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Equalization of appearance using individualized unique hues

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Abstract

Variability in the encoding of unique hues within the color vision system results in significant diversity in hue appearances among individuals. This paper introduces a novel algorithm that equalizes hue appearance for individual observers by incorporating their unique hue perception and replacing the default NCS unique hue in a modern color appearance model with individualized selections. By customizing the color representation to match the observer's perception, the algorithm enhances the consistency and personalized rendering of hue appearance. The findings of this study contribute to advancing color perception research and have practical implications in various domains such as, graphic design, and visual color reproduction.

Introduction

The objective of colorimetric reproduction is to minimize the color difference metric or maximize colorimetric accuracy between an original image or scene and its reproduction in a cross-media reproduction system [1]. Colorimetric reproduction aims to achieve a reasonable reproduction of color attributes, such as hue, chroma, lightness, etc., of the original content. However, it is important to acknowledge that this objective does not consistently yield the best possible reproduction of an image. Previous research suggests that observers tend to prefer reproduced object colors with higher saturation than the original [2]. Additionally, certain memory colors like green grass, skin, and blue sky are recalled with slightly different hues and greater purity [3].

In 2018, there is a very interesting query that came from a Twitter poll that of more than 60,000 participants, 65.7% said a tennis ball is yellow, and 34.3% said is green. The color of tennis balls exists on the border between colors that are widely agreed upon as yellow and those that are recognized as green. This ambiguity in categorization highlights the subjective nature of color perception and demonstrates how the perception of color can vary among individuals.

Individual difference in color perception not only happen at the input stage of color vision (receptor activities), but also in the representation of color at all levels (postreceptoral color mechanisms) of the visual system [4]. Unique hues, often referred to as anchor points in color perception, have been extensively studied to understand individual differences in color perception. Unique hues (red, green, yellow, blue), initially proposed by Hering, are a concept in color science that suggests certain hues can be perceived as "pure," meaning they appear to contain no perceived mixtures or combinations of other hues [5]. It is a plausible hypothesis that variations in cone sensitivity functions can influence the perception of unique hues. However, the variation of unique hues perception is largely independent of the cone sensitivity function [6] [7]. In other words, an observer's perception of a unique red may differ from another observer with the same color matching function, potentially appearing slightly yellowish or bluish. Therefore, in virtual color reproduction, generating the same hue quadrature or appearance is psychologically reasonable. The hue appearance, or quadrature, embedded in modern color appearance models (CIECAM02 and CIECAM16), can be calculated based on hue angles as well as NCS unique hue data [8]. In this paper, we develop an algorithm that can equalize hue appearance for individual observers.

Hue appearance (hue quadrature)

Two distinct types of hue scales or specifications can be identified: Munsell-type hue (Hue angle) and NCS-type hue (Hue quadrature). Munsell-type color models are devised to establish scales with equal color discrimination or color differences while NCS-type opponent models are designed to describe colors based on their appearance [9]. Each type of hue scale serves a different purpose and provides insights into color perception from different perspectives.

The hue angle or Munsell-type hue is widely used for evaluating the color difference in hue perception. However, the Munsell-type hues do not represent particularly meaningful hue appearance. In contrast, the NCS system specifies hues based on the visual perception of unique hues, aiming to capture more accurately hue appearance [10]. In the NCS system, a hue perception that falls midway between unique red and unique blue, such as a purple hue, would be denoted as R50B. This notation indicates that the perceived proportions of the hue are 50% red and 50% blue. By scaling all hue perceptions relative to the four unique hues, the NCS system provides a direct and consistent representation of hue appearance.

In modern color appearance models, such as CIECAM16, hue appearance (quadrature) is calculated based on Eqs 1.

$$H = H_i + \frac{100e_{i+1}(h' - h_i)}{e_{i+1}(h' - h_i) + e_i(h_{i+1} - h')} \quad (1)$$

H refers to the hue quadrature while H_i is the hue composition. e is the eccentricity factor and h represents the hue angles. Data for conversion from hue angle to hue quadrature are shown on table 1.

