Image Enhancement For Color Blindness

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Abstract

Color blindness affects millions of individuals worldwide, limiting their ability to perceive and differentiate colors accurately. This research explores various image enhancement techniques and algorithms designed to improve vision of people who has color blindness. The study categorizes color blindness into three main types: monochromacy, dichromacy, and anomalous trichromacy, analyzing their impact on daily life and professional activities. It further evaluates corrective algorithms such as LMS Daltonization, CBFS, LAB Color Corrector, and Shifting Color, alongside visual attention mechanisms like saliency maps. By integrating eye-tracking data and advanced color models, this study aims to provide innovative solutions for enhancing color perception for people with color blindness.

1 Introduction

Scientific studies have shown that color blindness develops depending on the X chromosome. Since women have a XX chromosome and men have an XY chromosome, if the color blindness gene is found on an X chromosome, the probability of this condition occurring phenotypically in men is higher. Even if a color blindness gene is found on one X chromosome in women, this may not be occur in the phenotype, because of the other X chromosome. According to statistics, while 1 in 12 men in the world is color blind, this rate is 1 in 200 for women. This means that approximately 353 million people in the world are color blind.

Color blindness is genetic and there is no cure yet for genetic color blindness. Additionally, color blindness can occur over time due to diseases as diabetes, multiple sclerosis or due to medications and aging.

Two types of photoreceptors exists in the human eye: rods and cones. Rods perceives light while cones perceives colors. Retina has three types of cone receptors; L cones, M cones, S cones. L-cones (red) are sensitive to long wavelengths, M-cones (green) are sensitive to medium wavelengths, and S-cones (blue) are sensitive to short wavelengths. This genetically based condition can be classified according to how different photoreceptor cells are affected. Types of color blindness are explained below.

1.1 Color Blindness Classification

Depending on the extent to which these photoreceptors are affected, color blindness is classified into three main categories: Monochromacy, Dichromacy, and Anomalous Trichromacy.

1.1.1 Monochromacy

Monochromacy is the condition where the eye has only one type of cone cell or no cone cells at all. This condition often results in a complete loss of color perception and the individual seeing the world in black and white. However, with a single cone cell, a person can only see the environment in shades of red, green, or blue. However, current testing methods focus on an individual's perceptual capacity and ability to distinguish differences between colors rather than directly examining photoreceptor cells. Therefore, no one has felt the need to determine which type of cone cell is active.

1.1.2 Dichromacy

Dichromacy is the condition in which one of the cones is missing. Types of dichromacy: Protanopia, Deuteranopia, Tritanopia.

- Protanopia: L-cones are missing and red light cannot be detected.
- Deuteranopia: M-cones are missing and green light cannot be detected.
- Tritanopia: S-cones are missing and blue light cannot be detected.

1.1.2 Anomalous Trichromacy

Anomalous Trichromacy is the condition of reduced sensitivity to a particular color. The types are Protanomaly, Deuteranomaly, and Tritanomaly.

- Protanomaly: Decreased sensitivity to red light.
- Deuteranomaly: Decreased sensitivity to green light.
- Tritanomaly: Decreased sensitivity to blue light.

1.2 Challenges

Individuals with color blindness face many difficulties in both daily and professional life. These challenges span a wide spectrum, from traffic to business. Individuals who has red-green color blindness may have a hard time distinguishing traffic lights. While knowledge of the location of traffic lights often helps to overcome this problem, attention and reaction times can be negatively affected in a new environment. Similarly, safety warnings marked in eye-catching colors such as red or green may not be obvious enough for color-blind individuals and this may increase security risks.

In the educational arena, color-coded materials (e.g., maps, graphs, and tables) can make it difficult to access information for students with color blindness. For example, in the chemistry, where color analysis is important in laboratory studies, they may not be able to anaylze correctly. In the digital world, individuals may not understand difference between colored icons and buttons used on web pages or in applications. Similarly, color-based puzzles or tasks in video games may become complex for color-blind individuals and important elements may not be noticed. In games that require instantaneous reactions, the attention and reaction times of individuals with color blindness may be negatively affected. Additionally, some critical elements in games may go unnoticed due to their indistinguishable colors. This may make in-game progression difficult or negatively impact player performance. For example, identifying a target by color in a particular mission or missing a color-based warning could prevent the player from gaining an advantage.

