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DISSERTATION ON

ALGORITHMIC COLORWAYS FOR GRAPHIC DESIGNS

In Partial Fulfillment of the Requirements for the

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by

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ABSTRACT

Color harmony is the aesthetically pleasing arrangement of colors within a composition. It is a fundamental concept in design, art and visual composition. It is important in fields such as graphic design, interior design, fashion, fine arts etc.

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. This study utilizes these datasets in two ways – a statistical and a geometrical method – to create new harmonious color combinations.

Analysis of these large datasets could provide insights into the nature of color harmony, but is usually overwhelming because of the sheer number of slightly differing colors. This study discusses the possibility of quantizing the colors in these color palettes to a manageable set of discrete colors without significantly affecting the aesthetics of the palette, and then builds on this finding to apply an n-Gram approach to create new harmonious color combinations.

To quantize the colors, two approaches were used – one was to map the palettes from continuous color space to a set of 2,744 perceptually uniform colors provided by the Munsell renotation data and another was to perform a K-means clustering of the colors of all the palettes to get a set of limited colors. It was found that the quantization error was minimum for the latter method. Colors from both the original and quantized color palettes were applied to a pattern. Several such colored patterns were presented to the respondents in random order and asked to like or dislike the colored pattern. It was found that when respondents liked/disliked a colored pattern, they also liked/disliked the same pattern colored with the quantized color palette, thus proving that color quantization has minimal impact on the harmony perception of the color palette.

Considering the quantized colors as words and palettes as sentences, it is now possible to use methods such as the n-Gram approach to create new color

combinations. In this study, we applied this approach by creating bigrams and trigrams from the corpus of highly ranked quantized color palettes and using them to predict new color combinations.

Additionally, 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 color combinations created using the n-Gram approach and the helical model. It was found that the new color combinations thus formed were almost as harmonious and pleasing as the originals.

Thus, this study establishes that the quantization of individual colors has minimal effect on the overall harmony perception of a color palette and proceeds to apply an n-Gram approach to create new harmonious color combinations. Additionally, by analyzing the large datasets, this study verifies that a significant number of highly ranked color palettes follow a helical pattern in CIELAB and OKLAB color spaces and then uses this model to create new harmonious color palettes.

BIOGRAPHICAL SKETCH

Shreeniwas Sharma is currently a PhD student at the Department of Computer Science and Engineering at Kathmandu University, Nepal. He received his Bachelor's degree from the Institute of Engineering, Tribhuvan University in 2000 and his Master's degree from the Asian Institute of Technology, Thailand in 2003. He received the Kul Ratna award for academic achievement during his Bachelor's degree and the WPMC award for his research during his Master's degree.

He is currently the CEO of Alternative Technology Pvt. Ltd., a company that develops graphics software for the carpet industry worldwide. Shreeniwas has been involved in the state of the art in computer graphics, image processing and color harmony for the past 25 years during the development of Galaincha and exploRUG, the company's flagship products.

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Dedicated to my father,

Late Binod Sharma

LIST OF ABBREVIATIONS

API	Application Programming Interface
CIE	International Commission on Illuminations
CIE76	CIE Color Distance Formula 1976
CIEDE2000	CIE Color Distance Formula 2000
CLT	Central Limit Theorem
CMY	Cyan, Magenta, Yellow
CNN	Convolutional Neural Network
CSS	Cascading Style Sheet
HSV	Hue, Saturation, Value
HVC	Hue, Value, Chroma
IoE	Institute of Engineering
KU	Kathmandu University
LAB	Lightness, Chromaticity in channel a, Chromaticity in channel b
LCh	Lightness, Chroma, Hue
RGB	Red, Green, Blue
RIT	Rochester Institute of Technology
sRGB	standard Red, Green, Blue
TU	Tribhuvan University

CHAPTER 1 INTRODUCTION

1.1 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. Albert H. Munsell, an American painter and teacher, developed the Munsell Color System, a three-dimensional model for describing colors based on hue, value and chroma. Munsell's work has had a lasting impact on the study of color harmony and has been widely used in various industries.

