A Helical Model for Color Harmony

Shreeniwas Sharma
PhD Student, Dept. of Computer Science and Engineering,
Kathmandu University,
Nepal
Email: shree220 [AT] gmail.com

Jyoti Tandukar
Associate Professor, Dept. of Electronics and Computer Engg.,
Tribhuvan University,
Nepal
Email: jyoti [AT] explorug.net

Rabindra Bista,
Associate Professor, Dept. Of Computer Science and Engineering,
Kathmandu University,
Nepal
Email: rbista [AT] ku.edu.np

Abstract— **Among the many approaches to the study of color harmony tried so far, a relatively recent method is to leverage the large number of human-created and ranked color palettes, such as those hosted at colourlovers.com. Analysis of these large datasets could provide insights into the nature of color harmony. In this study, a large number of palettes with five colors were observed in 3D in different color spaces. It was found that a significant number of such palettes fit a single pitch of a helix aligned along the lightness axis, but not centered at the origin of the a-b plane in CIELAB and Oklab spaces. Considering the presence of an accent color, more than 50% of the highly ranked palettes studied fit the helical model. The helical model was then used to create new color combinations. In a survey, respondents were asked to like or dislike the patterns colored with these color combinations. It was found that the new color combinations thus formed were almost as harmonious and pleasing as the originals.**

Keywords- color harmony; large datasets; Oklab; helical model; color combination

I. Introduction

A. Background

Color harmony is the aesthetically pleasing arrangement of colors within a composition [1]. It is a fundamental concept in design, art and visual composition. Color harmony is important in different fields such as graphic design, interior design, fashion, fine arts etc. Currently, it is a multi-disciplinary study involving principles from physiology, psychology and technology for creating visually impactful and engaging compositions.

Color and color arrangement has been piquing the interest of scholars of all times since Aristotle, Sir Isaac Newton, Johann Wolfgang von Goethe, ME Chevreul, Johannes Itten to name a few [2]. The 20th century saw continued development in the study of color harmony with new theories and advancements in technology influencing the field. In the 21st century, the study of color harmony has continued to evolve, with researchers incorporating advancements in technology, cognitive science and cultural studies [3].

In recent times, there has been a rapid increase in the number of human-created harmonious color combinations. At sites like colourlovers.com, color.adobe.com, coolors.co, users have created and ranked a large number of colors and color palettes. This study focuses on the data available at colourlovers.com which provides an API [4] that gives access to the full range of data that it has collected since 2005. Currently, there are more than 10 million colors, 5 million color palettes and 6 million colored patterns available for analysis of color aesthetics and color harmony.

In a study by O'Donovan et al. [5], the authors proposed an algorithm to extract harmonious color palettes from large datasets, specifically utilizing data from colourlovers.com. The authors analyzed over 200,000 color palettes from colourlovers.com and used an optimization-based approach to generate a compatibility model for color palettes. The study showed the potential of using large datasets from online communities to study color harmony trends and preferences.

B. The Problem

Models of color harmony developed so far are quite complex. For instance, in [5], the authors have derived a feature vector with 334 dimensions from a color palette and then feed it to a linear regressor to identify the top 40 features that affect the rank of a color palette. The resulting model is still quite complex.

While observing a large number of human-created and ranked color palettes in 3D space, it was observed that many such palettes could be following a helical pattern. If this is true, it should be possible to find a relatively simple relationship between colors in the palette – one that many palettes conform to. If such a relationship could be found, it would simplify further research in the field of color harmony, and also enable the creation of new color palettes for color harmony.

C. Objective

The objective of this study is to observe a large number of color palettes in 3D in different color spaces to verify that the colors in the palettes follow a helical pattern, and to find the color space in which this behavior is mostly exhibited. Once this is verified, find different methods that could be used to create new color combinations based on the helical model. Third, compare the likelihood that the user will like an algorithmically created color combination with the likelihood that the user will like the original color palette.