Color blindness also has serious effects in professions. Individuals working in design, fashion, graphic design and healthcare may face difficulties because they cannot distinguish colors correctly. Since color perception is critical in professions such as electrical engineering and piloting, color blindness can lead to serious limitations in these areas. Additionally, some workplaces may limit or reject applications from individuals with color blindness. This limits employment opportunities.

The effects of color blindness in daily life are not limited to work and security. For example, difficulties may occur even in seemingly simple activities such as choosing food. Factors such as the degree of cooking or freshness of food may be difficult to distinguish through colors; For example, the doneness of meat or the ripeness of a fruit may not be noticeable. These difficulties cause color blind individuals to face various obstacles in their lives.

With an estimated 353 million color blind individuals in the world. Therefore, developing solutions for color blindness has become a social necessity. For these and similar reasons, technological and scientific solutions are being developed to counter the disadvantages of color blindness; Innovations are offered to improve the quality of life of individuals. This study aims to evaluate existing algorithms and methods, simulators for color blindness.

2 Literature Review

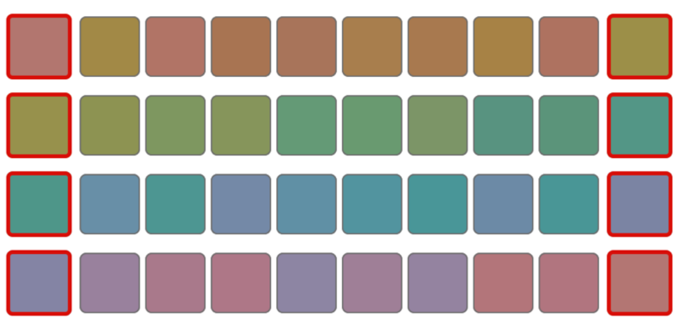
2.1 Color-blind Testers

2.1.1 Ishihara Color Blindness Test

This test was developed by Japanese ophthalmologist Dr. Shinobu Ishihara in 1917. It is intended to detect red-green color blindness such as Protanopia and Duteranopia. The test involves numbers or shapes created with dots of different sizes and colors located inside circles. Someone who is not color blind can easily see these numbers. A person who is color blind cannot distinguish numbers and colors or interprets them incorrectly. It is the most common color blindness test and can be performed quickly but it is not a sufficient test for tritanopia.

2.1.2 Farnsworth-Munsell 100 Hue Test

It aims to measure a person's color perception sensitivity. Rather than determining the severity or type of color blindness, It is significant to evaluate whether the person can distinguish color tones well. The test involves a series of colored disks. The user is asked to arrange these disks in the correct order along the color spectrum. For example, a color transition is expected to be created, such as from orange to red. The discs are arranged with subtle transitions between color tones. Incorrect rankings indicate that the user is having difficulty distinguishing the differences between certain color tones.



2.1.3 Anomaloscope

An anomaloscope is a special optical device used to determine the type and severity of color blindness. This device is specifically designed to examine cases of red-green vision deficits and, rarely, blue-yellow color blindness. When performing the test, the person tries to match the two halves of a circle according to their colors: Half of the circle is set to a mix of red, green light, while other half of the circle is a constant shade of yellow. Information about color blindness is obtained based on the degree to which the user can match colors. The anomaloscope is often used in clinical settings because it provides detailed analysis, but its application is complex and requires special expertise.

2.2 Color-blind Simulators

Color blindness simulators are tools designed to replicate how individuals with color vision deficiencies perceive the world. These simulators help developers, designers, and researchers understand the visual limitations experienced by people with different types of color blindness. By providing insights into color distortions and limitations, these tools facilitate the creation of more inclusive designs and assist in developing corrective algorithms.

There are several notable simulators:

- Color Oracle: A standalone program available for Windows, Mac, and Linux, simulating all types of dichromacy, including Protanopia, Deuteranopia, and Tritanopia.
- Vischeck: A web-based tool capable of simulating color blindness on uploaded images or as a plugin for software like Adobe Photoshop. It supports all types of dichromacy.
- CVD Simulator (Coblis): A web-based platform simulating both dichromacy and anomalous trichromacy types, offering zoom and adjustment features.
- Color Blindness Simulate Correct: An Android application that simulates and corrects color blindness in real time using the phone's built-in camera.

Algorithms which are discussed in this paper such as LMS Daltonization and CBFS algorithms, are not used only for color correction. They are also used for simulations. For instance, LMS Daltonization includes a simulation step that replicates how Protanopia, Deuteranopia, or Tritanopia distort color perception. Similarly, CBFS adjusts HSL parameters to model Protanopia while enhancing visual distinction for affected users.