Table 1: Unique hue data for calculation of hue quadrature [8].

	red	yellow	green	blue	red
i	1	2	3	4	5
hi	20.14	90.00	164.25	237.53	380.14
ei	0.8	0.7	1.0	1.2	0.8
Hi	0	100	200	300	400

In Table 1, the default unique hue data is based on the NCS system according to Hunt [11]. However, it is crucial to recognize that there is significant variability in the perception of unique hues, as demonstrated by studies conducted by Webster et al. [7] and Wuerger et al. [12]. This indicates that unique hues can vary among individuals, highlighting the diverse range of unique hue perceptions within the population. Therefore, it is important to consider the limitations of the NCS system in fully capturing this variability in unique hue perception.

The aim of this research is to achieve same hue appearance among individual observers. For instance, in the context of creating an avatar character with unique red hair for a movie, the goal is for all viewers to perceive the same unique red. To accomplish this, the display or presentation of the content needs to be customized or calibrated according to each observer's unique hue. By tuning the end user display based on the individual observer's unique hue, it becomes possible to ensure a consistent and desired hue appearance for all viewers. The proposed workflow is as followed:

1. Measure the unique hue perception of each individual observer.
2. Select a test image and convert it to tristimulus values (XYZ).
3. Utilize a standard color appearance model to calculate the hue angles (h_1) and hue quadrature (H).
4. Calculate the modified hue angles (h_2) using the obtained H value and the individual unique hue data (h_i') from step (1). Together with color appearance inverse model, we obtain Eqs.2:

$$h_2 = \frac{(H - H_i)(e_{i+1}h_i' - e_i h_{i+1}') - 100h_i' e_{i+1}}{(H - H_i)(e_{i+1} - e_i) - 100e_{i+1}} \quad (2)$$

By following this workflow, it becomes possible to adjust the color appearance of the test image based on each individual's unique hue perception, thereby achieving the goal of generating consistent hue appearance for all observers.

Visualization of the algorithm

A 17x17x17 look up table (LUT) was created to display and cover the entire sRGB gamut (red circle in figure 1). The four solid color lines in figure 1 represents the default unique hue (NCS unique hue) in $a_z b_z$ color space.

Now, let's consider an observer who perceives unique red, yellow, and green hues similar to the NCS unique hues, but with a deviation of +10 degrees from the NCS unique blue. By applying the algorithm and using the individual unique blue value (247.53°) in the Eqs.2, the hue rotation of this LUT is shown as the blue circle in Figure 1. Since this observer's unique hue is the same as NCS unique hue, there is no color shift between the sections from unique green to unique yellow and unique yellow to unique red. However, there is a slight expansion in the adjusted colors between unique green and the individual unique blue, while there is a subtle compression between the individual unique blue and unique red.

Figure 2 demonstrates additional examples of hue appearance adjustments using the algorithm described. In the top left example, only the unique red is shifted by +10 degrees. Similarly, in the top right example, unique yellow hue is altered by -10 degrees. In the bottom left example, the unique green is modified by -10 degrees. Lastly, in the bottom right example, both the unique red and blue are adjusted by +10 degrees, while the unique green and yellow are shifted by -10 degrees. All hue appearance is rescaled directly relative to the individual's unique hues.

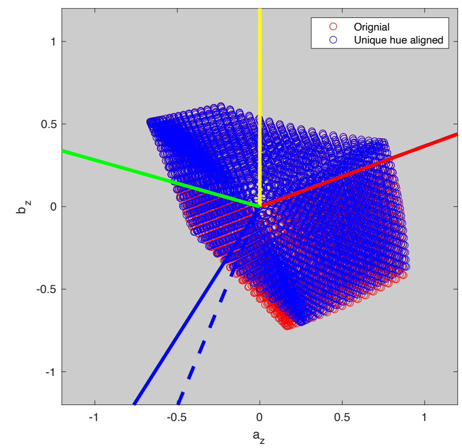

Figure 1: The red circle represents the sRGB color gamut, indicating the range of colors that can be accurately displayed on standard display. The solid color line represents the NCS unique hue, while the dotted blue line shows an individual unique blue hue, deviating by +10 degrees from the NCS unique blue. The blue circle represents the resulting color shift achieved by proposed algorithm.