In the 21st century, the study of color harmony has continued to evolve, with researchers incorporating technological advancements, cognitive science and cultural studies [3]. Recently, 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 utilizes the data available at colourlovers.com which provides an Application Programming Interface (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. The color palettes at colourlovers.com are used in two ways – a statistical method, and a geometrical method – to create new color combinations.

1.2 Problem Statement

The analysis of large datasets of crowdsourced color palettes could lead to novel ways of creating harmonious color palettes. However, the problem with using large datasets of colors to study color harmony is that there are several recurrences of colors that appear similar, but are considered different by algorithms because their numerical values vary slightly [5]. One aim of this study is to establish that it is possible to quantize the large dataset of colors to a limited set of colors without significantly affecting the user's preference with regard to color harmony.

As per Burchett [6], color preference may vary by different attributes such as order, similarity, association, area, interaction and configuration. The user may like or dislike a color or color palette based on these parameters, but the user's response should be the same for a palette consisting of slightly different colors. Once this is established, it should simplify the study of color harmony and make it possible to apply interdisciplinary approaches such as n-Grams [7] to create harmonious color combinations.

Models of color harmony have been developed without having to quantize the colors. However, such models developed so far are quite complex. For instance, in [8], the authors derived a feature vector with 334 dimensions from a color palette and then fed 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 harmonious color palettes.

1.3 Motivation

Colourlovers.com is a site where users submit a large number of color combinations applied to an equally large number of patterns. A large community of users rates these color combinations. With the availability of such a large number of human-created color palettes with ranking from best to worst, it should be possible to apply statistical methods to study the universal appeal of a color combination applied to a pattern and predict new color combinations.

The findings of this study could simplify the future studies of color harmony, so it could be a contribution to the global body of knowledge in color harmony.

In addition, the possibility to create new and creative color combinations could give a competitive edge to Nepal's best export industries – carpet, pashmina, garment and handicrafts – and prevent loss of material, time and effort spent in repeated sampling. The author has been working in the field of computer graphics for the carpet industry of Nepal and importers of Nepalese carpets worldwide and has felt the need for the creation of color combinations for a given pattern.

1.4 Research Questions

The research questions formulated for this study are as follows:

1. Do the traditional color theory assumptions hold true in the statistical analysis of a large number of human-created and ranked color palettes?
2. Does the quantization of the colors in a color palette affect the harmony perception of the palette?
3. Is it possible to use a statistical approach such as n-Gram, which is usually used in computational linguistics, to predict new color combinations based on the corpus of human-created and ranked color combinations?
4. Is it possible to derive a geometrical model in 3D color space from a large number of human-created and ranked color combinations, and derive new color combinations from this model?

1.5 Objectives

The major objective of this study is to find new ways of creating harmonious color combinations using algorithmic approaches. The specific objectives are:

- To study patterns of color harmony from available data sources and test traditional color theories against this data

- To simplify the study of color harmony by quantizing a vast number of colors to a fixed set without affecting the perception of color harmony
- To statistically analyze and utilize methods such as n-Gram to create harmonious color combinations
- To develop a geometrical model to explain the relation between colors of a palette and utilize this model to create harmonious color combinations.

1.6 Structure of the Thesis

This dissertation comprises of six chapters.

Chapter 1 – Introduction discusses the problem scenario, motivation of the study, research questions and research objectives.

Chapter 2 – Literature Review is a review of literature within the field of study of color and color harmony. This chapter contains previous research work related to similar studies, building into why the experiments in this study were necessary.

Chapter 3 – Theoretical Framework builds a theoretical framework for the research discussing color-related technical aspects applicable for this study.

Chapter 4 – Methodology offers a methodology of research and the experiments carried out to conduct the research. This chapter also includes the research approach, tools and data required for conducting the research.

Chapter 5 – Results and Discussion presents the results and analysis as well as the findings of the study. There are findings from the experiments and findings from the user survey. Discussion of the implications of the study are included in this chapter.

Chapter 6 – Conclusions and Recommendations summarizes the contribution, novelty, limitations and future steps of this study.

