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Characterization of Color Differences for Color Palettes

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Abstract

Various color difference metrics were developed for characterizing the perceived color difference between individual color patches. Color difference between palettes containing multiple color patches, however, is critically important in product design and computer graphics. This study aimed to investigate how the perceived color difference between a pair of color palettes containing more than a single color patch is affected by the order and number of color patches in the palette. Two reference color sets were generated and each set had four color palettes containing 1, 4, 9, and 16 color patches that were arranged as 1 × 1, 2 × 2, 3 × 3, and 4 × 4 patterns. Human observers scaled the color differences between a color palette of the reference set and a color palette that had revised colors, or revised orders, or a combination of revised colors and orders compared to the reference palette. The calculated color differences between the two palettes were derived using the Minimum Color Difference Model (MICDM) algorithm proposed in a recent work with different color difference metrics, including CIELAB, CMC, CIE94, and DE2000. It was found that the perceived color differences of pairs of individual color patches were significantly larger than those containing multiple patches, when the calculated color differences were the same. The color differences metrics, except for CIE94, had similar performance when characterizing perceived color differences between color palettes.

Introduction

Color difference characterization is an important topic in color science and imaging science [1, 2]. It is critically important to product quality and image quality management [3, 4]. Great efforts have been made to develop color different metrics, so that the calculated color differences can be used to predict the perceived color difference. The correlation between the calculated color differences in the CIELAB color space and the perceived color difference under different viewing conditions has been widely investigated [5-10]. Later, CMC [11], CIE 94 [12] and CIEDE2000 [13] were developed to improve the performance of the calculated color difference in CIELAB.

These metrics, however, mainly aim to characterize the perceived color difference between pairs of individual color patches, which is important to color specifications and measurements and to industries related to printing, paint, and fabrics. Color palettes containing a number of colors is more common in practice, which is important in product design and computer graphics. Past research related to color palettes focused on the color harmony of a palette [14] and image quantization in computer graphics and image processing [15].

Few studies investigated the characterization of perceived color difference between color palettes. Pan and Westland investigated the color differences between 96 pairs of color palettes of 5 × 5 color patches, and developed a color difference metric, which was found to be able to predict the perceived color differences [16, 17]. However, no past studies specifically investigated how the number of patches and the order of the patches in a color palette affect the perceived color differences, which was the objective of this study.

Psychophysical experiment

Preparation of color palettes and setup

Two sets of reference color palettes, as shown in Figure 1, were used in this study. They were derived from 30 landscape images using a k-means clustering, as described in [16]. Each set contain four different palettes containing 1 × 1, 2 × 2, 3 × 3, and 4 × 4 color patches (7 cm × 7 cm).

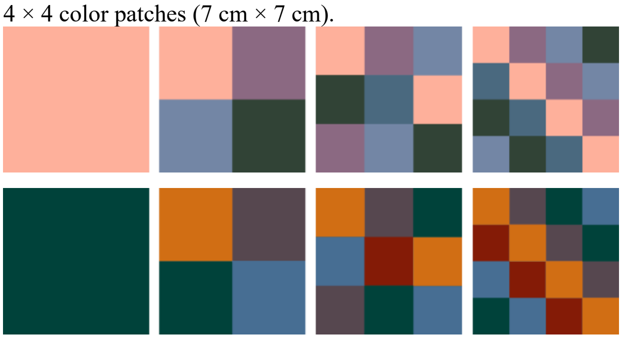


Figure 1. Two sets of reference color palettes. Top: Set 1; Bottom: Set 2.

Each reference palette was modified to produce 66 modified palettes. Among these 66 modified palettes, 9 palettes were single-patch palettes whose colors were modified along one of the lightness, chroma, and hue directions, 3 palettes (i.e., 2 × 2, 3 × 3, and 4 × 4 palettes) had the same colors as the reference palettes with the patches being arranged in a random order, 27 palettes had modified colors but same order, and the remaining 27 palettes had modified colors and random order. For the palettes having modified colors, all the colors in the palettes were simultaneously adjusted with an increase of 4, 8, or 16 unit along the lightness, chroma, or hue direction in the CIELAB color space.

Figure 2 Example of a pair of palettes shown on the display

Pairs of color palettes including a reference palette and a modified palette were presented on a neutral background on a computer display, with one pair each time. During the experiment, each observer was seated 50 cm in front of the display, with his or her chin being fixed on a chin rest, so that the observer's sagittal plane was aligned with the center between the two palettes. Figure 2 shows an example of a pair of palettes.