By using simulators, individuals with normal vision can better understand the color blind people. Additionally, simulators serve as a crucial step in testing and refining technologies, algorithms, and applications aimed at improving accessibility for color-blind individuals.

Color-blind Simulator	The supported color blindness types	Platforms
Color Oracle[3]	all types of Dichromacy: • Deuteranopia • Protanopia • Tritanopia	• a downloaded program that works offline for Window, Mac and Linux.
Vischeck[4]	all types of Dichromacy: • Deuteranopia • Protanopia • Tritanopia	• a website that can run on a chosen uploaded image after selecting the type of color vision to simulate • a web-page. • an offline plugin with the help of Adobe Photoshop or ImageJ for Window, Mac and Linux.
CVD simulator(Coblis)[5]	• Monochromacy all types of Dichromacy: • Deuteranopia • Protanopia • Tritanopia all types of Anomalous Trichromacy: • Protanomaly • Deuteranomaly • Tritanomaly	• a website that can run on a chosen uploaded image after selecting the type of color vision to simulate. Support image zooming feature.
Color Blindness Simulate Correct[6]	all common colorblindness types are supported.	• an Android application that simulates and corrects color blindness in real-time using the built-in camera of the mobile phone.

3 Approaches

3.1 Visual Attention Mechanism

While we work on human visual system, we needed to use some approaches for understanding visual attention mechanism. Thus, this makes it possible predicting where people will look first in the image. This information can be used specifically to improve the visual attention mechanism of color blind individuals to be similar to normal individuals. Some approaches to understand the attention mechanism are:

- Bottom-up approach
- Top-down approach
- Hybrid approaches

3.1.1 Bottom-up approach

It relies only on low-level features of the image while trying to detect prominent points in the image. These features are visual elements such as color, brightness, contrast, texture and movement. People instinctively pay attention to such features. For example, a high-contrast colored element attracts more attention than other elements around it, or to give a more obvious example, if we turn on a flashlight in the dark, this light attracts a lot of attention.

This approach identifies salient regions based on physical features in an image. An example of this is creating a saliency map using a system that models eye movements.

3.1.2 Top-down approach

This approach directs people's visual attention processes according to users' informational and contextual goals. This approach uses high-level features and prior knowledge. People often direct their gaze according to what they are looking for. What attention is directed to is shaped by people's current needs, goals, and context. Therefore, high-level detection techniques such as face recognition, text detection, and object recognition are used. The top-down approach may require more complex systems and technologies.

While bottom-up approach identifies regions that capture attention by focusing on low-level visual features, the top-down approach directs visual attention processes based on the individual's goals and context. So, while bottom-up offers a more instinctive analysis, top-down requires a more complex perception process. Lastly, hybrid approach uses both approaches.

Understanding the mechanisms of visual attention provides the basis for developing more effective visual enhancement techniques for individuals with color blindness. In this context, specific approaches to color blindness are discussed below.

3.2 Special Approaches to Visual Enhancement Studies for Color Blindness

Approaches developed for color blindness may be divided to two main groups: naming colors correctly (Color Naming) and making colors more distinct (Color Differentiation). Their aim is to improve the visual perception of color blind individuals.

3.2.1 Color Naming

This approach focuses on correctly naming and categorizing colors. It aims to help individuals with color blindness identify colors clearly. The prominent methods are:

- While LMS color space is often used in color correction algorithms, the CIE 1931 XYZ is preferred in graphic design and visual media applications where more accurate color representation is needed.
- Gaussian Mixture Models (GMM) can similarly divide colors to groups than assigns a name to each group.

3.2.2 Color Differantiation

This approach aims to optimize visual perception by making colors more distinct or increasing contrast. Some of the techniques used include:

- Histogram Equalization: The technique is used for increase the contrast. It balances the contrast of the image, making the colors more distinct. For an individual with color blindness, differences between colors may be more noticeable.
- Visual Contrast Enhancement: Contrast enhancement algorithms are also frequently used to differentiate colors. To improve the visual perception of individuals with color blindness, the contrast between different colors in the image can be increased.

These approaches aim to alleviate the difficulties that individuals with color blindness face in both daily and professional life and aim to bring their visual perception processes to closer to that of normal individuals.