The *Appendices* contain the palettes and patterns used for the study, the survey response data and the publications resulting from this study.

CHAPTER 2 LITERATURE REVIEW

2.1 Color Harmony

The Encyclopedia of Color Science and Technology [9] defines color harmony as a sense of accord and balance among colors in a visual composition or design, resulting in a positive affective response and/or cognitive judgment about color combination. Burchett [1] puts it in simpler terms as "colors seen together to produce a pleasing affective response are said to be in harmony".

Although the definition is simple, it has been found that it is very difficult to define, explain and predict color harmony [10]. The fundamental questions surrounding color harmony are – How are colors perceived together? How do they interact? What kind of response do they evoke from the viewer [11]? Artists, scientists and psychologists have been trying to answer these questions from the artistic, aesthetic, emotional and cultural perspectives.

After the discovery of the electromagnetic wave, Isaac Newton, in his book *Opticks* [12], observed that seven distinct spectral colors form a circular arrangement of hues and mix together to form other colors, resulting in one of the first color wheels.

Goethe [13] observed that colors were harmonious when there was color contrast and introduced his color wheel based on the idea that complementary colors are most beautiful as they form a whole. He developed a new color wheel based on symmetric arrangement of reciprocating colors on the wheel.

Chevreul [14] worked on what Goethe portrayed, and identified a fundamental law of simultaneous contrast of colors which detailed the effects that proximity between two colors has on what the eye sees.

Itten [15] went further and defined seven different kinds of contrasts based on a purposely designed color wheel. Itten introduced a color wheel in which he described color harmony, with an emphasis on hue. He referred to complementary colors as a two-color harmony. Itten also recognized the three-color harmony of hues that form an equilateral triangle, the four-color harmony of hues forming a square, the six-color harmony of a hexagon, etc. His schemes have been widely adopted by artists and designers.

Munsell [17] introduced the concept of color area in addition to color strength as determining factors for color harmony. A color with weaker color strength is assigned to a larger visual area.

Several theories were developed based on the available data and knowledge of the period. The theories used different primaries or color components, different wheels or color volumes and different measures of color harmony.

2.2 Color Harmony Models

Since the middle of the 20th century, models with strong computational aspects have emerged in the field of color harmony [3]. This section discusses some of these models and their relevance to this work.

2.2.1 Analytical Models

Analytical models have been developed from the long tradition of research into color harmony and the majority of studies so far can be divided into two categories – those based on the orderly arrangement of colors and those based on the interrelationship between colors [18].

Studies based on orderly arrangement of colors included those by Ostwald [16], Munsell [17], Itten [15], and Nemcsics [19] and suggested that colors could harmonize only when they were selected systematically from a hue circle or from a specific "path" within an ordered color space. On the other hand, studies based on the interrelationship of colors included those by Goethe [12], Chevreul [14], Moon and Spencer [20], Albers [21], and Chuang and Ou [22] and proposed that colors could harmonize only when they were complementary or analogous (similar) in either hue, lightness, or chroma.

Based on Itten's hue templates, Matsuda [23] performed extensive psychophysical research and introduced 80 color schemes, defined by combining 8 types of hue distributions and 10 types of tone distributions. These schemes were popularized by Tokumaru *et al.* [24] using fuzzy logic for harmony evaluation and color design.

These analytical models are less disruptive from the tradition of color harmony history and are still largely used in image processing for color harmonization. However, they are largely open to interpretation and leave out one or more color components. Matsuda's templates are based on data collected for fashion application, but they are now used for all kinds of applications.

Harkness [25] studied several color wheels from the art, perception, science and physiology perspectives and concluded that no one perfect or ideal color wheel could be identified and that we should understand the different philosophies behind each wheel and accept their well-established individual applications. Shamoi [26] highlighted the fact that not only the hue, but saturation and value also need to be considered for a universal model of color harmony.

In this work, we build upon the analytical models based on large datasets of publicly available color palette data including all components of the color data.

2.2.2 Numerical Models

Numerical models are empirical models that are developed from carefully designed experiments. The input stimuli are controlled and the user responses observed are used to model, predict and generalize the concept of color harmony.

