even though it is itself a reproduction of an original scene. It is often reproduced on paper by four-color process printing. The original is a three-primary subtractive object, designed to be viewed in transmission. The reproduction is made using four subtractive primaries, and is designed to be viewed by reflection.

The two media usually have different luminance ranges. A photographic transparency will have a luminance range of 500:1 to 1000:1, while four-color printing on uncoated paper is limited to a luminance range of less than 100:1. When translated into CIE L*, the differences are smaller, though still significant: The L* range of a typical photographic transparency is at least 95, compared to an L* range of 85 for printed reproductions. See Table 1.

	Ektachrome Transparency	Printed Reproduction
L* of Highlight	100	100
L* of Shadow	3	15
L* Range	97	85

Table 1.

The CIE 1976 L coordinates for two media are compared. Note that we have chosen the highlight luminance of each medium as the value of Yn in the L* computations.*

When faced with an original of a greater contrast range than the reproduction process is capable of producing, it is necessary to perform tone compression. The lightness values of each point in a picture must be modified during the reproduction process. Exactly how this modification is performed is the subject of this paper.

Mapping the Luminance / Lightness Component

There is a significant body of literature which explains how the luminance / lightness component should be mapped. This information was very important by itself when color reproductions were made by entirely analog systems. Hue correction, gray balance, and tone reproduction were all performed more or less independently. Entirely digital systems have a different set of requirements, and require more specific information. This paper endeavors to suggest mappings for the other components of color from original to reproduction.

Rhodes discovered a simple relationship between the Munsell values of the original and the reproduction. This is perhaps the first totally objective description of how the luminance component should be treated under tone compression:

> "A satisfactory compromise in the tone reproduction of high-density-range originals might be a straight line reproduction on graph paper whose coordinates are equal visual differences rather than density. . . . Assuming Munsell values to be equal visual steps, any tone reproduction which is straight line [in Munsell Value coordinates] could be interpreted to mean that equal visual differences in the original were also equal visual differences in the reproduction." [2]

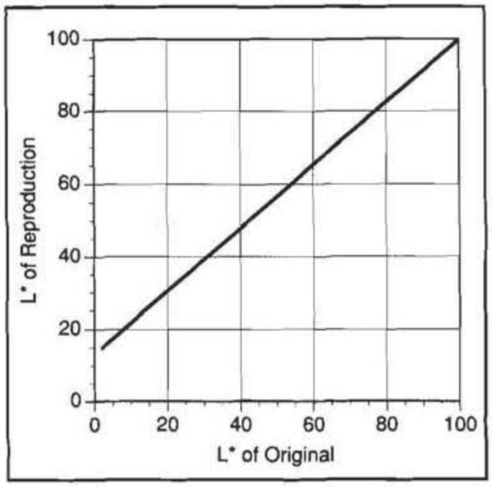

Figure 1.

Uniform Compression of L. Aside for our substitution of L* for Munsell Value, this is the mapping suggested by Rhodes in 1954.*

Figure 1 depicts a plot of a tone reproduction characteristic curve, plotted according to Rhodes's suggestion. We have substituted L* for Munsell Value. Rhodes also placed density scales and tick marks in his illustrations. Subsequently, RIT labelled the axes solely in density units, and offered the paper as a tone reproduction aid. Users could connect a line between the highlight and shadow points, obtaining a good tone reproduction characteristic curve. [3]

Rhodes's suggestion was an important and enduring one. Since his initial suggestion in 1954, some modifications have been introduced, but the central idea stands: *Tone reproduction is best examined in light of a visually uniform lightness scale.*

Based on work by C. J. Bartleson and E. J. Breneman which demonstrates that lightness can be perceived differently from the Munsell Value scale for photographic scenes, [4] Richard Maurer suggested using Bartleson and Breneman's lightness scale (or its complement, Bartleson and Breneman's Darkness) instead of Munsell Value. [5] This is a small but significant refinement to Rhodes's initial suggestion. Figure 2 shows a tone reproduction characteristic plotted in L*-space, but with uniform compression of Bartleson and Breneman's coordinates.