4 Methods and Algorithms

4.1 Creating Saliency Maps

Saliency Maps were given as an example when explaining the bottom-up approach. The purpose of creating Saliency Maps is to detect points in the image that are noticeable to people with normal vision and to highlight these important points to bring the attention of color blind individuals closer to those of individuals with normal vision. Below I will explain the process of creating a Saliency Map using Eye-Tracking Session with the steps of creating the EToCVD dataset.

4.1.1 Eye-Tracking Session

Eye-tracking devices track people's eye movements and record where they focus in images. Steps of creating EToCVD dateset as follows:

Device and Calibration

- Individuals' eye movements, saccadic movements (rapid eye movements) and scanpaths (ways of scanning images) were recorded using the Tobii EyeX device.

- Instead of the standard Tobii EyeX Engine Calibration, Tobii MATLAB Toolbox 3.1 Calibration was used. Because, they increased amount of calibration points from 9 to 13 and more precise data was obtained.

Experiment Process

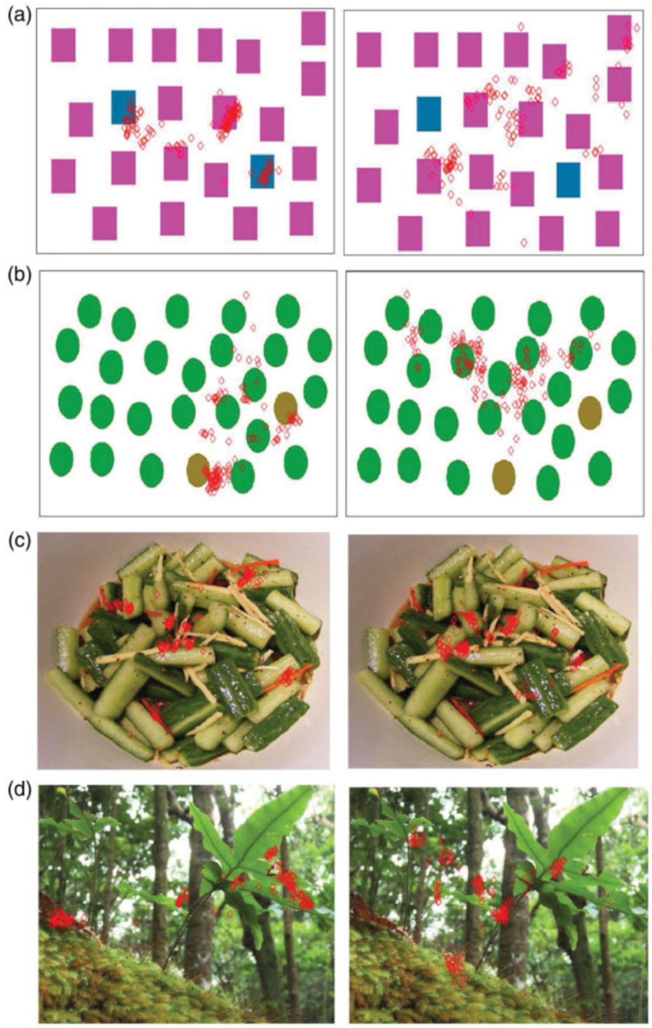
- Each image was shown to both color blind individuals and individuals with normal vision for 3 seconds.
- 1-second gray screens were placed between the images. These gray screens were used to clear the observer's retina of the signals from the previous image.
- An observation session lasted a total of 7 minutes.

Observers in the experiment consisted of individuals with normal vision and individuals with color blindness (protonopia, deutoronopia). Before the experiment, the individuals' color blindness was determined with the Ishihara Color Blindness Test.

Detection of Fixation Points

- The points where the observers' eyes looked were recorded as x and y coordinates.
- They took the average x coordinates and y coordinates of the eyes, the fixation points on which the individual focused at a particular moment were determined.
- In addition to collecting 3-second fixation point data, the first 200 ms of the 3 seconds were removed and the fixation points were recorded separately again. The purpose of this

process is to determine the points on which observers consciously focus, rather than the movements they make unconsciously at first glance.



In the figure, the fixation points of individuals with normal vision are shown in the pictures on the left, than the fixation points of individuals with color blindness are shown in the pictures on the right. This is clear that people with color blindness miss some important points in images. The study aims to make improvements in these areas for people with color blindness by creating a saliency map of individuals with normal vision.

