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Exploring and Practicing the Quantification of Interior Design Colors from an IKEA Design Perspective

Haitong Wei*

Artificial Intelligence Human Settlement Environment Joint Laboratory, DECOR.AI and Country Garden Group, Beijing 100089, China

HongHao Data Intelligence Technology Co., Ltd., Beijing 102699, China

Data Intelligence Branch, Enterprise Financial Management Association of China, Beijing 100195, China

***Corresponding Author**
Haitong Wei, Algorithm Scientist, Entrepreneurs, Beijing, China.

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Abstract

With the improvement of life quality, color plays an increasingly important role in interior design. This article, guided by IKEA's design philosophy, deeply explores the scientific method of interior design color quantification, aiming to enhance the aesthetics and functionality of the living environment through precise color matching. The method leverages the dkimageapp module to achieve scientific quantification and analysis of colors, thereby accomplishing efficient color pairing. In terms of methodology, this article elaborates on the importance and application of color palette, color difference, and color wheel calculations. Color palette calculation assists designers in grasping the distribution and harmony of colors; color difference calculation utilizes the CIEDE2000 formula to provide an accurate assessment of color differences; color wheel calculation serves as a visual tool for understanding color relationships. Empirical research has verified the effectiveness and practicality of the algorithms, ensuring the reliability of the study. This article ultimately summarizes the research findings and looks forward to their widespread application in the field of interior design, contributing to the creation of a better living environment, while stimulating further exploration and innovation to promote the continuous development of the interior design industry.

Keywords: Interior Design, Color Quantification, IKEA Design Philosophy, Color Palette, Color Difference, Color Wheel

1. Introduction

With the improvement of modern living standards, people's aesthetic and functional demands for their living environment are increasingly growing. Interior design, as an important means to enhance the quality of living, is not only related to the visual enjoyment of the residents but also affects their psychological and emotional states [1]. Against this backdrop, the color matching in interior design is not only a form of visual art but also a science. The rational use of colors can create a warm, comfortable, and even inspiring spatial atmosphere, thereby improving the quality of life of the residents.

As a globally renowned home furnishing brand, IKEA, with its design philosophy of "creating a better everyday life for the many people," has provided practical and aesthetic home solutions for consumers around the world. IKEA's design philosophy emphasizes simplicity, modernity, affordability, while focusing on environmental protection and sustainability. These concepts are also reflected in the color matching of IKEA's products, which are usually dominated by neutral and soft tones, easy to match, and adaptable to various living environments and personal preferences.

However, in the field of interior design color matching, how to quantify colors and achieve scientific and reasonable matching is still a question worth in-depth exploration. The scientific nature of color matching is not only reflected in the application of color theory but also involves the psychological impact of colors on people, the symbolic significance of colors in different cultures, and the visual effects of colors in space. Color plays a crucial role in interior design. It not only affects the atmosphere and emotional expression of the space but also influences people's behavior and psychological state to a certain extent. For example, warm colors can create a warm and comfortable atmosphere, while cool colors give a fresh and tranquil feeling. In addition, colors can also affect people's emotions, such as red stimulating vitality and blue helping to relax the mood.

Therefore, how to scientifically quantify and analyze colors, and how to apply these quantification results in interior design, has become an important subject in the field of design. This requires not only the quantification of the physical properties of colors (such as hue, brightness, and saturation) but also the consideration of the psychological and emotional impact of colors. This requires a color quantification algorithm that can comprehensively consider these factors. The cooperation between the Artificial Intelligence Human Settlement Environment Joint Laboratory (represented by lab), and IKEA aims to integrate the power of technology into the field of interior design to better meet customer needs.

In this context, Mr. Wei, the chief algorithm scientist of the lab, led the team to develop dkimageapp (https://gitee.com/weihaitong/dkimageapp), a practical tool for image processing, a Python dependency library module. This module is closely related to the cooperation project with IKEA Shanghai, providing strong technical support for the quantification of interior design colors. The dkimageapp module offers a range of functions, including image cropping, merging, image format conversion, extraction of color tone ratio, color similarity calculation, image positioning, and image retrieval. These functions not only provide convenience for designers but also make the development and practice of color quantification algorithms possible.

Based on this, this article aims to explore and practice a color quantification algorithm for interior design based on the IKEA design concept. The algorithm will use the functions of the dkimageapp module to scientifically quantify and analyze colors, thereby achieving more accurate and reasonable color matching. Through the dkimageapp module, designers can process and analyze image data in interior design more efficiently, thereby better understanding the performance and impact of colors in space.