Experiment procedure

Upon arrival, an observer completed a general information survey and the Ishihara Color Vision Test. Then he or she was escorted to the display and asked to be seated in front of the display with his or her chin being fixed on the chin rest. The introduction about the experiment task was shown on the display, both in English and Chinese. The entire experiment was divided into four sessions, with each session containing the same number of color patches in the palette.

At the beginning of each session, the display showed all the palettes that would appear in this session to helped the observer to have an idea about the ranges of color differences he or she would see. For each pair of color palettes, the observer was asked to observe and evaluate the color difference between them for six seconds. Then the palettes disappeared and the display shown the seven-point rating scale to the observer, with 1 representing no color difference and 7 representing the largest color difference he or she can think of. The positions of the two palettes within each pair were randomized and the orders of the pairs in each session were also randomized. The entire experiment took around 30 minutes for each observer.

In total, 19 observers (14 males and 5 females) between 20 and 50 years of age (mean = 25, std. dev. = 6.71) participated in the experiment. All of them had a normal color vision, as tested using the Ishihara Color Vision Test.

Results and discussions

Inter-observer variations

The inter-observer variations were evaluated using the Standardized Residual Sum of Squares (STRESS) [19]. Specifically, we compared the color difference ratings given by an observer and the average ratings of all the 19 observers (i.e., an average observer). The STRESS values were calculated based on the ratings given to the palettes containing a single color patch, color patches in the same order, and color patches in a random order, with the average STRESS values of 20.8, 23.0, and 26.7 respectively, as listed in Table 1. The STRESS values suggested the reliability of the experiment data.

Effects of order and number of patches in color palettes

If the evaluation of color difference was not affected by the order of the color patches, the palettes containing the same color patches but different orders should not cause different perceived color differences.

Figure 3 shows the average perceived color differences of the modified palettes having the same colors but different orders compared to the reference palettes. It can be observed that there were perceived differences even though only the order of the patches were different. In addition, no significant differences can be observed when the number of patches in a palette changed from 2 × 2, to 3 × 3, and to 4 × 4.

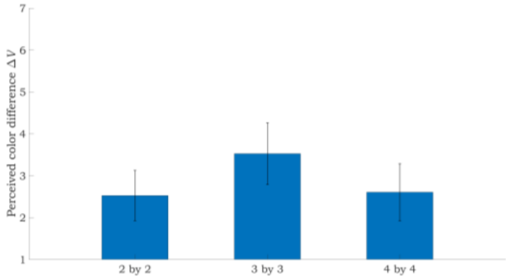


Figure 3 Average perceived color differences of the modified palettes having the same colors but different orders compared to the reference palettes.

Figure 4 shows the average perceived color differences of the modified palettes that had the same or different order compared to the reference palettes, no matter whether there were color differences or not. It can be observed that the palettes having a random order of patches were generally rated to have larger color difference than those having the same order compared to the reference palette.

These clearly suggested that the order of the color patches affected the evaluations of the color differences.

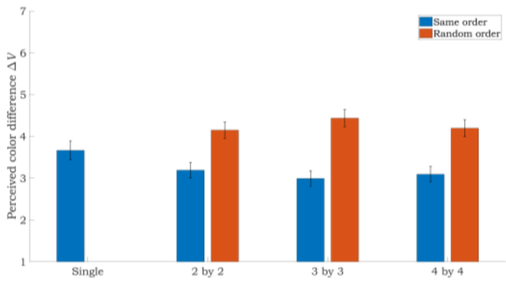


Figure 4 Average perceived color differences of the palettes that had the same or different order compared to the reference palettes, no matter whether there were color differences or not.

Table 1. STRESS values for characterizing inter-observer variations

Observer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Mean
Single color	11.9	18.1	26.2	27.5	13.5	17.0	31.8	14.6	20.3	32.7	13.8	19.1	20.4	19.9	22.6	25.3	23.1	16.5	21.0	20.8
Same order	20.8	21.1	20.1	23.2	18.0	22.9	27.1	21.5	27.4	30.8	30.6	21.0	26.7	27.4	22.2	25.8	27.1	25.7	21.1	24.2
Random order	24.9	37.1	21.8	25.9	25.9	22.3	31.8	25.1	28.7	25.4	23.1	25.8	36.2	30.2	29.5	18.1	30.3	25.7	19.4	26.7