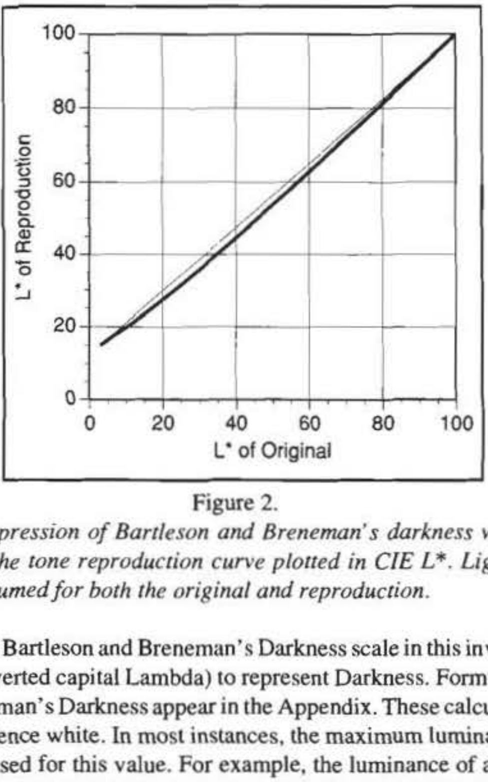

Figure 2.

Uniform Compression of Bartleson and Breneman's darkness will result in curvature of the tone reproduction curve plotted in CIE L. Light surround viewing is assumed for both the original and reproduction.*

We have used Bartleson and Breneman's Darkness scale in this investigation. We use the symbol V (an inverted capital Lambda) to represent Darkness. Formulae for computing Bartleson and Breneman's Darkness appear in the Appendix. These calculations involve the luminance of a reference white. In most instances, the maximum luminance a medium can produce should be used for this value. For example, the luminance of a minimum density patch should be used when calculating Darkness values for photographic film. The Darkness of the highlight will then be zero, and the Darkness range will be the material's "V-max."

Summary of Tone Reproduction Requirements

For "normal" scenes, the following criteria describe good tone reproduction:

> *Highlight Placement:* An object which appears white in the original should appear white in the reproduction. In printed reproductions, this is usually effected by reproducing the diffuse highlight of the original with a very small, just printable, halftone dot.

Shadow Placement: An object which appears black in the original should be reproduced so it appears black in the reproduction. This is usually effected by reproducing the darkest portion of the image with the smallest dot which produces the maximum density of the process.

Uniform Compression: For most originals, the Bartleson and Breneman Darkness of the reproduction should be linearly related to the Bartleson and Breneman Darkness of the Original.

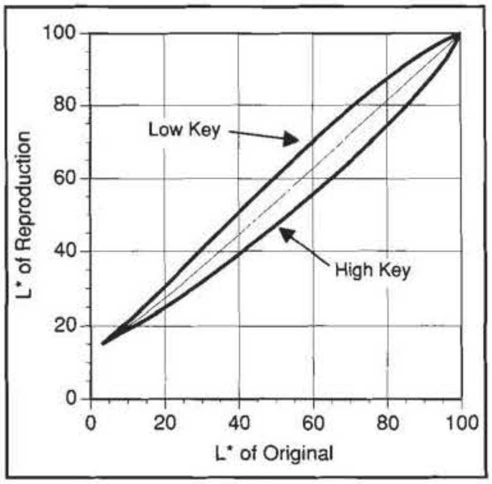

Figure 3.

The Tone Reproduction Characteristic may be curved to permit better reproduction of High Key (rich in highlights) and Low Key (rich in shadows) originals.

Effect of Original Gradation

When reproducing a photograph particularly rich in one lightness level, the tone reproduction characteristic is sometimes curved so that its derivative is higher at that level. For example, if a high-key (skewed towards the highlight end of the scale) original is to be reproduced, a slight curve may be introduced, making the curve concave from the bottom. Conversely, low-key (skewed towards the dark end of the scale) originals are often reproduced with the tone reproduction characteristic curved in the opposite direction. Tone reproduction characteristics for high- and low-key originals appear in Figure 3.