The exploration goals and scope of this article aim to achieve the following key points:

1. Deepening the foundation of color theory: By in-depth research on the basic concepts, properties, and principles of color matching of colors, to provide a solid theoretical support for interior design.
2. Integrating IKEA's design philosophy: An in-depth analysis of IKEA's design philosophy and exploration of how to combine these concepts with color quantification algorithms to achieve scientific color matching in IKEA-style interior design.
3. Developing color quantification methods: Exploring and developing a systematic methodology for quantifying colors, including color palette calculation, color difference calculation, and color wheel calculation, to provide a quantitative scientific basis for color matching.
4. Implementing algorithm development and application: Based on the above theories and methods, develop a color quantification algorithm and use the functions of the dkimageapp module to implement the algorithm on the computer, facilitating image processing and color analysis.
5. Verifying the effectiveness of the algorithm: Through carefully designed experiments and actual interior design cases, verify the effectiveness of the developed algorithm to ensure its reliability and accuracy in practical applications.
6. Promoting innovation in interior design: Through the exploration and practice of color quantification algorithms, bring innovative perspectives and methods to the field of interior design and enhance the professional level of interior design.
7. Promoting the development of home brands: Provide scientific color design guidance for home brands such as IKEA, helping the brand to maintain innovation and a leading position in the competitive market.

Through in-depth exploration of these research goals and scope, this article expects to provide a scientific quantification method for color matching in interior design, and at the same time, provide strong technical support for the color design of home brands, ultimately achieving technological progress and innovation and development in the field of interior design.

Additionally, by leveraging a knowledge graph, a color recommendation system can be developed to suggest appropriate color matching schemes. It can also be utilized to analyze trends and patterns in color usage, thereby optimizing design strategies. For instance, by analyzing user feedback on various color combinations, the recommendation algorithms can be adjusted to enhance user satisfaction [2].

2. Literature Review

2.1. Theoretical Foundation

Li, Z. and Chen, Y. in 2010 studied a parallel particle swarm optimization algorithm for the task of image color quantization. This algorithm leverages the parallelism of particle swarm optimization to iteratively evolve and select the optimal color palette, achieving rapid and accurate quantization of pixel colors. Experiments have demonstrated that this algorithm significantly outperforms traditional particle swarm optimization methods in terms of performance, providing an efficient solution for image color quantization [3].

In 2011, Jiang, Y. et al. proposed a new color quantization algorithm based on K-means clustering. By categorizing pixels by hue before clustering quantization, the algorithm not only enhances the quantization effect but also reduces execution time, showing a significant performance advantage over traditional algorithms [4]. In the same year, Tang, Z. proposed a new real-time color quantization algorithm that combines the speed of segmentation algorithms with the accuracy of clustering algorithms, improving the pixel matching process. This algorithm uses a data structure link to connect all the colors in the image based on the frequency of color occurrence and completes color quantization by manipulating these links. Experimental results show that the algorithm can effectively achieve the expected quantization effect, enhancing the quality and efficiency of the quantization process [5].

In 2014, Rahul, K. et al. proposed a CIQ algorithm that combines DBSCAN and K-means. By decomposing the image and filtering through clustering, the algorithm effectively improves color palette design and enhances the efficiency of data compression and the visual quality of image reconstruction [6].

Schaefer, G. et al. in 2015 proposed a new color quantization algorithm that employs simulated annealing optimization and the S-CIELAB image quality metric to mimic the human visual system, maximizing image fidelity rather than just minimizing MSE. Experiments showed that this algorithm outperforms traditional quantization methods in terms of image quality [7].

In 2020, Thompson, S. et al. proposed a new color quantization method based on online k-means, addressing the high computational cost and initialization sensitivity issues of traditional k-means algorithms in color quantization. By adaptive cluster center initialization and quasi-random sampling, the new method achieves fast and high-quality color quantization. Experimental results indicate that the method significantly improves quantization speed while maintaining results similar to batch k-means [8].

Pérez-Delgado, M.-L. in 2021 suggested that the iterative ant tree algorithm is an effective method for color quantization. By modifying the values of algorithm parameters and the order of pixel processing, the new variant surpasses the original version in image quality and exhibits better robustness in parameter selection. This indicates that algorithm adjustments can significantly enhance the effect of color quantization and the reliability of its applications [9].

In 2022, Abernathy, A. and Celebi, M. E. proposed a novel partitioning color quantization algorithm, an improvement over MacQueen's online k-means algorithm, addressing the initialization and speed issues of traditional k-means algorithms. Experimental results show that the new algorithm significantly improves processing speed while maintaining consistency in results, demonstrating potential as a general-purpose clustering algorithm [10]. In the same year, Yang, L. studied color transfer algorithms in interior design based on topological information. By comparing two different color transfer algorithms in different color spaces, it was found that the algorithm based on image segmentation performed better in reducing noise and improving the number of topological region matches, thereby enhancing the effect of color transfer [11].

In 2023, Yu, X. et al. proposed a new HSI color space binary color quantization algorithm that reduces the number of colors and improves the image display effect through a monotonic function and iterative optimization, and its effectiveness was verified through visual and numerical assessments [12]. In the same year, Liu, Y. proposed an improved color classification method that solves the high computational cost and initialization sensitivity issues of the K-means algorithm in color quantization through data sampling and optimization of the triangle inequality, improving the efficiency and effect of quantization [13].

Hou, Y. et al. in 2024 proposed C2Ideas, an innovative interior color design scheme. Through a three-stage process and an interactive interface, it helps designers creatively conceive color schemes based on user intentions and design principles, and its effectiveness and high recognition by designers have been verified through user research [14].