One of the well-known models is that of Ou and Luo [18]. They presented 1431 color pairs constructed using 54 colors and presented to 12 observers who rated the pairs on a scale from extremely harmonious to extremely disharmonious. From the response, they developed mathematical equations based on different color features and calculated the correlation between the harmony prediction from the equations compared with actual harmony score from the user.

A similar methodology was used by Szabó [26] presenting about 10,000 color combinations to a limited number of observers (less than 10) who annotated the combinations with a rating on eleven levels. Based on the responses, they developed color harmony models for monochromatic and dichromatic two-color combinations as well as monochromatic and trichromatic three-color combinations.

Solli and Lenz [28] used Ou's model to develop a predictive model for estimating the perceived harmony of multi-colored images in the context of image indexing.

Later in 2018, Ou, Szabó and other color scientists working in numerical modeling worked together to develop a universal model for predicting color harmony [29] of color pairs with better correlation coefficient between the predicted score and the actual observer response. We use their model to compare the harmony score of a color pair and its quantized version.

In this work, we touch upon numerical modeling, trying to derive an equation for color preference based on the statistical analysis of highly ranked color palettes.

2.2.3 Human Factors

The evaluation of color perception is affected not only by color properties, but also by human factors such as time, fashion, culture etc. [11]. Zena O'Connor [10] argued that deterministic laws of color harmony cannot hold up because its evaluation is influenced by the individual's affective state, cultural differences, contextual, perceptual and temporal factors. She developed a conceptual model factoring in individual differences, cultural experiences, context, perceptual effects and the effects of time. But this remains largely a conceptual model, without any quantitative specification of the different attributes included in the model.

The large datasets of COLOURlovers palettes only have pseudo names of the creators and there is little demographic or semantic information to include human factors in the study. Hence this study focuses only on the analytical study of the palette data. Also, in the user survey and analysis of the response data, we try to reduce the human factors as far as possible by requesting the user to like or dislike a colored pattern as their first instinctive response.

2.3 Applications of Color Harmony

This study was motivated by the author's experience while working on Galaincha[1] and exploRUG[2] software for the past 25 years. Galaincha and exploRUG are graphics tools for the carpet industry of Nepal and worldwide. Galaincha is used by designers to create, recolor and visualize handmade Nepalese carpets. exploRUG is used by larger audience of carpet end-customers to customize the colors of the carpet to match their room setting before deciding on a purchase. The need for automatic generation of harmonious color templates for these graphic designs led to a wider understanding of color harmony aspects and hence this work.

In this section, we discuss a non-exhaustive list of color harmony applications.

2.3.1 Tools for Choosing Colors

Choosing a good color combination is not an easy task for the designer. Some designers may lack knowledge about color and art theory, whereas others may struggle with the digital color picking tools [30]. One way for designers to overcome this is using color atlases that suggest harmonious color combinations [31], or by selecting colors from a discrete set of colors such as Pantone[3]. Though the most common online tools for color palette creation rely on the traditional hue templates, there are alternative tools developed by the scientific community such as Harmonic Color Generator Tool [32], the QCharm tool [33], or the Virtual Color Atlas [34]. In a geometric approach to harmonic color palette design [35], the authors consider that colors follow normal distributions in tone (chroma and lightness) and hue and develop a tool to create color combinations for clothing applications.

2.3.2 Image Color Extraction

It is many a times required to extract a certain number of predominant colors from an image, for example to recolor a carpet that will match a given room photo. The general approach is to segment the image using a hard K-means clustering [36] or a fuzzy C-means clustering and then extract the representative color from each cluster.

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[1] https://galaincha.com.np
[2] https://explorug.com
[3] https://www.pantone.com

Though there are several methods of getting the representative color, application of color harmony theories will result in a better appearing color palette.

2.3.3 Color Harmonization

The automatic color harmonization of an image is achieved by recoloring content based on harmony criteria. This application was pioneered by Cohen-Or *et al.* in 2006 [37]. Their approach is to find the closest among Tokumaru's color harmony template [23] that matches the image's hue distribution and then fitting the hue distribution of the image within the template. There are variations [38] on segmenting the image, finding the harmonious template type by minimizing a cost function, then mapping colors outside the harmonious sector to make them fit the harmony template.