In what was then the USSR, workers quantified the curvature of the tone reproduction characteristic, based on histogram analysis. [6] Their suggestion was refined by Robert Chung of RIT, [7] [8] and subsequently incorporated in a commercial product for tone reproduction analysis. [9]

We shall make the assumption in this investigation that a linear tone reproduction characteristic is appropriate. This is the case if "normal" scenes are being reproduced. This linear tone reproduction characteristic may be described symbolically in terms of Bartleson and Breneman's Darkness:

$$V_r = TCR \cdot V_o \tag{1}$$

where V_r is the Bartleson and Breneman darkness of the reproduction;
V_o is the Bartleson and Breneman darkness of the original; and
TCR, the Tone Compression Ratio, is the slope of the tone reproduction characteristic.

Usually, TCR is taken as the ratio of the Bartleson and Breneman darkness range of the reproduction to that of the original. It is important that the blackest black in the original be reproduced with the blackest black the reproduction medium is capable of producing.

Let us revisit the two sample media – the photographic transparency and its printed reproduction. Assuming both are viewed with light surround, the Bartleson and Breneman darkness ranges will be 0.9830 for the original, and 0.9220 for the reproduction. The ratio of the second to the first, or 0.9379, is the TCR.

We can use the relationship in Equation (1) to construct the mapping between the L*s of original and reproduction. The following steps would be performed for each L* in the original:

1. Convert the L* value of a point in the original to relative luminance (Y ÷ Yn).

2. Convert this relative luminance into Bartleson and Breneman's darkness, V_o, using one of the equations in the Appendix.

3. Compute the Bartleson and Breneman's darkness of the same point in the reproduction, V_r, using Equation (1), above.

4. Convert V_r into relative luminance of the reproduction, using one of the equations in the Appendix.

5. Convert the relative luminance of the reproduction to the L* of the reproduction.

Color Reproduction Requirements

In addition to the three rules for good tone reproduction, which Southworth cites as a key component, [10] there are some additional requirements for good color reproduction:

Neutral Integrity: Objects which appear neutral in the original should appear neutral in the reproduction. This is also referred to as "Gray Balance."

Hue Integrity: The hue of an object should appear identical in the original and the reproduction.

Southworth cites an additional rule, involving "memory" colors – green grass, blue skies, red apples, etc. We have found this rule to be more subjective than the others; we use it in visual evaluations.

These rules are not sufficient to completely describe a color reproduction algorithm; they fail to address, for example, the issue of Chroma. Nevertheless, they have been extremely useful in guiding us during this investigation. We shall find it helpful to consider, in addition to these five general rules, what happens to Saturation and Chroma.

It is expedient for us to consider, at least for the moment, the case in which the original and reproduction are viewed under similar conditions, with similar surrounds, and identical highlight luminances. The effect of varying these conditions may be factored out with an appropriate color appearance model. We first must consider what should be done when these conditions match.

Color Reproduction Algorithms

Stone, Cowan, and Beatty used the term, "Gamut Mapping" to describe the transformation of color coordinates from one medium to another. [11] Because this is actually a mapping of colors, rather than of gamuts, we have chosen the phrase "Color Mapping," which involves "Color Reproduction Algorithms," as more accurate a description.

A Color Reproduction Algorithm consists of two components: One handles the general mapping of colors from one medium to the other. Some of the target colors selected by this mapping will not be attainable in the reproduction medium. The second component of the color reproduction algorithm is responsible for replacing these "non-reproducible" colors with reproducible ones. This paper discusses only the first, general, component. The handling of non-reproducible colors is planned for a future paper.

A Naïve Color Reproduction Algorithm

Given that the luminance / lightness component must be changed, perhaps the simplest type of mapping would be to hold the X and Z tristimulus values constant, while performing the compression solely on Y. Let us examine this first Color Reproduction Algorithm in light of the CIELab color space.

In order to accommodate the shorter L* range of the reproduction, the L*s will be increased. This increase will be minor for light colors, more substantial for midtones, and most significant in the shadows. There is a linear relationship between L* and the function f (Y / Yn), which is involved in all three CIELab coordinates. Because the X and Z tristimulus values are unchanged, the CIELab coordinates a* and b* will be changed as we go from original to reproduction. As a consequence of the definitions of L*, a*, and b*:

$$\begin{aligned} a^* &= -500 \cdot L^* \div 116 \\ b^* &= 200 \cdot L^* \div 116 \end{aligned} \tag{2}$$

This means that all colors, except for those in the extreme highlights, will tend to get greener and slightly yellower as they are reproduced. This effect is greatest in the shadows, and is highly undesirable — it violates our requirements for Neutral and Hue Integrity. This naïve color reproduction algorithm is not satisfactory.