2.2. Theoretical Gaps and Innovations

In this article, we aim to fill the following theoretical gaps and achieve innovation:

1. Deepening of Color Quantization Theory: Currently, in the field of interior design, the application of color theory largely depends on the experience and intuition of designers. This article will bridge the gap in the application of color science theory in interior design practice by providing a systematic method for color quantization, offering a more precise quantitative analysis tool for color matching.
2. Integration of Technical Tools and Design Practice: Although there are various image processing tools on the market, integrated tools specifically for interior design color quantization are still lacking. Through the development and application of the dkimageapp module, this article will innovatively integrate technical tools with design practice, providing designers with a comprehensive and efficient solution for color quantization.
3. Cycle of Algorithm Optimization and Design Innovation: In the field of interior design color quantization, there is a lack of a continuous optimization and innovation cycle mechanism. This article will establish an algorithm optimization process based on experimental feedback and case analysis, achieving a virtuous cycle of design innovation and technical iteration, and promoting the interior design field to move towards a more efficient and scientific direction.

By filling these theoretical gaps and through innovative practice, the research in this article will not only provide new perspectives and tools for color matching in interior design but also promote the entire industry to develop in a more scientific and systematic direction.

3. Methodology

3.1. Color Palette Calculation

Color palette calculation is a widely applied technique in the field of image processing that analyzes and quantifies the distribution and characteristics of colors within an image. This technology is crucial for understanding the color composition of an image, playing a significant role in interior design by assisting designers in extracting color combinations from images and providing color schemes for interior decoration. Additionally, it is used in digital image processing for tasks such as color recognition, segmentation, and registration [15].

The core principle of color palette calculation is to quantify all the colors in an image and then identify the main or representative colors using statistical methods. This typically involves color space transformation, color clustering, and statistical analysis of color distribution [16].

Before performing color palette calculation, it is common to convert the image colors from the RGB color space to a color space more suitable for color analysis, such as HSV or Lab. This conversion helps to more accurately represent and differentiate color variations.

Color clustering is a key step in color palette calculation, involving grouping the colors in an image into several main color clusters. The K-means clustering algorithm is widely used in this step due to its simplicity and efficiency. The K-means algorithm classifies data points into K clusters through an iterative process, minimizing the sum of the distances between each data point and the center (mean) of its cluster. The application of the K-means algorithm in color palette calculation includes the following steps [17]:

1. Preprocessing: Converting the image to a color space suitable for analysis and scaling it.
2. Selecting the number of clusters (K-value): Determining the number of colors to extract.
3. Randomly initializing center points: Choosing initial cluster centers.
4. Assignment step: Assigning each color point to the nearest cluster center to form clusters.
5. Update step: Recalculating the center point of each cluster.
6. Iterative optimization: Repeating the assignment and update steps until the cluster centers no longer change significantly.
7. Extracting the color palette: The center point of each cluster represents a main color, constituting the image's color palette.

The advantage of the K-means algorithm lies in its simplicity and computational efficiency, making it suitable for processing large datasets and providing a color palette that intuitively reflects the main colors of the image. However, the K-means algorithm also has limitations, such as sensitivity to the choice of K-value, the impact of initial center point selection on clustering results, and varying performance in different color spaces. To overcome the limitations of the K-means algorithm, this article proposes a new method for selecting initial seeds based on the maximum minimum distance for K-means.

The basic idea of the algorithm is as follows:
If there is only one cluster, i.e., all data objects are in the same cluster, the object that contributes the least to the total distance within the cluster is most likely to become the cluster center. Therefore, we can calculate the contribution of each data object to the total distance within the cluster and then select the object with the minimum value as the first initial seed c1. If all data objects are divided into two clusters, we can choose the object farthest from c1 as the second initial seed c2. These centers, selected in this way, will not be too concentrated, which is conducive to obtaining better clustering results. Similarly, if the dataset is divided into three clusters, we can choose the object farthest from c1 and c2 as the next initial seed. This process continues until all required initial seeds are found.

The maximum minimum distance algorithm can be described as using "the maximum Euclidean distance between tentative clusters" as a condition for pre-selecting the initial cluster centers; determining the remaining cluster centers based on the maximum distance in the minimum distance situation; after all cluster centers are determined, classifying all patterns into categories based on the nearest distance. The key to the algorithm is how to calculate new clusters and how to determine the centers of new clusters. Since the core of the algorithm is to find the maximum distance among the minimum distances, it is also known as the "smallest among the largest distance algorithm."