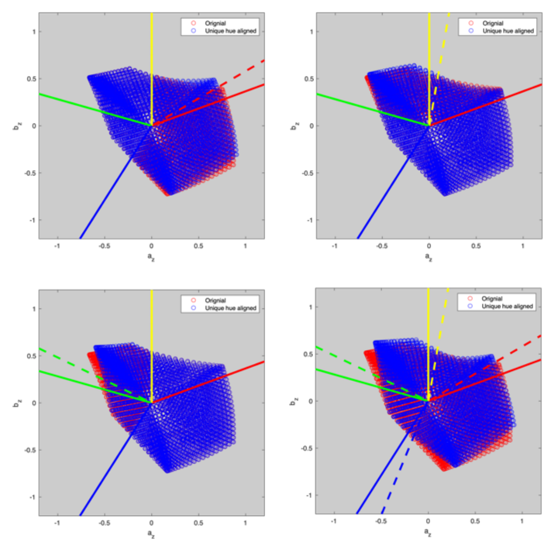

Figure 2: Similar examples to figure 1. In the top left, the unique red hue is shifted by +10 degrees. In the top right, the unique yellow hue is altered by -10 degrees. In the bottom left, the unique green hue is modified by -10 degrees. Lastly, in the bottom right, both the unique red and blue hues are adjusted by +10 degrees, while the unique green and yellow hues are shifted by -10 degrees.

Algorithm test

While unique hue perception varies among different observers, the perceived color difference between the original image and the image after applying our algorithm may not be significant. Additionally, it is crucial to acknowledge that the effectiveness of this algorithm heavily relies on the image content. For example, consider an observer whose unique red, green, and blue hue are similar to the NCS unique hues, but deviate by -10 degrees from the

NCS unique yellow (as shown in Figure 2, top right). When applying this algorithm to an image predominantly featuring blue colors, this observer may not perceive any noticeable color difference. Figure 3 illustrates this scenario, where the left image represents the original image, and the right image is the result after equalizing the hue appearance by -10 degrees for the unique yellow. It is evident that, for most observers, there is no perceived color difference between these two images.

In order to assess the effectiveness of the proposed algorithm, a dataset comprising 318 images was carefully selected from publicly available sources, ensuring a wide representation of image content including both memory color and non-memory color. The unique hue data of ten observers were obtained from a prior study conducted by Shen et al [5]. These unique hue data, represented as dR, dY, dG, and dB in Table 2, quantify the deviations from the NCS unique hue.

The color difference between the original image and the image after applying the algorithm was evaluated by calculating the pixel-wise differences and averaging them across the entire image. Additionally, Table 2 presents the mean, minimum, and maximum values of the color difference ($\Delta E2000$) observed across the 318 images. In addition, the percentage of larger than 2 $\Delta E2000$ is also included in table 2.

Based on the simulation results, it was found that for most observers, the mean color difference between the original image and the image with the applied algorithm was greater than 1. This result indicates that the applied algorithm produces a small but potentially noticeable color difference that can be perceived by observers. These findings highlight the effectiveness of equating the appearance for individual observers.

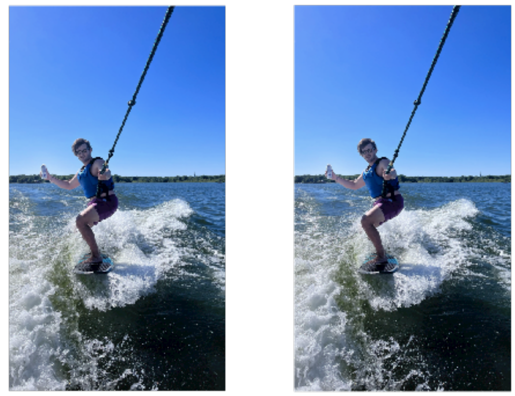

Figure 3: Left: original image. Right: unique hue aligned image.

Table 2: Individual unique hue data [5] and simulation results

	obs1	obs2	obs3	obs4	obs5	obs6	obs7	obs8	obs9	obs10
dR	-3.85	-3.2	3.64	1.19	1.32	-2.06	-3.33	5.47	4.38	-3.51
dY	-1.7	-5.04	-0.39	-3.02	-3.99	-3.47	-3.32	-0.98	-1.4	-8.42
dG	-16.82	10.39	-13.55	14.29	27.16	-12.11	8.66	-6.04	0.3	9.84
dB	4.24	9.63	12.08	14.86	10.55	-1.52	10.44	10.67	7.85	11.82
min	0.16	0.12	0.18	0.09	0.11	0.146	0.12	0.17	0.02	0.13
mean	1.19	1.26	1.3	1.44	1.73	1.06	1.16	1.12	0.75	1.6
max	5.31	3.67	4.48	5.33	7.47	4.14	3.6	4.09	3.05	4.39
ΔE2000>2	11.32%	12.89%	19.18%	24.21%	31.45%	7.23%	11.32%	15.72%	5.66%	22.96%