2.3.4 Image Indexing

While performing an image-based search, it is most natural that the user is looking for similar images. Similar images have similar colors and coverage. [39] extended Ou and Luo's model [18] to index multi-color images by their color harmony aspects and demonstrated that this could be used to find similar images based on harmony score request.

2.4 Large Datasets of Color Palettes

Since 2005, social websites dedicated to color theme design and curation have evolved. Starting with COLOURlovers and Adobe Kuler (later Adobe Color CC), there are now many websites that provide designers access to a huge communal dataset of harmonious color combinations. Although no expertise is required to explore, create or share a color theme, the community rates the color schemes, associating a rank with each color scheme.

These sites not only provide the designer with color harmony inspiration for design, they are also the sources of an unprecedented amount of data for color preference and color harmony analyses using current trends. The graph in Figure 2.1 illustrates the historical growth of users and data in COLOURlovers.

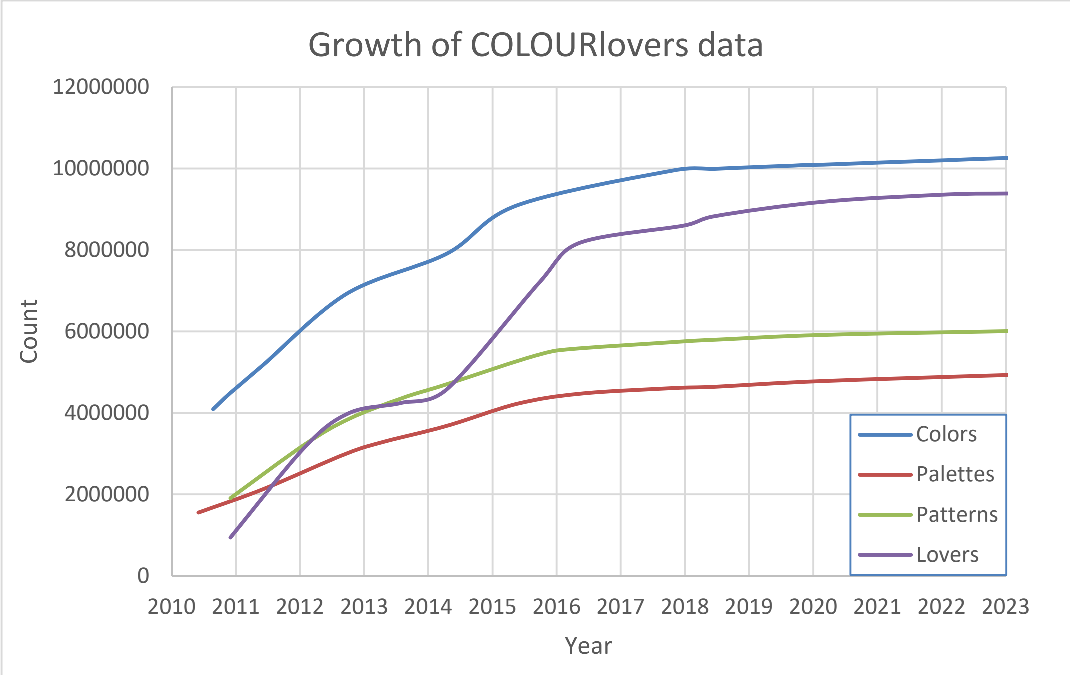

Figure 2.1 Growth of COLOURlovers data over time

2.4.1 Color Compatibility from Large Datasets

The pioneering study using such datasets was performed by O'Donovan *et al.* in 2011 [8]. The authors developed an algorithm to extract harmonious color palettes from large datasets, utilizing data from colourlovers.com. They analyzed over 200,000 color palettes from the site and used an optimization-based approach to generate a compatibility model for color palettes. The huge number of available color themes evidenced potential biases or limitations of existing color harmony theories.