Figure 1 is a Python example code for color palette calculation using the K-means algorithm. This code uses the PIL library for image processing, the numpy library for mathematical operations, the K-means clustering algorithm from the sklearn library, and our proposed maximum minimum distance algorithm for custom initial points.

```python
from sklearn.cluster import KMeans
from PIL import Image
import numpy as np

class MaxMinDistance(object):
    def __init__(self, k):
        self.centers = []
        self.k = k

    @staticmethod
    def euclidean(a: list, b: list):
        return np.linalg.norm(
            np.array(a, dtype=np.float) - np.array(b, dtype=np.float),
            axis=1
        )

    def fit(self, X: list):
        if isinstance(X, np.ndarray):
            X = X.tolist()
        for k_ in range(self.k):

            if k_ == 0:
                # Step 1: Calculate the contribution of each data point to the
                total distance within the cluster,and then select the object
                with the smallest total distance as the first initial center c1.
                 ck_ind = np.argmin([
                     np.sum(self.euclidean(a=[point], b=X))
                     for point in X
                 ])
            else:
                X = list(filter(lambda x: x not in self.centers, X))

                if not len(X):
                    return self

                # Step 2: Select the object farthest from c1 as the second
                  initial center c2.
                # Step 3: d(ci, cj) = max(min(d(xk, cj)))
                # Steps 2 and 3 can be combined.
                ck_ind = np.argmax([
                    np.min(self.euclidean(a=[point], b=self.centers))
                    for point in X
                ])
            self.centers.append(X[ck_ind])
        return self

def kmeans_color_quantization(image_path, k=5):
    """
    A function that performs color palette calculation using the K-means
    algorithm.

    Parameters:
    image_path : str
        The path to the image file.
    k : int
        The number of colors to extract.

    Returns:
    cluster_centers : ndarray
        The cluster centers, i.e., the colors of the color palette.
    """
    # Open the image and convert to RGB
    image = Image.open(image_path)
    image = image.convert('RGB')

    # Convert the image to a numpy array
    image_data = np.array(image)

    # Convert the image data to a one-dimensional array, where each element is
    a color value
    pixels = image_data.reshape((-1, 3))

    # Apply the K-means algorithm
    maxMinDist = MaxMinDistance(k=k)
    maxMinDist.fit(X=pixels)
    kmeans = KMeans(n_clusters=k, init='manual')
    kmeans.fit(pixels)
    kmeans.cluster_centers_ = maxMinDist.centers

    # Get the cluster centers, i.e., the colors of the color palette
    cluster_centers = kmeans.cluster_centers_

    return cluster_centers

# Usage example
image_path = 'your_image_path.jpg'  # Replace with your image path
number_of_colors = 5  # The number of colors you want to extract
palette_colors = kmeans_color_quantization(image_path, number_of_colors)

# Print the color palette colors
for color in palette_colors:
    print(color)
```

Figure 1: K-Means Python Code

As a powerful image analysis tool, color palette calculation has broad application prospects in various fields. In the field of interior design, designers can use color palette calculation to extract color schemes from images of natural scenery, artworks, or any source of inspiration for interior decoration. In the field of digital image processing, color palette calculation is also used for tasks such as color recognition, segmentation, and registration, such as facial recognition and satellite image analysis.

With the development of technology, color palette calculation is also continuously advancing. Modern algorithms pay more attention to the perceptual consistency of colors, improving the accuracy of color analysis by considering the differences in human eye sensitivity to different colors. At the same time, the introduction of machine learning and artificial intelligence technologies makes color palette calculation more adaptable to different image content and application scenarios, further enhancing its practicality and flexibility.

In summary, color palette calculation is not only theoretically significant but also has extensive practical application value. By deeply understanding and applying color palette calculation, we can better analyze and utilize colors, providing support for design and creative work, and also providing a powerful tool for image processing and analysis.

3.2. Color Difference Calculation

Color difference calculation is a core component in the field of color science, involving the quantification of the difference between two colors. This assessment is crucial for understanding color variations, ensuring color quality, and reproducing colors on different devices and materials. Quantifying color differences not only aids color experts and designers in making precise color decisions during creative and production processes but also enables non-specialists to objectively evaluate colors.

Among the many color difference formulas, the CIEDE2000 color difference formula is widely regarded for its high accuracy and consistency with human visual perception. Recommended by the International Commission on Illumination (CIE) in 2001, CIEDE2000 represents a significant advancement in color difference calculation methods. Compared to earlier color difference formulas such as CIE94 and CIELAB, CIEDE2000 is more accurate in predicting the perception of color differences by the human eye, especially when dealing with colors of different hues and lightness.

The calculation process of the CIEDE2000 color difference formula integrates multiple attributes of color, including luminance (L*), chroma (C*), and hue (H*), and introduces several weighting factors related to human visual perception. These weighting factors take into account the interaction of colors and the varying sensitivity of the human eye to different colors, making the results of color difference calculation more aligned with the visual experience of humans.

Detailed Procedure of the CIEDE2000 Algorithm Formula:
1. Data Preparation: Obtain the L* (lightness), a* (red-green chroma), and b* (yellow-blue chroma) values of two color samples in the CIELAB color space.
2. Calculation of Color Attribute Differences: Compute the differences in lightness (ΔL*), chroma (ΔCab*), and hue (ΔHab*) between the two color samples:

$$\Delta L^* = L_b^* - L_a^*$$

$$\Delta C_{ab}^* = C_{ab,b}^* - C_{ab,a}^*$$

$$\Delta H_{ab}^* = \operatorname{atan2}(b_b^* - b_a^*, a_b^* - a_a^*)$$

Where $C_{ab}{}^*$ is the chroma, which can be calculated using:

$$\Delta C_{ab}^* = \sqrt{(a^*)^2 + (b^*)^2}$$

3. Determination of Weighting Factors: Determine the weighting factors KL, KC, KH based on the viewing conditions, which affect the weighting of differences in lightness, chroma, and hue.
4. Calculation of Visual Perception Weights: Compute the visual perception weights for lightness, chroma, and hue (SL, SC, SH):

$$S_L = 1 + \frac{0.015 \times (L^* - 50)^2}{\sqrt{20 + (L^* - 50)^2}}$$

$$S_C = 1 + 0.045 \times C_{ab}^*$$

$$S_H = 1 + 0.015 \times C_{ab}^* \times T$$

Where T is a function of the hue angle, used to adjust the weight of the hue difference.
5. Calculation of Rotation Factor RT: Calculate the rotation factor RT, which adjusts the hue difference calculation to align with human color perception:

$$R_T = -\sin\left(\frac{\pi}{2} \times H_{ab}^*\right) \times \frac{1}{3}$$

6. Calculation of CIEDE2000 Color Difference Value: Use the following formula to calculate the CIEDE2000 color difference value ΔE0:

$$\Delta E_0 = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C_{ab}^*}{k_C S_C}\right)^2 + \left(\frac{\Delta H_{ab}^* + R_T \times \Delta C_{ab}^*}{k_H S_H}\right)^2}$$

Where $k_L = k_C = k_H = 1$ are the default values, but may need adjustment under non-standard viewing conditions.
7. Interpretation of Results: The smaller the value of ΔE_0, the smaller the difference between the two colors, and the less noticeable the color difference perceived by the human eye.

The application scope of color difference calculation is extremely broad. It is not only used in industrial production and quality control to ensure the consistency and accuracy of product colors but also extensively applied in the fields of color design, artistic creation, and image processing. In the digital age, with the advancement of display and printing technologies, color difference calculation plays a significant role in electronic display color calibration and printer color management.

The promotion and application of the CIEDE2000 color difference formula have greatly enhanced the scientific and precise nature of color management. It has enabled the communication and control of colors to move beyond subjective evaluation to precise numerical values. This quantification method has brought revolutionary changes to the field of color science and has provided crucial support for the technological progress and innovative development of related industries. As the demand for color accuracy continues to increase, the CIEDE2000 color difference formula will continue to play its vital role in color science and related industries.

This article introduces an innovative evaluation metric called Quantitative Measure Mirroring Qualitative Perception (QMMQP), which aims to link the objective results of color difference calculations with subjective visual perception. QMMQP is an objective score derived from the color difference value ΔE calculated by the CIEDE2000 color difference formula through a specific nonlinear transformation, with a value range of [0, 5]. The purpose of this score is to provide a quantified indicator that directly reflects subjective visual perception, enabling the color difference assessment results obtained by computers to be consistent with the visual evaluations of human observers.

The transformation formula for QMMQP is as follows:

$$\text{QMMQP} = \begin{cases} 5, & \Delta E < 0.5, k = 1, \\ 7 - k - \dfrac{\Delta E - \Delta E_{min}(k)}{\Delta E_{max}(k) - \Delta E_{min}(k)}, & 0.5 \le \Delta E \le 24, k \in [2,6], \\ 0, & \Delta E > 24, k = 7. \end{cases}$$

This transformation involves mapping the ΔE value calculated by the CIEDE2000 color difference formula to an objective score corresponding to subjective ratings. The following table provides a detailed relationship between subjective assessment indicators based on the CIEDE2000 color difference. This information is commonly used to link objective color difference values with people's subjective perceptions.

k	$\Delta E_{min}(k)$	$\Delta E_{max}(k)$	Perceived Color Difference	QMMQP
1	0.0	0.5	Almost imperceptible	5
2	0.5	1.5	Slightly perceptible	5 - (ΔE - 0.5)
3	1.5	3.0	Perceptible	4 - (ΔE - 1.5) / 1.5
4	3.0	6.0	Moderately perceptible	3 - (ΔE - 3) / 3
5	6.0	12.0	Largely perceptible	2 - (ΔE - 6) / 6
6	12.0	24.0	Very perceptible	1 - (ΔE - 12) / 12
7	24.0	∞	Extremely perceptible	0

Table 1: QMMQP Color Difference

In Table 1, ΔEmin(k) and ΔEmax(k) represent the minimum and maximum ranges of the color difference value ΔE, used to define the degree of color differences perceived at different levels. "Perceived color difference" describes the degree of color difference that people may perceive within the corresponding ΔE range. QMMQP is a score based on the ΔE value, calculated through a transformation formula, which quantifies the subjective perception of color differences. This transformation allows researchers and professionals to link color difference values with people's perceptual experiences, thereby more accurately assessing the quality of images or color samples. For example, if the calculated ΔE value is below 0.5, the perceived color difference is considered "almost none," with a corresponding QMMQP value of 5. As the ΔE value increases, the degree of perceived difference increases, and the QMMQP value decreases accordingly, until the ΔE value exceeds 24, at which point the perceived difference is "extremely significant," and the QMMQP value is 0.