Creating EToCVD Dataset

- Images for the EToCVD Dataset were collected from various public datasets. (Datasets: MIT1003, CAT2000, NUSEF, MIT300)
- All fixation points obtained were collected in the dataset named EToCVD.
- The dataset provides a rich resource for comparing visual perceptions of both color blind individuals and individuals with normal vision.

Processing of Fixation Data

- They got x coordinates and y coordinates from the EToCVD dataset and it processed to create a heatmap.
- Regions where fixation points are concentrated represent areas that attract attention.

4.1.2 Creating Saliency Map

The Saliency Map creation process is a combination of CIE Lab* color space and Eye-Tracking data. These maps play an important role in visual enhancement algorithms or in directing the attention of color blind individuals to important areas.

The images were first transformed from sRGB space to CIE XYZ space, and then from CIE XYZ to CIE Lab*a*b* space.

- CIE Lab* space allows luminance and color to be analyzed independently. The L* channel carries luminance information, while the a* and b* channels carry color information (red-green and blue-yellow). Saliency maps have been created for the L*, b*, a* channels.
- The saliency map of each channel is normalized to identify salient areas of the channel. The normalized saliency maps of the channels were combined to obtain an overall saliency map.

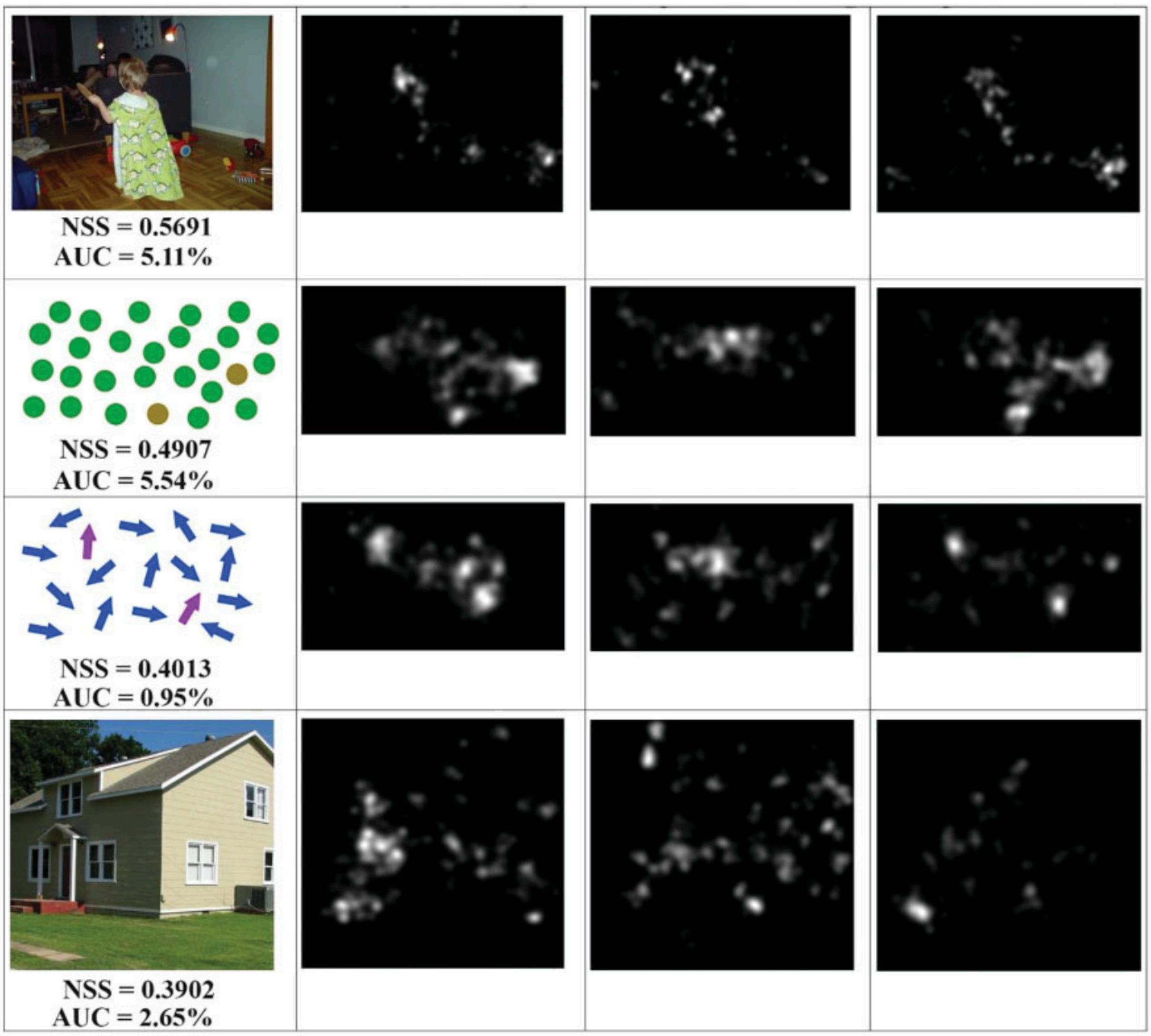
4.1.3 Color Enhancement

Visual enhancement process was performed in CIE L*a*b* space. Especially in a* (for red-green colors), b* (for blue-yellow colors) channels, contrast was increased according to the attention areas determined by Saliency Map. This process is designed to direct the attention of color blind individuals to these areas.

After the visual enhancement operations were completed, the edits in CIE Lab* space were converted to the sRGB. This is necessary so that the enhanced image can be viewed on standard devices (screens, projectors, etc.)

CIE Lab → CIE XYZ Transformation

CIE XYZ → sRGB Transformation



The upper image shows the fixation points. Normal observer, protanpia, protanopia (from enhanced image) respectively

4.1.4 Result

Saliency Map was used as a basic tool to detect critical areas that cannot be perceived due to color blindness. These maps determined in which regions the improvement algorithm would be more effective.