Calculated color differences

The performance of various color difference metrics is typically evaluated by comparing the correlation between the perceived color difference (ΔV) and the calculated color differences (ΔE). The various color metrics, such as ΔE_{Lab}, CMC(1,1), CMC(2,1), CIE94, DE2000(1,1,1), and DE2000(2,1,1), were all developed for individual color patches. A recent work [16] proposed three algorithms (i.e., Single Color Difference Model, Mean Color Difference Model, and Minimum Color Difference Model) for characterizing the color difference between two color palettes, with the Minimum Color Difference

Model (MICDM) being found to have the best performance in [17]. Therefore, we adopted MICDM with the ΔE_{Lab} to calculate the color differences between the reference and modified color palettes (ΔE_p) below.

Calculated versus perceived color difference

Figure 5 shows the relationship between the calculated and perceived color differences, as categorized based on the number of patches in the palette. It can be observed that when the palettes had the calculated color difference greater than 6, the perceived color difference of the single-patch palette was larger than those of the palettes containing multiple patches.

To better understand the effects of patch order and patch number, Figure 6 shows the relationships for the palettes with the same order and those with the random order. It can be observed that the same calculated color differences caused larger perceived color differences to the single-patch palette, when the patch order of the reference and modified palettes were the same. In addition, if the palettes contained multiple color patches, the exact number of patches did not have a significant effect, as shown in both Figures 6 (a) and (b). The insignificant effect of patch number could be due to fixed size of the palette in the experiment. If the size of each color patch in the palette was fixed, a greater number of patch number may cause a larger perceived color difference.

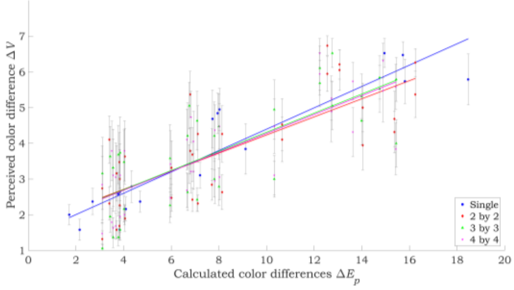
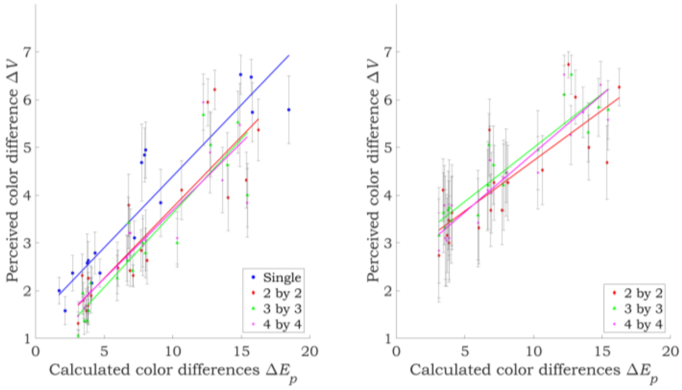


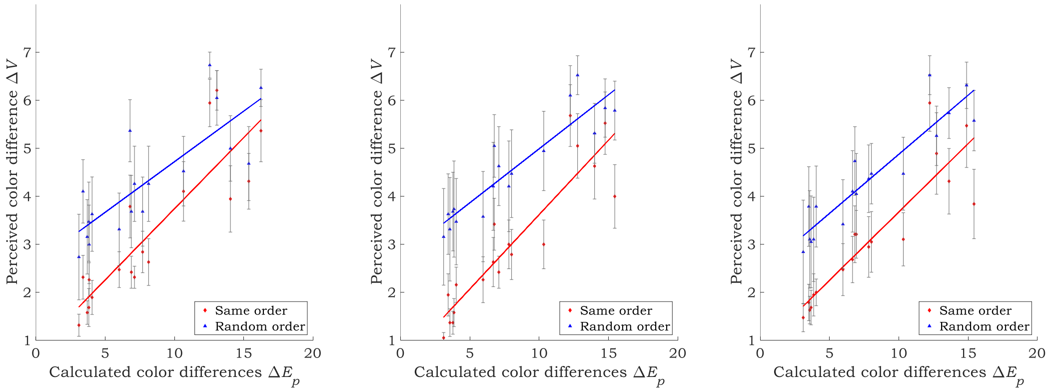
Figure 5 Scatter plot of perceived versus calculated color differences.