Most color harmonization methods [37] and popular tools such as Color Schemer Studio, Colour Impact and Kuler are based on traditional color theory [40] extended by Matsuda and Tokumaru's hue templates. Even latest color harmony algorithms based on geometric approach [35], qualitative models [33], fuzzy logic [41], metaheuristic search [42] and Convolutional Neural Networks (CNN) [43] are based on some version of the hue templates. Contrary to popular belief, no evidence is found that geometric rules in a color circle, i.e., the hue templates, can directly predict compatible colors [30] and preferences are not rotationally-invariant about the color wheel.

O'Donovan *et al.* thus scrutinize the traditional approach of using hue templates for color harmony and open up the search for newer methods of creating harmonious color schemes and showcase the potential of using large datasets from online communities to study color harmony trends and preferences.

The finding of [8], combined with the author's practical experience that using hue templates to create color combinations didn't always work, was another motivation for the present work to find alternative means of creating harmonious color combinations based on these large datasets.

While the model was based on palettes with five colors, Kita and Miyata [44] later modified the model, excluding parameters related to the number of colors to create a rating prediction model for a palette with any number of colors and a method of expanding the palette while retaining color harmony. Although the implementation is different, palette expansion is one application of the n-Gram approach we propose in this study.

Lu [45] used a large dataset of annotated images to propose a Bayesian framework for color harmony for image aesthetics applications, utilizing knowledge from domain experts and clues discovered from large datasets. However, color harmony of photographic images is not in the scope of the present study.

2.4.2 Hue Template Validity

Skurowski [46] utilized the large datasets from Kuler not only to confirm the use of original Matsuda's templates, but also to derive new Matsuda-like templates. However, O'Donovan *et al.* [8] compared the results from COLOURlovers and Kuler and graphically evidenced that the palette creator in Kuler had easier access to the templates than the palette creator in COLOURlovers, and hence the results were biased towards Matsuda's templates. They concluded that designers do not gravitate to Matsuda's templates unless encouraged by the palette creator. Hence, in this study, we focus on the COLOURlovers data, rather than datasets from Kuler.

2.5 The Need for Color Quantization

The problem of an infinite number of colors and conditions discouraged many scientists in their investigation of color harmony, as pointed out by Sivik [11]. Studies of color combinations are still relatively scarce in scientific literature. Sivik attributes this to the complexity of the task, one of the reasons being the manifold of color and different possibilities there are to organize them. Quantitatively measuring colors is already a large research problem that suffers from adding the notion of color harmony as a new variable [3].

Different methods are used to overcome this. Tokumaru [24] used fuzzy logic to assign colors to hue templates. Skurowski [46] used Jaccard distance to group similar color together. Sunkavalli [47] used histogram matching. Color segmentation is an integral part of Cohen-Or's approach [37] to avoid similar hues being shifted to two different sectors in the hue template. Solli and Lenz [28] use the mean shift algorithm. These methods may introduce inefficiency and inaccuracy to the studies.

Since color quantization is commonly used in image processing algorithms [36] to simplify the analysis of an image containing a large number of perceptually similar colors that appear different to the algorithm, this study proposes to use similar methods to the study of color harmony provided that the changes in individual colors introduced by the quantization did not have a significant impact on the overall harmony perception of a given color palette.

2.6 Text Prediction Analogy – A Novel Interdisciplinary Approach

n-Grams have found uses in many fields such as cryptography, machine translation speech recognition, machine translation, spelling correction, information extraction and others. In this study, we propose an interdisciplinary approach of using the text prediction algorithm to a quantized dictionary of colors and a corpus of quantized color palettes derived from crowdsourced color palettes such as those available at colourlovers.com to create new color combinations. To our knowledge, there are no previous studies using this approach on large datasets of harmonious colors.

The proposed approach builds on the additivity of color harmony [48] which stipulates that a three-color combination can be seen as a combination of three separate color pairs, each generating a harmonious/disharmonious feeling, and that the approach also applies to combinations generated by any number of colors.