II. METHODOLOGY

A. Data Acquisition

The top ranked color palettes from colourlovers.com were acquired with a syntax such as https://www.colourlovers.com/api/palettes/top?format=json&showPaletteWidths=1&numResults=100&resultOffset=0&hueOption=red. The resultOffset can take values such as 100, 200 and so on up to 900 and the hueOption parameter can be one of red, orange, yellow, green, aqua, blue, violet, and fuchsia, thus providing access to 8000 color palettes. A majority of color palettes in colourlovers.com have 5 colors. Out of the 8000 color palettes, 7152 had 5 colors. This study makes use of these 7152 color palettes having rank from 1 to 25000.

Alternately, a syntax such as https://www.colourlovers.com/api/palette/113451 provides access to individual color palette data. By varying the last query parameter from 1 to 400,000, a larger dataset was acquired. Out of these, 386,400 had 5 colors and were used in this study.

B. Color Spaces

In this study, color palettes were plotted in four color spaces – the HSV color space, the Munsell color space, CIELAB color space and Oklab color space. The HSV color space was considered because colourlovers.com palette offers a HSV color picker to create color palettes. CIELAB and Munsell color spaces were considered because they are established in the scientific community as perceptually uniform color spaces.

The Oklab color space was proposed by Björn Ottosson in 2021 as a new perceptual color space for image processing. Oklab was included in this study as it is said to be able to predict perceived lightness, chroma and hue well, while being simple and well-behaved numerically and easy to adopt [6].

C. Munsell Color Space

The Munsell color space is a three-dimensional color space developed by Albert H. Munsell in the early 20th century [7]. It is based on the concept of a perceptually uniform color space where equal distance between colors represents equal differences in perceived color. The color space is organized in the form of a color tree, with hue (H) as the circular axis, value (V) as the vertical axis and chroma (C) as the radial axis.

The Munsell renotation data is a set of numerical values that describe the Munsell color space in terms of the CIE xyY color space [8]. The renotation data consists of a table of Munsell color samples, where each sample is represented by its Munsell hue, value and chroma coordinates (HVC) along with its corresponding CIE xyY tristimulus values. The renotation data are currently made publicly available by the Munsell Color Science Lab Educational Resources [9] at http://www.rit-mcsl.org/MunsellRenotation/real.dat.

This study uses 2734 colors from the renotation data and 10 additional neutral values from black to white to quantize palettes from continuous color space in order to study the helical fit of the palette in Munsell color space. The CIEDE2000 color distance formula [10] was used to find the closest color among the discrete colors.

D. Best Fitting Helix

In this section the method used to fit the helix in CIELAB and Oklab color spaces is described. In these spaces, L is plotted along the z-axis, a and b are plotted along the x and y axes respectively. A similar method was used for HSV and Munsell HVC using the V component in the z-axis and the other two components in the x-y plane.

The five points of the palette plotted in 3D space were projected onto the x-y plane. First, a best fit circle was found using the orthogonal distance regression method [11] which determines the curve that minimizes the sum of square of distances from each data point to the closest point on the curve. Given a set of n points (x_1, y_1), (x_2, y_2) … (x_n, y_n), the linear least squares analysis [12] gives (1).