A Second Attempt

A somewhat more sophisticated approach might be to perform visually uniform compression on the lightness / luminance component, and hold the chromaticity coordinates constant. This avoids the problems encountered with the previous attempt: hues will be maintained, and neutrals in the original will remain neutral in the reproduction. Is this a satisfactory scheme for mapping original color to reproduction color?

Consider what happens to saturation, which is defined in terms of chromaticities. Because the chromaticities will be the same in the original and reproduction, there will be no change in saturation. However, if we consider Chroma, which also takes into account an object's lightness, we will observe a change. In the CIELUV color space, Chroma is the product of Lightness and Saturation. Recall that except for the extreme highlights the lightness of the reproduction will be greater than the lightness of the original. Thus:

$$C^* = S_{uv} \cdot L^* \tag{3}$$

In other words, the Chroma of most colors — particularly for the darker colors — will be higher in the reproduction than in the original. While this does not violate any of our ground rules, it does produce unpleasing results. Dark colors which exhibit a small, barely perceptible, level of chroma in the original may be decidedly chromatic in the reproduction. Further, in seeing such a reproduction, one gets the distinct impression that something is wrong. We must reject this second approach for these reasons.

Constant Hue and Chroma

Our third attempt shall be to hold both Hue and Chroma constant while performing tone compression. This scheme satisfies all five rules for good color reproduction. Because, as we have just seen, satisfaction of these ground rules does not insure good reproductions, we shall reserve judgement on this scheme until subjective evaluations are introduced.

It is interesting to note, however, that this particular method causes a decrease in Saturation, particularly in the shadows. Again, using the CIELUV color space, we can arrive at this answer. Two colors, one lighter than the other, but both with the same Chroma, will have different saturations:

$$S_{uv} = C^* \div L^* \tag{4}$$

The saturation of the lighter color, which has a larger L^*, will be lower.

In their important comparison of printed reproductions to their originals, Pobboravsky, Pearson, and Yule describe a specimen of "exceptionally good reproduction." [12] One of the important features of this particular reproduction was the consistency of the Chroma mapping. The ratios of the reproduced Chromas to those in the original were always close to unity. *

Constant Compression

As an alternative to Hunt's six types of color reproduction ideals, Gordon, Holub, and Poe offered a seventh type, which allows the lightness ranges of the original and reproduction to be different. In essence, they suggested that a common compression factor be applied to both Chroma and Lightness. They called their algorithm the "Gamut Compression Transformation," and argued that it "preserves as much color difference information as possible." [13]

This color reproduction algorithm satisfies all five of our ground rules, so it deserves further consideration. Although Gordon, Holub, and Poe used the CIELUV color space in their paper, it is instructive to examine it using CIELab. If the three tristimulus ratios (X / Xn, Y / Yn, and Z / Zn) of a point are all greater than $(6/29)^3$, then it can be shown that all three tristimulus ratios have received identical compression. We refer to this method as "Constant Compression" for this reason.

To some extent, this mimics the operation of a photographic color separation system. The tone scale, as measured through Red, Green, and Blue sensitive filters, receives relatively uniform compression through each. This scheme replaces X, Y, and Z for Red, Green, and Blue filter reflectances.

Strictly speaking, the "Gamut Compression Transformation" as originally described would require the compression on the Lightness component to be uniform in CIE L*. (This would introduce a small amount of curvature in Bartleson and Breneman darkness coordinates.) The slope of the tone reproduction characteristic, plotted in CIE L*, would also be the factor applied to the Chroma. When making a uniform compression in Bartleson and Breneman's darkness, the ratio of the L* ranges may be used instead. We may symbolically describe what happens to Chroma under this method as follows:

$$C^*_r = CCR \cdot C^*_o \tag{5}$$

where the subscripts o and r indicate the original and reproduction, respectively, and CCR, the Chroma Compression Ratio, is computed as follows:

$$CCR = L^*\ \textit{range of reproduction} \div L^*\ \textit{range of original} \tag{6}$$

The L* ranges of the two media described earlier in Table 1 are 97 for the original and 85 for the reproduction. Thus, under the Constant Compression method, the Chromas in the reproduction would be 0.8763 times as large as the Chromas in the original.