(a) (b)

Figure 6 Comparisons of the perceived versus calculated color differences among the different number of patches in the color palettes. (a) the patches in the modified palettes having the same order as those in the reference palettes; (b) the patches in the modified palettes having a random order.

Figure 7 shows the comparison between the two orders for the 2 × 2, to 3 × 3, and to 4 × 4 palettes. The palettes that had the patches arranged in a random order were always perceived to have larger color difference than those having the same order as the reference palettes. The differences between the perceived color difference of the two orders, however, became smaller with the increase of the calculated color differences. Figure 8 directly compares the perceived color difference of the two palettes that had the same calculated color difference to the corresponding reference palettes, with one having the color patches in the same order and the other in a random order. It can be observed that the perceived color differences became similar when they became larger. This suggested that the order of color patches affected the color difference evaluations, and its effect became weaker when the calculated color differences became larger.



(a) (b) (c)

Figure 7 Comparisons of the perceived versus calculated color differences between the color patches in the modified color palettes having the same and a random order as the those in the reference palettes. (a) 2 × 2 palettes; (b) 3 × 3 palettes; (c) 4 × 4 palettes.

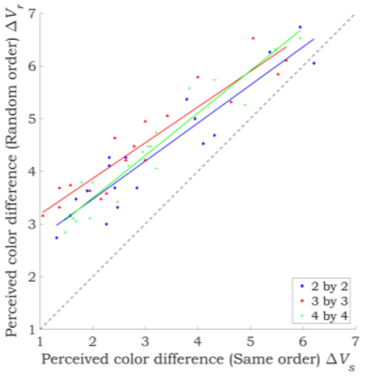


Figure 8 Comparison of the perceived color differences between the palettes that had the same calculated color differences to the reference palettes, with one having the patches in the same order and the other having the patches in a random order as the reference palettes.

Comparisons of MICDM performance using different color difference calculations

The color difference ΔE_{Lab} was used in the MICDM calculations above. The performance of MICDM using other color difference metrics also merits investigations, especially all of these metrics were designed for single color patches. Specifically, CMC (1,1), CMC (2,1), CIE94, DE2000 (1,1,1), and DE2000 (2,1,1) were all used in the MICDM algorithm to calculate the calculated color difference between each modified palette and its reference palette. STRESS values between the calculated color differences and the average perceived color differences are summarized in Table 2. It can be observed that the performance of these color difference metrics were generally worse when the color patches had a random order. For the palettes containing multiple patches, the performance of these metrics became worse when the palettes changed from 2 × 2 to 3 × 3, but became better when they further changed to 4 × 4.

Table 2. STRESS values between the average perceived color differences and the calculated color differences using the MICDM algorithm but different color difference metrics

	Same order	Random order	1 × 1	2 × 2	3 × 3	4 × 4	Overall
CIELAB	23.4	35.2	25.2	33.3	35.5	31.5	32.5
CMC (1, 1)	27.1	38.5	30.3	35.7	38.4	35.3	35.8
CMC (2, 1)	21.4	32.9	30.6	28.9	33.3	29.8	31.2
CIE94	39.5	46.7	40.9	46.0	46.5	43.7	44.9
DE2000 (1, 1, 1)	25.5	38.6	25.9	35.7	38.1	34.9	35.0
DE2000 (2, 1, 1)	24.9	33.8	30.3	29.3	33.9	30.7	34.9

Conclusions

A psychophysical experiment was carried out to investigate how color differences between color palettes containing different numbers of patches were evaluated. Nineteen human observers evaluated the color differences between series pairs of color palettes. Each pair contained one reference palette and a revised palette. The revised palette was designed to have color patches that had color shifts along the lightness, chroma, or hue dimensions in the CIELAB color space, or a random order, or a combination of color shifts and random order in comparison to the reference palette.

The order of the color patches in the palettes was found to have a significant impact on the color difference evaluations. The palettes with the patches in a random order were judged to have larger color differences. For the palettes having the same order as the reference palettes, those containing multiple patches were judged to have smaller color differences than those containing a single color patch. However, no significant difference was found between those containing 2 × 2, 3 × 3, and 4 × 4 patches.

The Minimum Color Difference Model (MICDM) algorithm, which was recently proposed in [17], was used to calculate the color differences between palettes. Though linear correlation was found between the calculated and perceived color differences, the algorithm cannot accurately characterize the effects of the number and order of the color patches in a color palettes, no matter which color difference metrics were used in the algorithm.

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