Gamut Mapping with Enhanced Chromaticness

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Abstract

In a color perception experiment, we found that, in CIE perceptual color attributes terms, the darker (lower L*) of a pair of highly chromatic colors of the same chroma (C^*_{ab}) appear to be more colorful. We further derived a model to factor in L* along with C^*_{ab} to describe the perceived colorfulness. In cross media color gamut mapping, it is often desired to reproduce highly chromatic colors to be as chromatic as the system can produce. We apply the found relationship to gamut mapping in the CIELAB space to demonstrate that we can map colors of high C^*_{ab} to darker colors to create the effect of a more colorful, more chromatic mapping.

Introduction

Gamut mapping on the iso-hue plane, the so-called 2D gamut mapping, makes adjustment to lightness and chroma by setting a set of mapping goals. Reported 2D gamut mapping goals include preservation or enhancement of certain properties of the images to be reproduced such as chroma, lightness, luminance contrast, etc.[1] The specification and realization of these goals inevitably relies on the classification of various image color attributes often represented by the CIE attribute correlates or predictors, namely, L*, C^*_{ab}, and h_{ab}. It is well known that these predictors only crudely represent their actual perceptual counterparts. Further, Melgosa et. al. reported data to show that although the three attributes of color are easy to understand from their definitions, discernment of these attributes in Munsell color samples pairs are difficult even for experienced observers.[2] These facts imply that when a reproduced image is evaluated at the end, fulfillment of some of the mapping goals will be compromised.

For example, one important quality aspect of color image reproduction is the chromaticness, colorfulness or vividness of the reproduced highly chromatic colors. They are often used as an indicator of the color reproduction capability of a system. Vividness, colorfulness, and chromaticness correspond to the CIE C^*_{ab}. Therefore mapping algorithms can aim to favor higher C^*_{ab} for highly chromatic colors along with fulfilling other mapping goals. (Chromaticness and colorfulness are used in appearance modeling to represent absolute perceptual strength of a color hue, as compared to chroma, which is relative to the white point. Here, we use these terms in the same senses that they are used by a naïve customer in everyday life. When used to describe two copies of an image, these terms are equivalent.)

In this paper, we describe a visual experiment to determine the effect of CIE lightness (L*) on the perceived colorfulness of a series of highly chromatic color samples of the same h_{ab} value but with small variations in C^*_{ab} and L*. We found that L* significantly contributed to the perceived colorfulness for this set of samples. We apply the found relationship to gamut mapping in the CIELAB space to demonstrate that we can map colors to darker colors to create the effect of a more chromatic mapping.

Experiment

For each primary color (red, green, blue, yellow), nine samples of the same CIELAB hues but of small variations of L* and C^*_{ab} were produced. Samples were printed using a Lexmark Optra45™ color inkjet printer on high resolution premium inkjet paper. The average h_{ab} of these samples are shown in Table 1. For each primary color, the nine samples were all within a 0.6 h_{ab} range of variation.

Table 1. Average CIELAB hue angles of the samples.

Color	red	green	blue	yellow
CIELAB h_{ab} (°)	24.2	176.7	264.2	84.7

Fifty observers participated in the test. All of the observers passed the Ishihara™ color vision test immediately prior to this test in the same test room and therefore considered fully adapted to the D50 illumination used in this test. The test was conducted using the method of rank order. The observers were asked to simply rank the samples from the most colorful to the least colorful according to their own definition of colorfulness. The order of presentation of the four different sets of samples was randomized for each observer.

Results

The purpose of the test is to investigate the correlation between the perceived colorfulness with the colorimetric perceptual attributes (in this case, C^*_{ab} and L*). Therefore, the goal was to derive the perceived scaled colorfulness of the samples. The results of the rank ordering were converted into paired comparison data. The converted paired comparison data were used to derive the scaled colorfulness data based on the case V model of Thurstone's law of comparative judgment using the least square method.[3] The results are shown in Figure 1 (values for the green samples are from the newer model as will be described in the next section).