The application of QMMQP lies in providing a quantified assessment consistent with human visual perception, which is very useful in various fields such as image and video quality assessment, color management, and the printing industry. Through QMMQP, the impact of color differences on human observers can be more accurately predicted and assessed.

QMMQP is an innovative evaluation metric that transforms the results of the CIEDE2000 color difference formula into a quantified score consistent with subjective visual perception, thus providing a color image quality assessment method that is more in line with human visual perception. This method is not only scientifically rigorous but also has practical application value, providing support for research and practice in related fields.

3.3. Color Wheel Calculation

The color wheel, also known as the color circle or color wheel, is a visual tool used to display and understand the relationships between colors. It is based on the spectral order of colors, arranging them in a circular pattern to form a closed loop, thereby visually demonstrating the continuity and periodicity of colors.

The color wheel is usually arranged in the order of red, orange, yellow, green, blue, indigo, and violet, representing the colors in the visible spectrum. The design of the color wheel allows adjacent colors to transition gradually in appearance, while opposite colors (such as red and green, blue and orange) are complementary, directly opposite each other on the wheel. The color wheel is not only used to display basic hues but also enriches expression through variations in lightness and saturation.

The color wheel has applications in various fields, such as art, design, fashion, education, and image processing. In art and design, the color wheel helps creators explore color combinations to achieve visual harmony and contrast. In education, the color wheel is a fundamental tool for teaching color theory. In image processing, color wheel calculation can be used for color correction, color enhancement, and automated color selection.

The design of the color wheel is based on the three basic properties of color: hue, saturation, and brightness. Hue is the primary characteristic of a color, determined by the wavelength of light, and determines the type of color we see. Saturation describes the purity of a color, the amount of gray in the color, with higher saturation indicating a purer color. Brightness is the lightness or darkness of a color, with higher brightness indicating a lighter color.

The color wheel is based on the spectral order of red, orange, yellow, green, blue, indigo, and violet, representing the range of wavelengths of visible light in nature. By connecting violet back to red, the color wheel forms a continuous hue cycle, representing the infinite possibilities of hue. The opposite colors on the color wheel are called complementary colors, which create a strong visual contrast effect. The concept of complementary colors is very important in art and design because they can enhance visual effects and attract visual attention. The color wheel also considers the psychological impact of colors, as different colors can evoke different emotional responses, such as warmth, calmness, vitality, or relaxation. The colors on the color wheel are not isolated; their relationships are relative. Through the color wheel, similarities and differences between colors can be more easily identified and understood. The color wheel provides a method to explore and achieve color harmony by selecting colors adjacent to or at a certain angle apart on the wheel to create harmonious color combinations.

The principles of the color wheel not only help us understand the physical properties of colors but also provide a way to explore and express the aesthetic value of colors in visual arts. Through the color wheel, we can gain a deeper understanding of how colors interact and how to use these interactions to create beautiful visual works.

This article proposes a systematic algorithmic process for color wheel calculation to analyze and represent the relationships of colors in hue. The following is a detailed description of the algorithmic process:

1. Color Space Selection: Choose an appropriate color space for analysis, including common color spaces such as HSV (Hue, Saturation, Value), HSL (Hue, Saturation, Lightness), and CIELAB.
2. Color Sample Preparation: Collect a set of color samples, which can be color pixels from an image, predefined color sets, or user-defined colors.
3. Color Space Conversion: Convert all color samples from the original color space (e.g., RGB) to the selected hue representation color space. For example, use conversion formulas to transform RGB colors into HSV or HSL.
4. Hue Extraction: For each color sample, extract the hue attribute (Hue). Hue is the position of the color on the color wheel, typically represented as an angular value ranging from 0 to 360 degrees.
5. Hue Normalization: Normalize the hue values onto the color wheel to ensure continuity. For instance, convert the hue values from a [0, 360] range to a [0, 1] range for even distribution on the color wheel.
6. Color Wheel Mapping: Map the normalized hue values onto the color wheel. This can be done by multiplying the hue values by the circumference of the color wheel to determine the specific position of the color on the wheel.
7. Color Distribution Analysis: Analyze the distribution of color samples on the color wheel, identifying areas where colors are concentrated or dispersed, and whether there are any gaps or oversaturated areas in the color spectrum.
8. Calculation of Color Distance: Calculate the distance between any two colors on the color wheel, which can be achieved by calculating the difference in their hue values. The calculation of distance provides a quantitative measure of color differences.
9. Identification of Complementary and Analogous Colors: Identify complementary colors (colors directly opposite each other on the wheel) and analogous colors (colors adjacent to or near each other on the wheel). These identifications help understand the contrast and harmony of colors.
10. Color Harmony Assessment: Assess the harmony of colors on the color wheel by analyzing the distribution of colors and the relationships of complementary/analogous colors to determine if the color combinations are harmonious.
11. Algorithm Optimization: Optimize the algorithm as needed to handle a large number of color samples or improve the accuracy of color analysis. This may include improving the accuracy of color space conversion or adjusting the method of color wheel mapping.
12. Result Interpretation and Application: Interpret the results of color wheel calculation and apply them to practical problems, such as image editing, color matching suggestions, or color trend analysis.