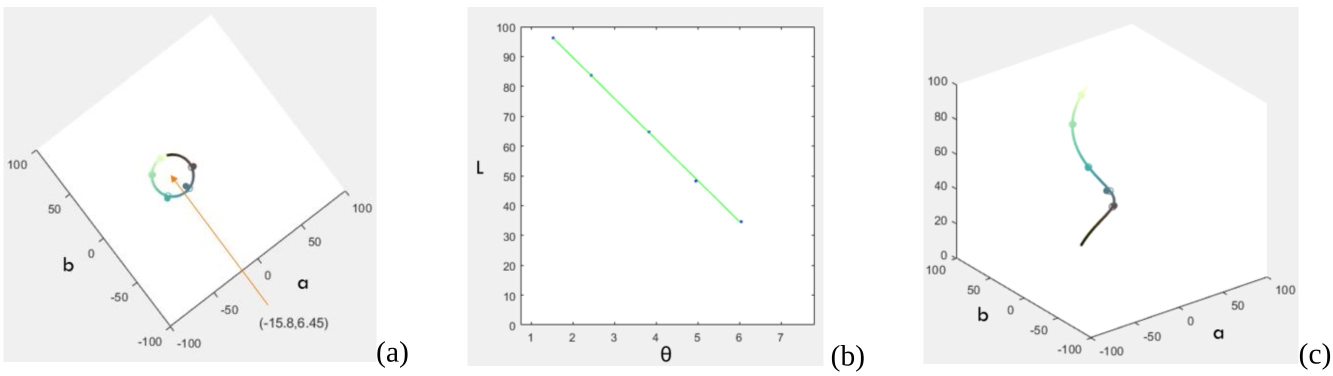

Figure 1: (a) Lab coordinates of palette colors were projected to the a-b plane and a best fit circle was found. This gives the radius and center of a cylinder. (b) The circle was unrolled on a 2D plane. The θ of the points were plotted against L values of palette colors. A best fit line was found by linear regression. (c) The line was projected back onto the cylinder to get a helix that fit the palette colors in CIELAB color space.

The co-ordinates of the circle's center (x_c, y_c) and radius r can then be calculated as in (2).

$$x_c = a/2$$
$$y_c = -b/2 \qquad (2)$$
$$r = \sqrt{(a^2/4) + (b^2/4) - c}$$

The circle when extruded along the z axis gives us the cylinder whose surface contains the desired helix.

The circle thus obtained was then rolled out along the circumference on a 2D plane. A scatter plot was drawn on this plane with the x-coordinate being the θ of the points as they are encountered on the circumference and the y-coordinate being the z values that we left out earlier. Linear regression of these points gave the best fit line on this 2D plane. When the line is projected back on the cylinder, we get the best fit helix.

This process performed on the L-a-b coordinates of the palette colors is illustrated in Figure 1. Adding 2π to θ does not affect a point's position on the circumference, but it affects the best fit line. Whether or not to add 2π to the θ of each point was determined iteratively to maximize the goodness of fit.

While computing the best fit line, the coefficient of determination, R^2 was considered the goodness of fit and a threshold of 90% distinguished whether a color palette fit the helix or not.

Graphics designers usually add an accent color to a color palette. If a palette did not fit the helix above, the presence of an accent color was considered. In such a case, each point was removed while fitting the line and R^2 was calculated for fitting the remaining four points. The removal of the point that resulted in the largest R^2 was considered the accent color. If this also didn't result in a R^2 greater than 90%, it was considered that the palette did not fit the helix.

E. Deriving New Color Combinations

Once we have the helix and the cylinder it inscribes, we can derive new color combinations from it. Minor variations to the original color palette can be obtained by selecting points on the same helix. For instance, points uniformly spaced on the helix, points randomly spread on the helix, original points randomly perturbed on the helix. More varied color combinations can be derived by drawing a different helix on the same cylinder and selecting points on this helix. To draw a new helix, a 2D line was drawn in the 2D plane and projected back to the cylinder.

F. Hue Templates

The traditional method of creating harmonious color combinations is using hue templates. In this study, we use traditional hue templates [13] to create color combinations for comparison purposes.

G. User Validation

A set of 24 patterns with 5 colors each were selected. Each pattern was colored with a randomly selected palette from colourlovers.com, a version of the palette mapped to the helix, a palette derived from the helix and a palette derived using the traditional hue template method. An app was developed to present 200 of such images in random order interspersed with 300 other colored versions of the same 24 patterns to 20 respondents. The respondents were asked to like or dislike the colored patterns. To check the consistency of the responses, 50 check images were also introduced. The check images were the same as the original images. If the responses for check images were different than the response for the original image in 75% of the cases, the respondent's response was discarded.

III. RESULT AND DISCUSSION

The two datasets, one with highly ranked 7152 palettes, and another with a random sample of 386,000 palettes were plotted in four 3D spaces – HSV, Munsell, CIELAB and Oklab. To verify that a significant number of palettes could be following a helical path, the best fitting helix was found in each of these spaces. Considering R2 > 90% as a good fit, the percentages of palettes that fit a helix were as listed in Table 1.