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* Pobboravsky, Pearson, and Yule used the word "saturation" to describe what we now refer to as "Chroma." For this excellent reproduction, they cite a "saturation" ratio of unity.

Independent Compression of Chroma and Lightness

The last two methods presented differ in the treatment of the Chroma. The Constant Compression approach applies a factor which depends on the L* ranges of the original and reproduction; the Constant Hue and Chroma approach leaves Chroma unchanged. Both these techniques may be thought of as being special cases of a more general method in which the Chroma may be compressed, but to a different degree. In other words, the compression applied to Chroma is independent from the compression applied to Lightness.

Color reproduction involves a series of tradeoffs. On one hand, we would like a reproduction to appear as chromatic as the original. On the other hand, we may loose detail and introduce undesirable artifacts, such as false contours, if too many desired colors are outside the gamut of the reproduction medium. Some compromise is necessary. The object of this approach is to permit such a compromise.

Instead of computing the CCR as the ratio of the L* ranges, or making it equal to unity (as is done for under the Constant Hue and Chroma mapping), an intermediate value is chosen. We have found a value halfway between these two values (they are not extremes) is satisfactory. Values of the CCR lower than that indicated by Equation (6) have been found in an empirical investigation of color mapping: Montecalvo [14] reproduced a Kodak Q-60B target, and had an L* range ratio of 0.8004, with a CCR of approximately 68 percent.*

Of the five color reproduction algorithms described in this paper, two were rejected as being unsatisfactory on theoretical grounds. Two of the remaining algorithms are actually special cases of this fifth method. With the exception of deliberate distortions for certain colors, such as grass, sky water, and Caucasian skin, [1] the question of how to map colors from an original to a reproduction would seem to reduce to determination of the optimal level of Chroma compression.

EXPERIMENTAL

We conducted a formal subjective evaluation of these five color mappings. A series of scanned color photographs served as originals. These scenes included a group of three people (all of different race and complexion), a still life, a night scene, a building, etc. These scanned images, displayed on a CRT monitor, served as our originals.

Rather than present a reproduction in a different medium, we chose to *simulate* a new medium on the CRT. This simulated medium has a reduced luminance range, similar to that

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* In fact, Montecalvo reported separate compression ratios for CIELAB a* and b*. These were nearly equal: 0.6934 and 0.6754, respectively. In his examination of a reproduction of a Kodak Q-60C target, he found significantly different compression ratios for a* and b*: 0.9316 and 0.7762, respectively. These bracket the L* range ratio of 0.8250. This disparity in compression ratios for a* and b* can lead to hue shifts – which we have deemed undesirable.

of a printed reproduction. The reproductions were displayed beside their corresponding original, on the same monitor. There was no need to account for differences in surround, highlight luminance, or other factors. Instead of requiring an appearance model which accounts for these factors, we used a uniform color space, CIELab.

Using a highly accurate model for the color performance of the CRT [15] enables us to transform back and forth between monitor drive values and device independent color specifications, such as CIELab. We had measured an L* range of 97 for the monitor under controlled ambient conditions, and set an L* range of 80 for the reproduction medium.

We first performed a small number of preliminary visual comparisons. The images were sized so a reproduction could be displayed beside its original. Both original and reproduction were viewed with a surround of monitor white, comprising one-third to one-half the available area. Our observers were asked to describe each reproduction as being either "acceptable" or "unacceptable."

Without exception, all reproductions made by the naïve approach (in which X and Z were held constant) were rejected as being unacceptable. The darker neutrals appeared greenish in these reproductions. This approach was clearly unacceptable.

The problem with the second method, Constant Chromaticity, was more subtle. In this technique, the Chromas of darker colors were increased. This was apparent in the side-by-side comparison. That it was unacceptable was not as obvious as in the previous case. However, for most originals (the night scene was a possible exception) this method of reproduction was not preferred.