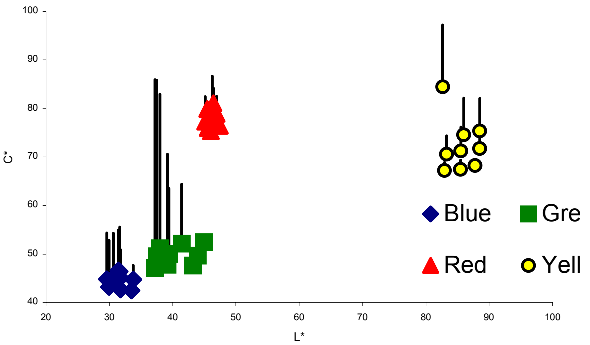

Figure 2. Scaled colorfulness for all the samples. Colorfulness is represented by the corresponding vertical bars(magnified 10 times for display clarity).

The average proportion of choice fit errors were calculated and given in Table 1. To test the appropriateness of the Case V model, the χ^2 values were also computed using Mosteller method4 and shown in Table 2. In this case, the degree of freedom for nine stimuli is 28 and the critical χ^2 value at the p=0.05 level is 41.[3,4] Therefore, the green sample test data cannot be appropriately fitted by the Thurstone's case V model.

Table 2. Average proportion of choice errors fitted with the Case V model and the corresponding χ^2 value of the fit for all four color groups.

	Red	Green	Blue	Yellow
Average error(%)	3	8	4	4
χ^2	10.44	71.80	13.38	14.14

The obtained scaled colorfulness values are subject to various potential error sources. The high χ^2 value for the green sample group indicates that Thurstone's case V model cannot adequately fit the test data. It is therefore necessary to use a more complex model. Here we use a newer model that combines the Thurstone's general model with the Bradley-Terry model. For this specific case, we assume that the discriminal dispersion is a function of the difference of the scaled values of the two stimuli. Applying the newer model and maximizing the maximal likelihood function according to the model (Eq. 1), an average proportion of choice fit error of 3% and a χ^2 value of 13.13 was achieved. Because two more parameters were introduced, the degree of freedom became 26. The χ^2 value is still below the critical χ^2 value of 38.89 at p=0.05.

$$MLL = \sum_{j=1}^{n} \sum_{k=j+1}^{n-1} \left\{ \begin{array}{l} p_{jk} \log\left[1-\alpha\int_{-\infty}^{s_j-s_k} \Phi(x,\sigma_{jk})dx\right] \\ +(N-p_{jk})\log\left[\alpha\int_{-\infty}^{s_j-s_k} \Phi(x,\sigma_{jk})dx\right] \end{array} \right\} \quad (1)$$

where $\Phi(x,\sigma_{jk})$ is the normal distribution with,

$$\sigma_{jk} = 1 + \alpha \left| s_j - s_k \right|^{\beta} \quad (2)$$

as the standard deviation; N is the total number of observers; p_{jk} is the total number of observers that judged sample j (with colorfulness s_j) is more colorful than sample k (with colorfulness s_k); α and β are constants to be determined. The obtained colorfulness is plotted against that obtained based on Thurstone's case V model as shown in Fig. 2. The α and β obtained were 0.147 and 1.933, respectively. The dependence of dispersion on scaled value difference is shown in Fig. 3 by plotting Equation 2. The improvement of the newer model over Thurstone's case V model can also be seen by comparing the fit residues by the two models as shown in Fig. 4 and Fig. 5.

Figure 6 shows the relationship between the scaled colorfulness and L* for the blue sample group as an example. Fig.7 shows the relationship between the scaled colorfulness and C' for the blue samples. The C' used here is C^*_{ab} corrected for non-uniformity based on the CIE94 by integrating its chroma difference component as given by Equation 5. [5]

A colorfulness scale is constructed to combine the effects of both C^*_{ab} and L* on the perceived colorfulness of all four color sample groups by using,

$$C_{Colorfulness} = C_0^{'} + 0.1C^{'}\left[1+\frac{C'}{L^*}\right]^3 \quad (3)$$

where C' is,

$$C^{'} = \frac{\ln(1+0.045C^*_{ab})}{0.045} \quad (4)$$

C_0' is the C' of the sample of the lowest scaled colorfulness value. The reconstructed or fitted colorfulness is plotted against the measured colorfulness for the blue color sample group as shown in Fig. 9.

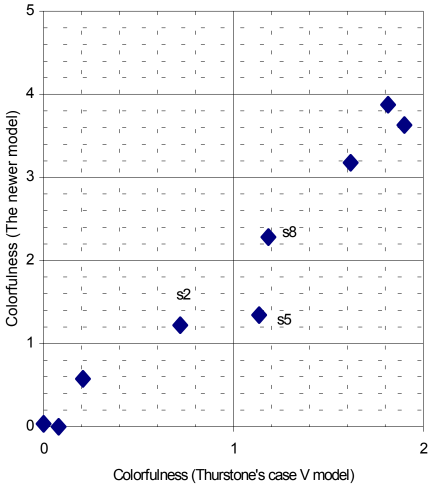

Figure 2. Comparison of colorfulness derived based on Thurstone's case V model and that based on the newer model.s2, s5, and s8 represents sample No. 2, 5, and 8, respectively.