Figure 2 is a Python code defining a function cal_colors_angle for calculating the angular difference between two RGB color values on the color wheel. The code uses the colormath library, a Python library dedicated to color conversion and color space operations.

```python
from colormath.color_conversions import convert_color
from colormath.color_objects import HSLColor, BaseRGBColor


def cal_colors_angle(rgb_base, rgb_compare):
    """
    Calculate the angle between two colors

    :param rgb_base:
    :param rgb_compare:
    :return:
    """
    rgb_base = BaseRGBColor(*rgb_base)
    rgb_compare = BaseRGBColor(*rgb_compare)

    hsl_base = convert_color(rgb_base, HSLColor)
    hsl_compare = convert_color(rgb_compare, HSLColor)

    angle = abs(round(hsl_base.hsl_h) - round(hsl_compare.hsl_h))
    if angle > 180.0:
        angle = 360.0 - angle
    return angle

```

Figure 2: Colors Angle Python Code

Through these steps, the color wheel calculation algorithm not only provides an in-depth understanding of the visual characteristics of colors but also offers a scientific basis for color selection and matching. This algorithm has broad application potential in fields such as design, artistic creation, and image processing.

3.4. Empirical Cases

In 2019, IKEA Shanghai presented us with a challenging task: to explore aesthetic strategies for color matching in interior furniture and to achieve its visualization. This task not only required us to deeply understand the art of color matching but also demanded that we implement automation and intelligence in color pairing through technical means. Our goal was to automatically match and render indoor scene images that coordinate with individual furniture product images, thereby providing consumers with more intuitive and personalized furniture matching solutions.

IKEA's design philosophy emphasizes the contrast and harmony of colors, which is particularly important in interior decoration. Contrast can highlight the characteristics of furniture, while harmony creates a unified visual effect. However, finding the balance between contrast and harmony is a problem that requires in-depth research. Our team, through continuous exploration and practice, ultimately developed an effective color matching strategy that successfully solved this challenge.

For example, as shown in Figure 3, we first performed a color palette calculation on the product image of the bookcase, determining the main color of the bookcase to be RGB values of (138, 120, 106), with a secondary color of (50, 43, 39). In the generated scene image, we carefully selected a coffee table with a color close to the bookcase's secondary color, with RGB values of (48, 43, 41), forming a good harmony with the bookcase's secondary color. Through color difference calculation, we obtained a matching score of 4.45 between the coffee table and the bookcase's secondary color, and color wheel calculation showed that the two are similar colors at an angle of 5 degrees, proving the harmony of our matching strategy in terms of color.

Figure 3: Furniture Generation Scene Example 1

Furthermore, to create contrast in the scene, we chose a sofa with a main color that forms a strong contrast with the coffee table, with RGB values of (205, 207, 217). Color wheel calculation showed that the contrast angle between the sofa and the main color of the coffee table is 156 degrees. This contrast not only meets IKEA's design requirements but also makes the sofa more prominent in the scene, becoming the visual focus.

Figure 4 demonstrates the application of our matching theory in different scenes. In this example, since the product sofa is designed in a single color, we chose contrasting colors for the carpet and coffee table in the scene image. The application of this contrasting color not only follows IKEA's design principles but also makes the entire scene more vivid and attractive. Through the clever use of contrast and harmony, we have not only enhanced the aesthetics of the interior space but also provided more inspiration and possibilities for furniture design and interior decoration.

Figure 4: Furniture Generation Scene Example 2

In addition, our research also involves the field of color psychology. Different colors can trigger different emotional responses from people. For example, warm colors can create a cozy atmosphere, while cool colors can bring a fresh and tranquil feeling. In our color matching strategy, we fully considered the psychological impact of colors, striving to provide consumers with a more comfortable and pleasant living environment.

In an IKEA bedroom design case, we faced a new challenge: how to transform a client's personalized desire for a fashionable bedroom into reality. A real client of IKEA wished to create a stylish bedroom themed around a pink and white color clash. This requirement not only tested our understanding of color matching but also the capability of our design tools to automatically generate bedroom design renderings. IKEA's headquarters color palette manual provided us with a rich selection of colors and a guide for color pairing. In this case, we strictly adhered to IKEA's design philosophy and color matching principles, ensuring that the design outcome met both the client's personalized needs and reflected the IKEA brand style.