Our three remaining color reproduction algorithms differ in their treatment of Chroma. The third type, which leaves Chroma unchanged, has a CCR of unity. The fourth type, in which all tristimulus values are given equal compression, involves a CCR of 0.8247. The fifth type of reproduction, with independent compression of Lightness and Chroma, was represented with two CCRs: 0.87, and 0.93. These are between the values used for the other two techniques. All were judged acceptable, and it was difficult to choose a clear winner.

A paired comparison test was then performed. These tests were conducted at the Munsell Color Science Laboratory at the Rochester Institute of Technology. Observers were presented with an original image, and two reproductions of it. In this experiment, only one image could be viewed at a time, but the observer could toggle back and forth between the original and the two reproductions. They were asked to choose the better of the two reproductions. The process was repeated until all combinations of color reproduction algorithms have been compared, for all original scenes.

Our panel consisted of 11 observers, nine of them male. All were experienced at viewing color images; several were Graphic Arts professionals. We performed a replication of one observer's evaluations.

RESULTS

Table 2 contains the results of our paired comparison experiment. The rows and columns are ordered in increasing magnitude of CCR.

This reproduction:	CCR = 0.82	CCR = 0.87	CCR = 0.93	CCR = 1.00
is preferred over				
CCR = 0.82		66%	65%	64%
CCR = 0.87	34%		67%	67%
CCR = 0.93	35%	33%		47%
CCR = 1.00	36%	33%	53%	

Table 2.

The results of our paired comparison evaluations are reported. The table indicates, for example, that reproductions with a CCR of 0.82 were preferred over reproductions with a CCR of 0.87 34 percent of the time.

Applying Thurstone's method of Comparative Judgements, [16] we arrived at an interval preference scale. These appear in Table 3. In computing these values we assumed equal discriminal dispersions. The preference values are displayed in graphical form in Figure 4.

CCR:	0.82	0.87	0.93	1.00
Preference Coordinate:	-1.16	-0.47	0.91	0.72

Table 3.

The interval preference scale, based on our paired comparison evaluations.

DISCUSSION

Our panel of observers has expressed preference for one of the reproduction types made with independent compression of Lightness and Chroma. The preferred CCR is 0.93, nearly midway between the CCR used by the Constant Compression algorithm (0.82) and the CCR used by the Constant Hue and Chroma algorithm (1.00). Therefore, we recommend that CCR be calculated as follows:

$$CCR = \frac{1}{2}\left(1 + \frac{L^*\, range\, of\, Reproduction}{L^*\, range\, of\, Original}\right) \tag{7}$$

In practice, this factor could be applied to both a* and b*, for example, of a color in the original to compute the a* and b* of the corresponding point in the reproduction:

$$a_r^* = CCR \quad a_o^*$$
$$b_r^* = CCR \quad b_o^* \tag{8}$$

The reproductions in our subjective paired comparison test involved tone reproduction characteristics which, when plotted in L*, involved very little curvature. More curvature is sometimes introduced because the original may be high- or low-key, or viewed in different surround conditions than the reproduction. Our results may not apply to situations which involve large deviations from linear compression in L*. We believe they will be at least an excellent departure point in these situations.

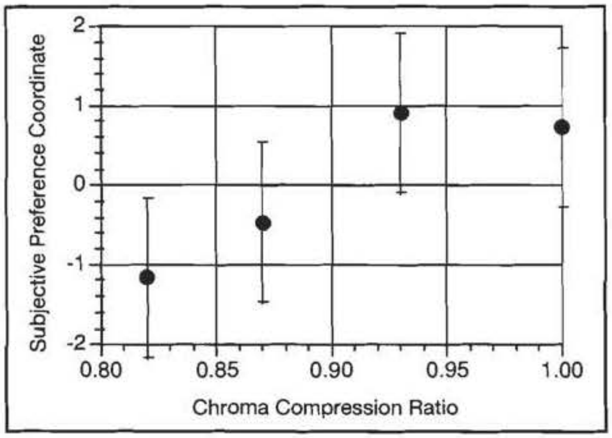

Figure 4.
The relationship between CCR and viewer preference. The error bars indicate ±1 standard deviation.