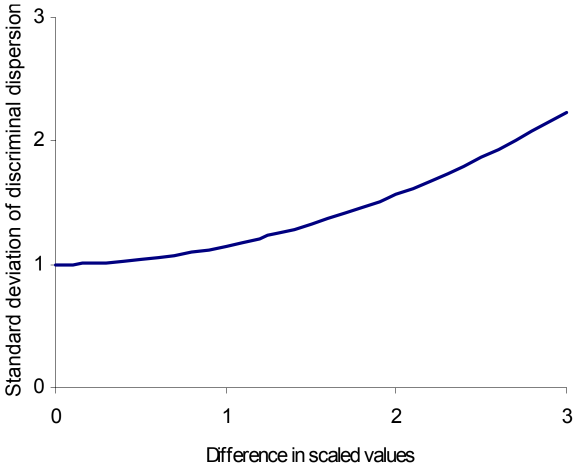

Figure 3. Dependence of the standard deviation of discriminal dispersion on the difference of perceived colorfulness between two green samples.

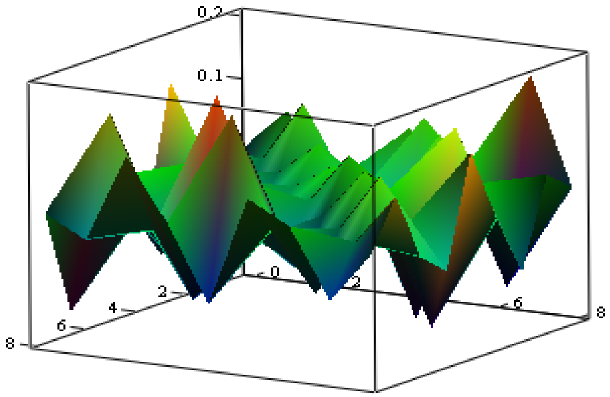

Figure 4. Fit residues (proportion of choice) of the Case V model to the green samples.

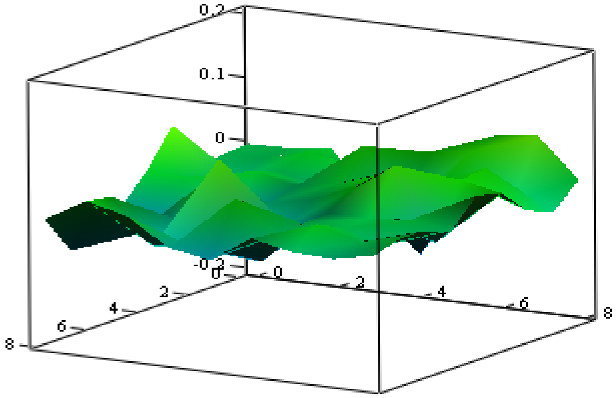

Figure 5. Fit residues (proportion of choice) of the newer model to the green samples.

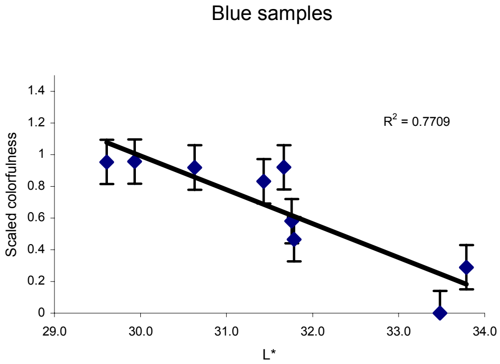

Figure 6. Scaled colorfulness versus the CIE1976 L lightness for the blue samples. The error bars represent the estimated standard deviations for each scaled colorfulness value estimated using a method given in reference 7. The solid line is the least square linear regression of the corresponding relationship with the R^2 value shown on the plot.*