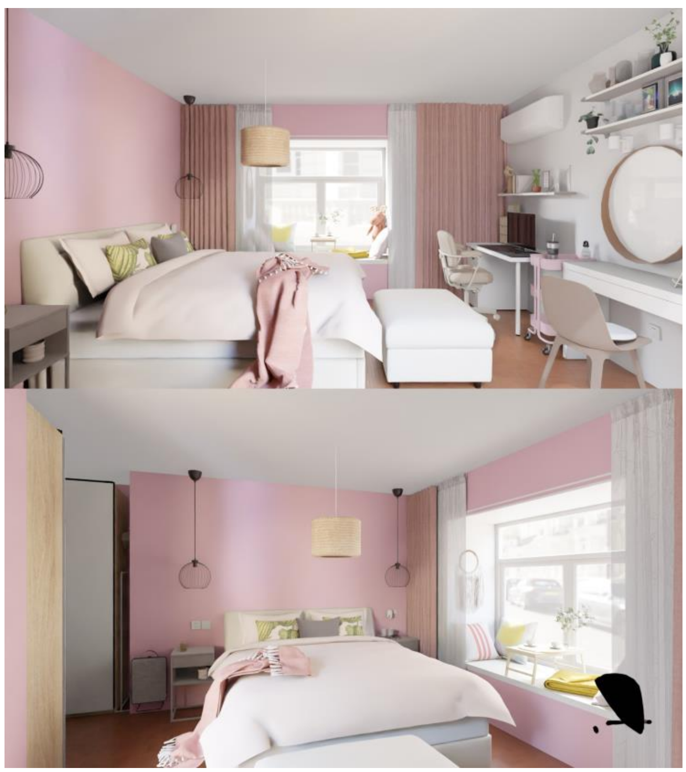

Figure 5: Bedroom Design

As shown in Figure 5, our design tool automatically generated a rendering of the bedroom design. In this rendering, we used soft pink and pure white as the main colors, creating a striking contrast while also establishing a warm and stylish atmosphere. The pink walls and white furniture complement each other, satisfying the client's pursuit of a color clash effect while maintaining the freshness and brightness of the bedroom space.

In terms of detail processing, we also put in great effort. For example, we chose pink bed linen and white pillows, as well as pink curtains and a white bed footstool; these detailed matches further reinforced the theme of pink and white color clash. At the same time, we cleverly used some metallic elements, such as golden bedside lamps and decorations, adding a touch of modernity to the bedroom.

Furthermore, we also considered the psychological impact of color. Pink is generally considered to bring a sense of relaxation and pleasure, while white can create an atmosphere of tranquility and purity. Through this color matching, we hope to create a comfortable and stylish bedroom space for our clients, allowing them to get ample rest and relaxation after a busy day.

In summary, the two bedroom design case studies demonstrated our in-depth understanding of color matching and the efficient capabilities of our design tools in automatically generating renderings. We believe that through continuous innovation and optimization, we can provide personalized, high-quality interior design services to more clients, meeting their pursuit of a beautiful living space.

4. Conclusion

In this article, we have delved deeply into the theory of color quantification and successfully developed a systematic method for color quantification, aiming to fill the gap in the application of color science theory in interior design practice. By deepening the theory of color quantification, we have not only provided designers with a more precise quantitative analysis tool but also promoted the development of the interior design field towards a more scientific and systematic direction through the application of these tools.

The dkimageapp module we developed serves as an innovative solution that integrates technical tools with design practice, greatly enhancing the efficiency and accuracy of color quantification. This module not only provides basic functions such as image cropping, merging, and format conversion but also offers advanced functions such as color tone ratio extraction and color similarity calculation, providing strong technical support for designers in color matching decisions. This integration of technology and design marks an important step in the application of tools in the interior design field.

Furthermore, we have established an algorithm optimization process based on experimental feedback and case analysis, forming a continuous cycle of optimization and innovation. This process not only ensures the continuous improvement of the algorithm but also promotes design innovation through technical iteration. Through this cyclical mechanism, we can continuously adapt to the changing needs of the interior design field, ensuring the forward-looking nature and applicability of the color quantification method.

In terms of color palette calculation, our research provides a new perspective for designers on color matching by quantifying the distribution of colors in images. Through color palette calculation, designers can more intuitively understand the distribution and harmony of colors in space, thereby achieving more harmonious color matching in interior design. Color palette calculation not only reveals the dominant trends of colors but also helps to identify and emphasize the diversity and balance of colors, which is crucial for creating visually appealing and emotionally rich indoor environments.

As another important part of this article, color difference calculation provides a more accurate method for assessing color differences through the application of advanced color difference formulas such as CIEDE2000. This method takes into account not only the brightness, chroma, and hue of colors but also the differences in the human eye's sensitivity to colors, playing a significant role in color quality control and color reproduction. The precision of color difference calculation is essential for ensuring the consistency and expected effect of design works under different materials and lighting conditions.

Finally, the introduction of color wheel calculation provides us with a visual tool for understanding and representing color relationships. The color wheel not only shows the spectral order of colors but also reveals the interrelationships between colors through variations in hue, saturation, and brightness. This provides an important reference for designers in color selection and matching. As an intuitive educational and design tool, the color wheel helps designers and non-specialists understand complex color theory and make quick color decisions in practice.

In summary, this article provides new theoretical support and practical tools for the interior design field through the comprehensive application of color palette calculation, color difference calculation, and color wheel calculation. Moreover, by integrating technological innovation and design practice, it promotes the development of the entire industry. We look forward to the widespread application of these research results in future interior design practices, contributing to the creation of a more beautiful and harmonious living environment. At the same time, we also hope that this article can inspire more researchers and designers to explore and innovate in the field of color quantification, jointly promoting the technological progress and artistic prosperity of the interior design industry. Through these efforts, we believe that we can further enhance the professional level of interior design, enrich people's visual experience, and improve the quality of life.

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