CONCLUSIONS

A color reproduction will often have a different luminance range than its original. This precludes a colorimetric match. It is necessary to map the colors from the original medium to the reproduction medium. A color reproduction algorithm is used for this.

Color reproduction algorithms have two components. The first describes a general mapping of colors. Some of the colors selected by this general mapping will not be producible by the reproduction medium; they are called non-reproducible colors. An important goal of this first component is to reduce the number of non-reproducible colors. The second component of a color reproduction algorithm handles the mapping of the non-reproducible colors. This paper discussed only the first component.

Existing literature described how the luminance / lightness component of color should be mapped. This mapping is referred to as tone reproduction. A linear compression in Bartleson and Breneman darkness coordinates is recommended for most originals. This differs slightly from linear mapping in L* or Munsell Value. Proper placement of highlight and shadows is important for good tone reproduction.

We have described a color reproduction algorithm for reproducible colors. In addition to proper tone reproduction, the algorithm preserves hue and neutral balance. (It is necessary, of course, to have a calibrated model of the output process to actually produce these colors.) The algorithm postulates a simple proportional relationship between the chromatic components of the colors in the original and reproduction. Mapping of the luminance / lightness component is performed by a linear compression in Bartleson and Breneman Darkness.

In this paper we have introduced the Chroma Compression Ratio, or CCR. In a subjective paired comparison test we performed, we found preference for a CCR value midway between unity and the ratio of the L* range of the reproduction to that of the original.

ACKNOWLEDGEMENTS

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APPENDIX

CALCULATION OF BARTLESON AND BRENEMAN'S LIGHTNESS AND DARKNESS

Bartleson and Breneman's original form for brightness involved two nonlinear terms, and was not invertible in closed form. It depended not only on surround conditions, but also on highlight luminance. Bartleson has since made a recommendation for a simplified version. He pointed out, "the relative brightness functions for a given surround condition do not change very much over the entire range of illumination conditions of normal interest in image assessment," and suggested that "a single brightness function for each surround condition of general interest would probably suffice for most purposes." [17]

Bartleson offered a simplified, invertible alternative for three different surround conditions: Dark, Dim, and Light. We have introduced small modifications to the formula for the Light surround condition.

We have found it convenient to work with Darkness, which is a complemented and normalized version of Lightness. A value of zero indicates white, with the same luminance as the media highlight. A Darkness of unity indicates black, with a luminance of zero. (Some authors report this as a percentage, so 100 percent represents an absolute black.)

Luminance to Lightness and Darkness

Dark Surround:

$$L^{**} = 25.4\left(100\frac{Y}{Yn} + 0.1\right)^{0.33}\quad 16 \qquad V = 1.16\quad 0.254\left(100\frac{Y}{Yn} + 0.1\right)^{0.33}$$

Dim Surround:

$$L^{**} = 17.5\left(100\frac{Y}{Yn} + 0.6\right)^{0.41}\quad 16 \qquad V = 1.16\quad 0.175\left(100\frac{Y}{Yn} + 0.6\right)^{0.41}$$

Light Surround:

$$L^{**} = 110.50\left(\frac{Y}{Yn} + 0.01\right)^{0.50}\quad 11.05 \qquad V = 1.1105\quad 1.1050\left(\frac{Y}{Yn} + 0.01\right)^{0.50}$$

Lightness and Darkness to Luminance

Dark Surround:

$$Y = \frac{Yn}{100}\left[\left(\frac{L^{**}+16}{25.4}\right)^{1/0.33}\quad 0.1\right] = \frac{Yn}{100}\left[\left(\frac{1.16\quad V}{0.254}\right)^{1/0.33}\quad 0.1\right]$$

Dim Surround:

$$Y = \frac{Yn}{100}\left[\left(\frac{L^{**}+16}{17.5}\right)^{1/0.41}\quad 0.6\right] = \frac{Yn}{100}\left[\left(\frac{1.16\quad V}{0.175}\right)^{1/0.41}\quad 0.6\right]$$

Light Surround:

$$Y = Yn\left[\left(\frac{L^{**}+11.05}{110.50}\right)^{2}\quad 0.01\right] = Yn\left[\left(\frac{1.1105\quad V}{1.1050}\right)^{2}\quad 0.01\right]$$

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