Expanding a palette composed of N colors to a palette containing $N + \alpha$ colors while choosing colors that are compatible with the original colors is difficult [44]. The text prediction analogy should solve this problem easily. Given the first few colors, the algorithm will pick the next compatible color in sequence to form color palettes of arbitrary length.

2.7 A Geometrical Model from Large Datasets

The idea that there are certain paths in color space that hold a key to color harmony has received much attention. The Ostwald system [16] is preeminent for exhibiting the most paths in color space intended to show harmonious colors. However, Granville [49] states that the smooth visual progression through color space gives the harmonious result, not that the colors bear some unique harmonious relationship to each other.

With the availability of large datasets of color harmony that were created without biases of paths in color space, we can now study whether Granville's statement holds true. In this study, we try to fit the color palettes created by human users to a simple path in different color spaces in search for a curve that fits a significant percentage of color palettes thus created.

Pridmore [50] reports a curious helical structure of complementary colors' relative spectral power distribution (SPD) function. Another example of the double helix in sensory perception is in music, where pitch space is modeled with helices or double helices. This led us to pondering whether a helix could accommodate harmonious color schemes.

When the hue, saturation and value components of color palettes were plotted in 3D color space in a similar manner as [51], some palettes exhibited a distinct helical structure. This led to a study of a larger number of palettes in different color spaces and the proposition of the helical model fitting harmonious color palettes. If true, it would realize Sivik's idea of being able to express the relationship between stimulus and experience in a mathematical formula with as few variables as possible [11].

In this study, we use the helical model to create new harmonious color combinations. Although we do not claim that the helical model absolutely defines color harmony, nor that palettes not adhering to the helix are disharmonious, we share this interesting observation for future scholars in the color science community. This would not have been possible without the availability of large datasets.

2.8 Summary

Color and color harmony has been the subject of scientific study for a long time. Different theories of color harmony have been put forth based on different primaries or color components, different wheels or color volumes and different measures of color harmony. But no consensus has been reached on what exactly determines harmony of a color palette.

The need for color harmony for the arts and industry has been largely agreed upon. Hence there have been many attempts in scientific literature to create harmonious color combinations for photographic images. Interior design, product design, building facades, garments, logos, web design, geographical maps, billboards, cosmetics and many other applications. This study focuses on the creation of harmonious color combinations for color separated images such as those used for carpets, but also applicable for pashmina, Dhaka, felt, knitwear, papercraft etc. Whose production inherently depends on materials with a limited number of distinct colors. Thus, the outcome of this study will have a more practical implication creating better color combinations for these applications

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Analytical models of color harmony developed so far imply that colors could harmonize when they were selected systematically from a specific path within an ordered color space or from a hue circle (Ou & Luo, 2006). Theories that depend solely on the hue circle are largely open to interpretation (Chamaret,2016) regarding the color wheel to be used or which components to keep constant while varying others. Other theories which suggest that harmonious colors from a specific path within an ordered color space are more convincing. There has been some criticism (Granville, 1987) that the smooth visual progression through color space gives the harmonious appearance, and it is not that the colors bear some unique harmonious relationship among each other. In this study, we get a chance to see if color palettes created by humans without awareness of the order in color space, do indeed follow a simple path in ordered color space. From this, we purpose one more analytical model-the helical model, which fit a large number of human-created color palettes, and take into consideration, all three components- hue, chroma and lightness at the same time.

Numerical models for color harmony developed from user experiments in controlled environments have resulted in empirical models of color harmony for color pairs (Ou & Luo, 2006). These models have been refined over the years (Ou, et al., 2018) and have been appreciated in that they are more specific regarding the circumstances and describe color harmony for a color pair reasonably well. Another numerical model for calculating the color harmony of five-color palettes was developed by O'Donovan *et al.* (2011) based on a model trained with human-created in (Chamaret, 2016) we use them in this study as they are the best available means for objectively evaluating the color combinations created using the methods proposed in this study.

Large datasets of human-created and ranked color palettes are curated by several online sites. These datasets have been used to study color preference and color harmony. In his

PhD dissertation, O' Donovan (2015) demonstrated that the large datasets do not conform to all the prevalent color theories. So, the search for processes, methods and models for creating harmonious color combination continues.