Proposed pipeline

The proposed pipeline is illustrated in Figure 4. The input data for this algorithm are RGB-encoded images, which can be transformed into CIE XYZ tristimulus values using a display characterization model. Once the input image has been converted to an independent color space, the color appearance model (CAM16) should be utilized to calculate the hue appearance scaling (hue quadrature) of the input image. Additional input data include individual unique hue angles. By applying the inverse color appearance model and replacing the NCS unique hue with the individual unique hue, the hue appearance can be converted back to the modified tristimulus values.

When applying the inverse display model to convert XYZ' to the output encoding RGB, gamut mapping may present potential issues, as this algorithm may move a few colors that were previously within the display gamut outside of it. It is important to note that this issue is heavy image depended. Therefore, gamut mapping algorithm is optional at this stage.

Figure 5 illustrates an example of an avatar with unique red hair, as discussed early in the hue appearance section. The center image represents the original version, while the left image exhibits a deviation of +10 degrees from the NCS unique red. Consequently, the hair in the left image appears slightly yellowish in comparison to the center image. On the other hand, the right image demonstrates a deviation of -10 degrees from the NCS unique red, resulting in a slightly bluish hue for the hair when compared to the center image. By implementing this algorithm, it becomes possible to ensure a consistent perception of hue appearance among different observers.

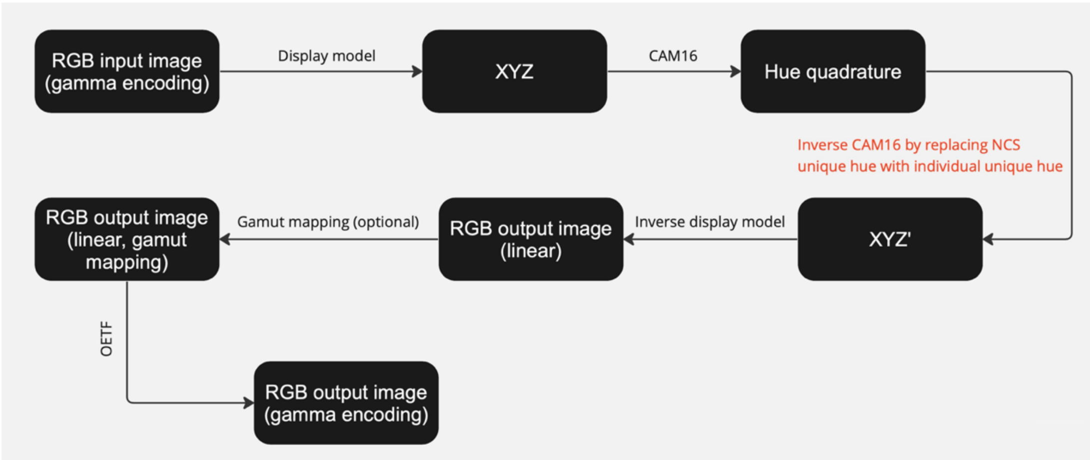

Figure 4: Flowchart of equalizing appearance by lining up unique hue.

Figure 5: Avatar example with +10 degree unique red (left), NCS unique red (center) and -10 degree unique red (right).

Conclusions

The presented algorithm constitutes a significant advancement in equalizing hue appearance for individual observers by replacing the default NCS unique hue with their individual unique hue within the inverse color appearance model process (converting hue quadrature to XYZ). The algorithm achieves its objective of rescaling the hue appearance relative to individual unique hues, resulting in consistent hue perception among observers, regardless of the specific hue angle. The efficacy of the algorithm is evidenced by the results obtained from Figure 2, where the Look-Up Table (LUT) demonstrates the successful adjustment of hue appearance, and Figure 5, showcasing an avatar example. These outcomes highlight the algorithm's potential for providing a standardized and personalized color experience for individuals.

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