The improvement in attention of color blind individuals after image enhancement was tested with new Eye-Tracking Sessions. In the improved images, it was observed that the attention points of color blind individuals approached the attention points of normal individuals. A 10% improvement was achieved for Protanopia and a 5% improvement was achieved for Deuteranopia. Also, if we consider that dataset includes only 90 images, the developed method has a potential in the future.

4.2 LMS Daltonization Algorithm

The LMS Daltonization algorithm aims to correct images for individuals with color blindness using a model based on the photoreceptors L, M, S (cones sensitive to wavelengths). The algorithm works by converting the RGB to the LMS color space. This makes it possible to simulate and correct for different types of color blindness. It can both simulate color blindness (for example, showing how a colorblind person sees the world) and perform color correction. LMS makes images more perceptible to color blind people through matrix transformations and calculation of color differences.

Algorithm 1: LMS Daltonization

//**Input**: RGB input image
//**Output**: RGB color corrected image

1: Convert RGB image to LMS color space using equation (1)

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 17.8824 & 43.5161 & 4.11935 \\ 3.45565 & 27.1554 & 3.86714 \\ 0.0299566 & 0.184309 & 1.46709 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (1)$$

2: Simulate color-blindness using equation (2) for Protanopia, (3) for Duteranopia and (4) for Tritanopia

$$\begin{bmatrix} L_P \\ M_P \\ S_P \end{bmatrix} = \begin{bmatrix} 0 & 2.02344 & -2.52581 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} L_D \\ M_D \\ S_D \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0.49421 & 0 & 1.24827 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} L_T \\ M_T \\ S_T \end{bmatrix} = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 \\ -0.395913 & 0.801109 & 0.0 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix} \quad (4)$$

3: Convert $L_iM_iS_i$ back to $R_iG_iB_i$ using equation (5), i= {P, D, T}

$$\begin{bmatrix} R_i \\ G_i \\ B_i \end{bmatrix} = \begin{bmatrix} 0.0809444479 & -0.130504409 & 0.116721066 \\ 0.113614708 & -0.0102485335 & 0.0540193266 \\ -0.000365296938 & -0.00412161469 & 0.693511405 \end{bmatrix} \begin{bmatrix} L_i \\ M_i \\ S_i \end{bmatrix} \quad (5)$$

4: Find Difference between original and simulated images by (6), (7) and (8)

$$D_{R(i)=}R - R_i \quad (6)$$
$$D_{G(i)=}G - G_i \quad (7)$$
$$D_{B(i)=}B - B_i \quad (8)$$