TABLE I. PERCENTAGE OF PALETTES THAT FIT A HELIX IN DIFFERENT COLOR SPACES

	HSV	***Munsell***	***CIELAB***	***Oklab***
Random samples	9.35%	9.05%	16.19%	16.82%
Highly ranked samples	14.25%	13.74%	22.99%	23.50%

If all 5 points in the palette did not fit the helix, the presence of an accent color was considered. With the consideration of an accent color an even larger percentage of colors conformed to the helical model. The results (including palettes that fit without accent color) are listed in Table 2.

TABLE II. PERCENTAGE OF PALETTES THAT FIT A HELIX WITH THE CONSIDERATION OF AN ACCENT COLOR

	HSV	***Munsell***	***CIELAB***	***Oklab***
Random samples	34.31%	36.60%	44.68%	46.44%
Highly ranked samples	45.09%	44.55%	55.86%	58.14%

It is interesting to observe that colourlovers.com offers a HSV color picker, and any pattern due to selection bias would be visible in the HSV color space. However, it is seen that a significant number of palettes fit a single pitch of a helix aligned along the lightness axis in the CIELAB color space and slightly more in the Oklab color space. It is also interesting to note that the axis of the helix does not pass through the origin on the a-b plane as seen in Figure 2 and Figure 3.

Several color combinations were derived from the helix thus formed. These are shown in Figure 4.

The designs in the first and last column in Figure 4 were presented to respondents as described in section 2.7 above. A total of 20 respondents participated in the survey. The results of 3 respondents were discarded because the consistency of responses among original and check (repeating the original) images were not same in more than 75% of the cases. The responses of the remaining 17 participants are summarized in Table 3.