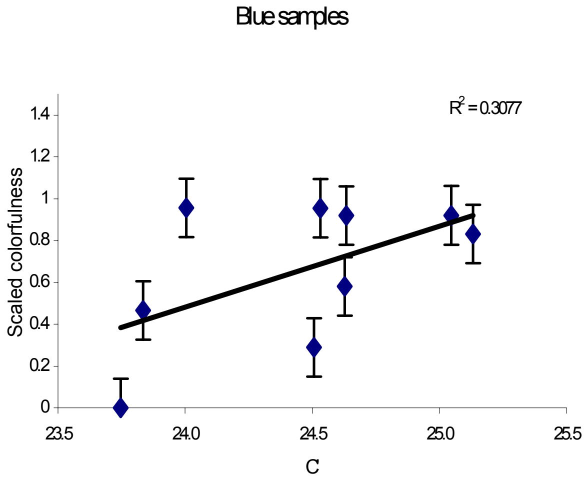

Figure 7. Scaled colorfulness versus C' for blue sample group.

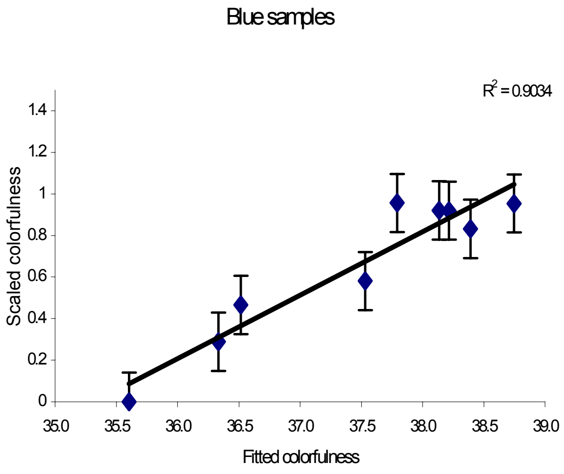

Figure 8. Scaled colorfulness versus the fitted colorfulness for the blue sample group.

Discussion

As shown in Fig. 1, the blue samples and the green samples had relative low C^*_{ab} in comparison to that of the red and yellow samples. The green samples also had relatively larger differences in L* in comparison to that in C^*_{ab}. Fig.1 shows the scaled colorfulness for each sample. The scaled colorfulness is only relative to each other within one group. The higher scaled colorfulness for the green samples does not indicate that they had higher perceived colorfulness over the red samples.

Thurstone's case V model proves to be appropriate for the red, blue and yellow samples groups. However, for the green samples, Thurstone's case V model does not provide a good fit. The newer model as shown in Eq.1 significantly improves the fit for the green samples. Comparison of the scaled colorfulness from the two models as shown in Fig.2 indicates that the results can be misleading when a wrong model is used. Fig. 2 shows that Sample 5 (s5) and Sample 8 (s8) have similar scaled colorfulness and higher than Sample 2 (s2) by about half a unit when Thurstone's case V is used. However, according to the newer model with the better fit, Sample 5 and Sample 2 have similar scaled colorfulness but lower than Sample 8 by about one unit. Fig. 5 and 6 show the fitting improvement by the newer model. Fig. 4 shows the dependence of the discriminal dispersion on scaled colorfulness difference. The discriminal dispersion could be twice as large when the two samples appeared distinctively different in colorfulness as compared to small difference in colorfulness. It indicates that the observers, as a whole, were less sure as to which sample was more colorful when there was a distinctive difference in colorfulness between the samples.

As an example, Fig.6 shows the relationship between lightness and scaled colorfulness for the blue samples. The results also show that there is clearly no correlation between scaled colorfulness and lightness for the red and the yellow samples (not shown here). However, there is significant correlation between scaled colorfulness and lightness for the green and blue samples. Especially for the green samples, the r^2 value is as high as 0.92, indicating that the observers simply regarded L* value as a measure of the perceived colorfulness, that is, the lower the lightness, the more colorful the samples appeared to the observers. We can probably trace this seemingly contradicting phenomenon back to the origin of our color perception. Color, to an average person, can usually be linked to a certain color material. Hence, purity, concentration, or density of the color material is linked to the term "colorful". When the concentration of colorant is high, it usually gets darker and more colorful. Fig. 7 shows an example of the relationship between CIE chroma C' and scaled colorfulness for the blue samples. The results also show that the red and yellow sample groups show significant correlations while there is little correlation for the green and blue samples (not shown here). The C' parameter is used here in an attempt to compensate for the non-uniformity of the CIELAB space. The conversion from C^*_{ab} to C' significantly compress the chroma scale. It made the chroma ranges smaller than desired although these were still discernable range for each color group.