5: Shift colors towards visible spectrum by multiplying by error matrices using (9) for Protanopia, (10) for Duteranopia and (11) for Tritanopia

$$\begin{bmatrix} R_{map(P)} \\ G_{map(P)} \\ B_{map(P)} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0.7 & 1 & 0 \\ 0.7 & 0 & 1 \end{bmatrix} \begin{bmatrix} D_{R(P)} \\ D_{G(P)} \\ D_{B(P)} \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} R_{map(D)} \\ G_{map(D)} \\ B_{map(D)} \end{bmatrix} = \begin{bmatrix} 1 & 0.7 & 0 \\ 0 & 0 & 0 \\ 0 & 0.7 & 1 \end{bmatrix} \begin{bmatrix} D_{R(D)} \\ D_{G(D)} \\ D_{B(D)} \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} R_{map(T)} \\ G_{map(T)} \\ B_{map(T)} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0.7 \\ 0 & 1 & 0.7 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} D_{R(T)} \\ D_{G(T)} \\ D_{B(T)} \end{bmatrix} \quad (11)$$

6: Add shifted colors to original image using (12), (13) and (14)

$$R_{F(i)=}R + R_{map(i)} \quad (12)$$
$$G_{F(i)=}G + G_{map(i)} \quad (13)$$
$$B_{F(i)=}B + B_{map(i)} \quad (14)$$

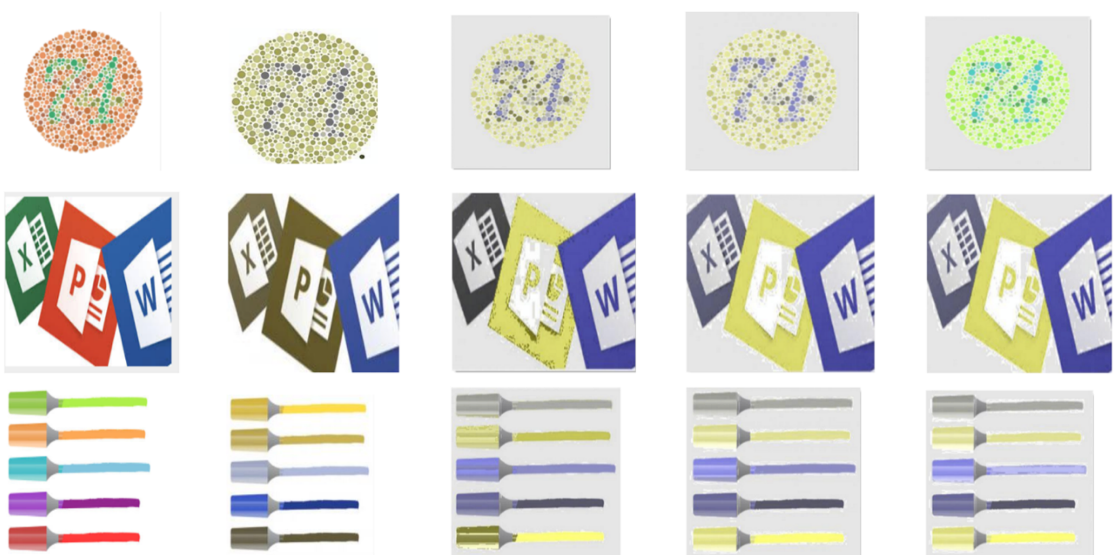
4.3 CBFS (Color-blind Filter Service) Algorithm

The CBFS algorithm is a color blindness correction algorithm designed for Protanopia (Red Blindness). This algorithm works in the HSL color space. HSL expresses the tone (Hue), amount of color (Saturation), and how much light or dark color is (Lightness) and provides a suitable basis for color blindness corrections.

Algorithm 2: Color-Blind Filter Service
//**Input**: RGB input image //**Output**: RGB color corrected image
1: Convert RGB image to HSL. 2: for each image pixel, **If** the pixel color is close to the dominant color of the RGB image pixels (red/green) **then** Hue ← Hue − 30% (15) Saturation ← Saturation − 10% (16) Lightness ← Lightness + 25% (17) **else** Saturation ← Saturation + 10% (18) Lightness ← Lightness − 10% (19) 3: Convert HSL image back to RGB.

The closeness parameter in the CBFS algorithm is a measure used to determine how closely the color of the pixel in the HSL color space resembles the dominant color in the image in the RGB color space. We calculate the absolute difference between the HSL pixel value and the dominant RGB color value. Different values for parameter 10 to 90 are tested for protonopia. In the figure, you can see some setted parameters and their results as image for test.

Closeness=|HSL Valuei−Dominant RGB Color Value|



Testing results shown in the figure, respectively: original image, image seen by Protanopia, CBFS processed image seen by Protanopia with closeness parameters 30, 70, 90.