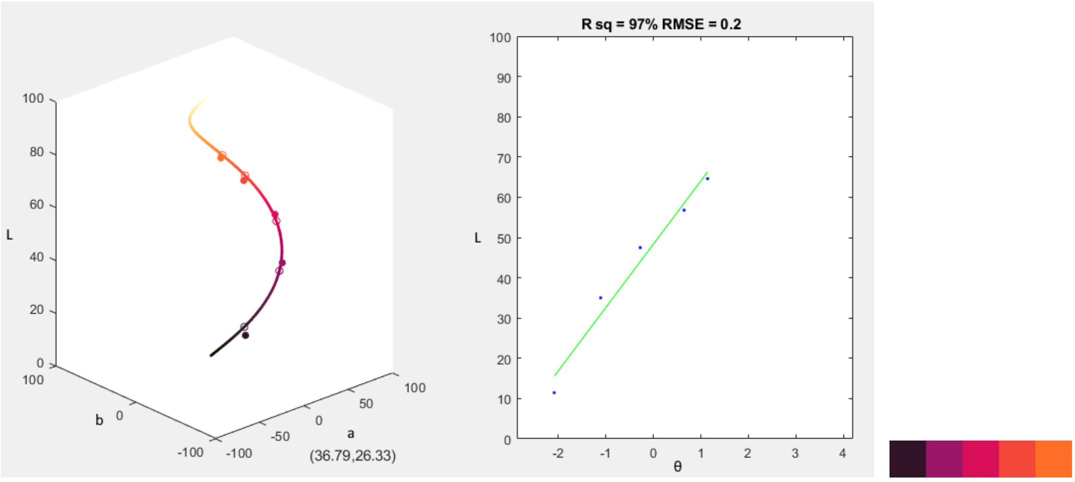

Figure 2: A palette that fits a helix without considering an accent color

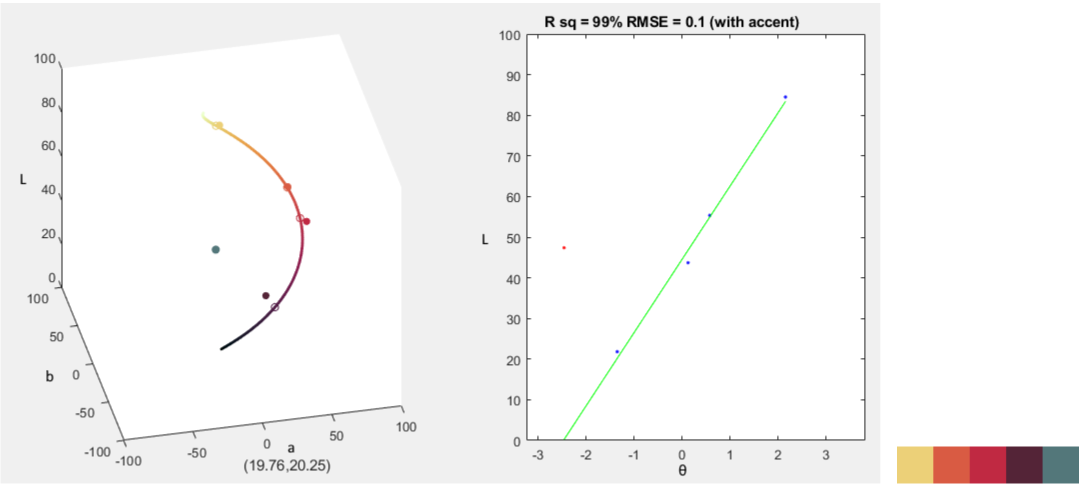

Figure 3: A palette that fits a helix with the consideration of an accent color

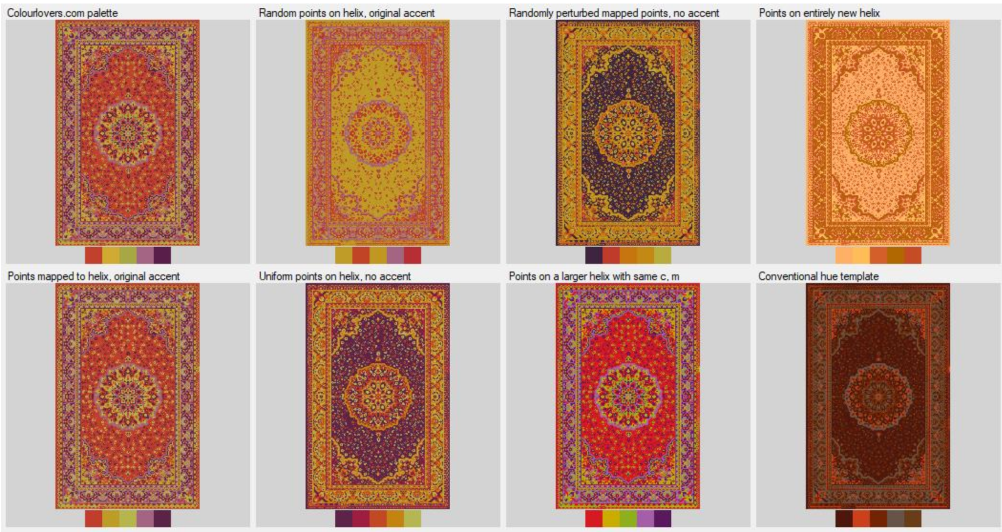

Figure 4: New color combinations derived from the helix using different methods

TABLE III. LIKELIHOOD THAT THE RESPONDENT LIKES A PATTERN

Pattern colored with colourlovers.com palette	49.9%
Pattern colored with original palette mapped to helix	45.8%
Pattern colored with palette created from new helix	43.2%

From the results, we can infer that the algorithmically created color combinations using the helical model are 87% as likely to be preferred as human created high-ranking palettes. This is a significant improvement compared to traditional hue template approach where the relative success rate was found to be 63%.

IV. CONCLUSION

It was verified that a significant number of highly ranked color palettes at colourlovers.com follow a helical pattern in CIELAB and Oklab color spaces. The consideration of the presence of an accent color in the palette resulted in a model that more than 50% of the highly ranked color palettes conformed to. The helical model was then used to create new color combinations and a user survey showed that algorithmically created color combinations using the helical model were also harmonious and performed comparably well as human created palettes.

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