The relationships shown in Fig. 6 and 7 suggest that both lightness and chroma can contribute to the perceived colorfulness of a color sample. Equation 3 combines the effects of both lightness L* and C' on the scaled colorfulness and provides a new scale for colorfulness (fitted colorfulness). The fitted colorfulness was then plotted versus the scaled colorfulness as shown in Fig. 8 for the blue samples. The fitted colorfulness with Eq.3 generally correlates better or equal than either C' or L* except for the green samples. The average r^2 value for the correlation of scaled colorfulness with L*, C' and the fitted colorfulness are 0.49, 0.53, and 0.81, respectively.

Gamut Mapping with Enhanced Chromaticness

The impact of L* to the perceived colorfulness (or chromaticness, vividness) found in this color perception study can be applied to color gamut mapping. The relationship described by Eq.3 indicates that we can achieve more chromatic mapping for the highly chromatic colors (both in and outside of the destination gamut) by reducing the L* of these colors.

One of the ways to implement such a mapping principle is to systematically reducing L* of the original colors of high C^*_{ab} values. As shown in Fig. 9, triangle ABC represents the original (source) gamut and A'B'C' represents the destination gamut on the L* C^*_{ab} plane for a specific hue angle. Prior to map ABC to A'B'C', a pre-mapping can be done to map P to P1 according to Eq. 5. Therefore, colors of the same lightness on the dash-dot line will be mapped onto the corresponding points on the curved dash line.

$$PP_1 = r\left[\frac{O_1P}{OB}\right]^2 \tag{5}$$

where PP_1 is the amount of lightness to be reduced for color P; *r* is a coefficient determines the maximum magnitude of lightness allowed to reduce.

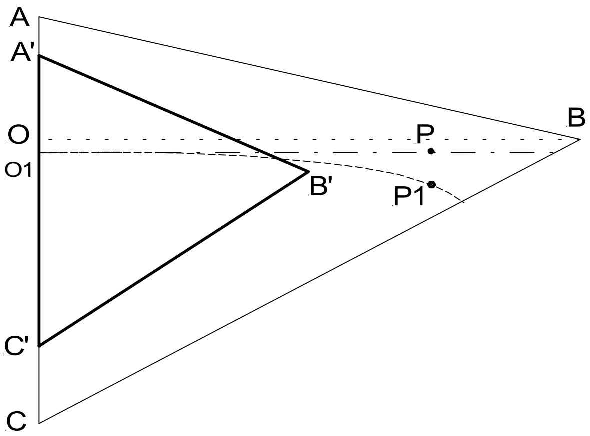

Figure 9. Pre-mapping to decrease the L.*

Once the pre-mapping is implemented, regular mapping algorithms can be used to accomplish the final mapping. To demonstrate the results of such a mapping scheme, we printed a sRGB copy of the ISO 400 standard image "Fruit basket" with and without the pre-mapping with a Lexmark C720 printer. Fig. 10 a) shows the ISO image printed with a shortest distance clipping mapping algorithm. Fig. 10 b) shows the print mapped with same clipping algorithm except with a pre-mapping lightness adjustment according to Eq. 5 (r=10). Most of the fruits' colors are out-of-gamut highly chromatic colors, their lightnesses were reduced according to Eq. 5 in Fig. 10 b), and it can be seen that they all look more chromatic, colorful and vivid.

Conclusions

Through a visual scaling experiment, we show that the CIE L* also contribute the perception of colorfulness (or chromaticness, vividness) of a high chromatic color. Using four groups of highly saturated color samples with identical h_{ab} but small variations in lightness (L*) and chroma (C^*_{ab}), we demonstrated the dependence of perceived colorfulness on lightness L* by scaling the perceived colorfulness of these samples. Such a dependence on L* may be attributed to the inaccuracy of the representation of the perceptual chromaticness by the CIE C^*_{ab}; It may also indicate that the visual system may not clearly discriminate the perceptual lightness from the perceptual colorfulness, chromaticness or vividness.

We apply the results to gamut mapping by systematically reducing the L* of colors of high C^*_{ab} prior to applying conventional gamut mapping algorithms. We present the result of the mapping with a pair of actual printed images to clearly show the enhanced chromaticness of the mapping.

Acknowledgement

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Figure. 10. a) shortest-distance clipping only; b) mapping with chromaticness enhancement and shortest- distance clipping