Newer principles of color harmony (Ou, et al., 2018) have been proposed after O'Donovan's study. These principles were proposed based on the experiments with a limited number of color pairs and a limited number of observers. We use methods similar to O'Donovan's analysis to check whether these principles hold true in the light of large datasets of color pairs created and ranked by a large audience.

The study of color harmony is usually complicated by the fact that visually similar colors vary in their numerical values. Several methods such as fuzzy logic, Jaccard distance, histogram matching, mean shift algorithm are used in various studies to overcome this limitation but they add to algorithm complexity. We propose color quantization as a simple solution to the problem. Although color quantization introduces changes in individual colors, this study demonstrates that this process does not significantly impact the overall harmony perception of the palette.

Once the colors are quantized, the study of color harmony becomes simpler, as do the methods for creating new color combinations. For instance, text prediction is a commonplace activity that uses a language model to predict the next character, word or phrase in sequence. In this study, we propose a novel interdisciplinary method to use n-Grams to learn from highly-ranked color combinations to build a probability table, and then create a sequence of harmonious colors based on this table. This approach solves the problem of expanding N colors to a palette of N+1 colors (Kita & Miyata, 2016).

Thus, this study analyzes data from large datasets of color palettes from a color harmony perspective to propose a process to simplify the study of large datasets of color palettes for color harmony, a statistical method for creating new color combinations and a geometrical model to fit human-created color palettes from which new color combinations could be created.

EFFECT OF COLOR QUANTIZATION ON COLOR HARMONY

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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, but is usually overwhelming because of the sheer number of slightly differing colors. This paper discusses the possibility of quantizing the colors in these color palettes to a manageable set of discrete colors without significantly affecting the aesthetics of the palette. One method of quantization is to map the palettes from continuous color space to the set of 2744 perceptually uniform colors provided by the Munsell renotation data. Another method of quantization is to perform a K-means clustering of the colors of all the palettes to get a set of limited colors. For comparison purposes, this paper divides the colors into 2744 clusters in CIELAB color space and quantizes to their centroids. It was found that the quantization error was minimum for the latter method. Colors from both the original and quantized color palettes were applied to a pattern. Several such combinations were presented to the respondents in random order and asked to like or dislike the colored pattern. It was found that when respondents liked a colored pattern, they also liked the same pattern colored with the quantized color palette. Likewise, when they disliked a colored pattern, they also disliked the pattern with the quantized color palette. This means that color quantization has minimal impact on the harmony perception of the color palette. This simplification makes it possible to perform further analysis on the relationships of colors for color harmony. Considering the quantized colors as words and palettes as sentences, it is now possible to use methods such as the n-Gram approach to create new color combinations.

Keywords: color harmony, large datasets, color quantization, Munsell color space, K-means clustering

INTRODUCTION

Background

Color harmony is the aesthetically pleasing arrangement of colors within a composition. 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 [1]. The 20th century saw continued development in the study of color harmony with new theories and advancements in technology influencing the field. Albert H. Munsell, an American painter and teacher, developed the Munsell Color System, a three-dimensional model for describing colors based on hue, value and chroma. Munsell's work has had a lasting impact on the study of color harmony and has been widely used in various industries.

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Research Article

Generating Harmonious Colors through the Combination of n-Grams and K-means

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Abstract: Among the many approaches to studying color harmony tried so far, a relatively recent method is to leverage a 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 but is usually overwhelming because of the sheer number of slightly differing colors. It is possible to quantize the colors in these color palettes to a manageable set of discrete colors without significantly affecting the harmony perception of the palette. Considering the quantized colors as words and the palettes as sentences, it is possible to form and compute the probabilities of n-Grams in the sentences. In this study, we create bigrams and trigrams from the corpus of highly ranked color palettes and use them to predict new color combinations. 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 combination; Color harmony; Color quantization; Large datasets; n-Gram

1. Introduction

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

Recently, there has been a rapid increase in the number of human-created harmonious color combinations. At sites like colourlovers.com, color.adobe.com, and 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.

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