As seen in the picture, different threshold values such as 30, 70, 90 were tried. In the end, It was decided that the most appropriate threshold value was 70. Thus, according to the algorithm, if the closeness parameter is less than (or equal to) 70, the if condition is applied, if it is greater than 70, the else condition is applied for each pixel. This process affects each pixel individually, resulting in more customized results across different images.

4.4 LAB Color Corrector Algorithm

The LAB Color Corrector Algorithm is specifically designed for Duteranopia (green color blindness) and aims to improve the color contrast between reds and greens in an image. The image is converted from the RGB to the LAB color space. LAB is the color space that separates brightness (L) from chromatic information (A and B components). The A component in the LAB color space represents the red-green axis. Positive A values correspond to colors closer to red. Negative A values correspond to colors closer to green.

The A component is modified experimentally to increase the contrast between red and green, making it more noticeable for someone with Duteranopia. For example, Pixels closer to red may have their A values further increased. Pixels closer to green may have their A values decreased. This algorithm is experiment base and it does not have a strong theoretical foundation. The goal is to achieve the best visual contrast between colors for red-green color blindness.

Algorithm 3: LAB Color Corrector

//**Input**: RGB input image
//**Output**: RGB color corrected image

1: Convert RGB image to LAB color space.
2: Adjust the A values relative to its maximum, making positive values a bit more positive and negative values a bit more negative.
3: Adjust the B values relative to how green or red it is.
4: Change L pixels which is the brightness of the pixel relative to pixels A values.
5: The image is converted back to the RGB color space and concatenated to ensure that pixel values lie between zero and one.

4.5 Shifting Color Algorithm

The Shifting Color Algorithm is specifically implemented for Tritanopia (blue-yellow color blindness) in the developed application. The algorithm modifies colors in an image by shifting their hues in the HSV (Hue, Saturation, Value) color space. So, it is aimed to make them more distinguishable while preserving the overall information. h determines how much to shift the colors in the image. The h value for tritanopia was tested with different ratios ranging from 0.1 to 0.9. Different h values were tested to investigate their effects on colors. h = 0.3 gave the best results. This value clarified the difference between green and blue, while not distorting the other colors too much.

Algorithm 4: Shifting Color

//**Input**: RGB input image
//**Output**: RGB color corrected image

1: Convert RGB image to HSV color space
2: Shifting colors for each pixel (x, y) using equation (20)

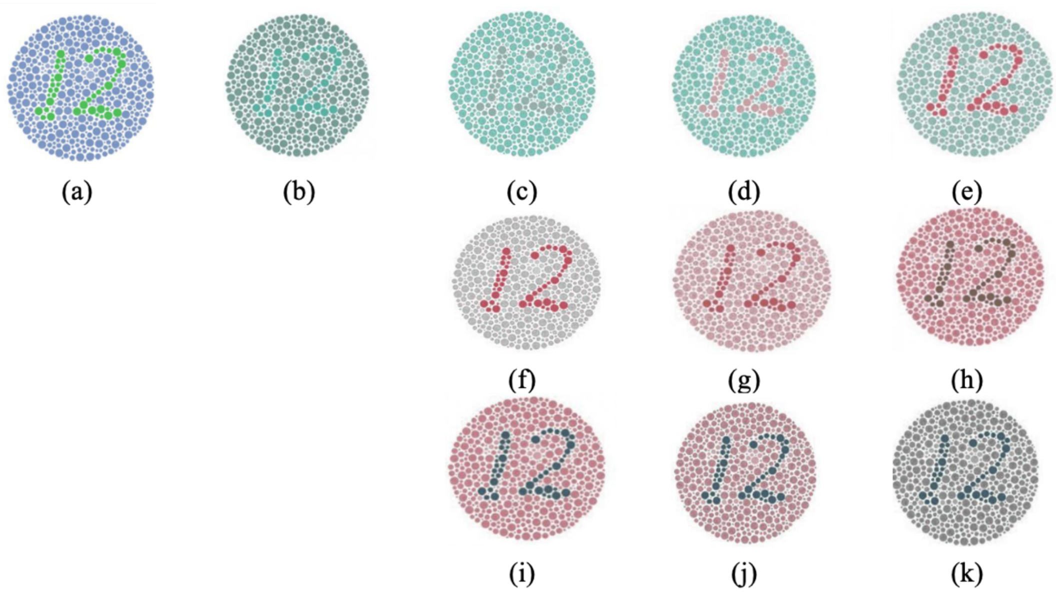
$$\mathrm{H_{xy}} = \mathrm{H_{xy}} + h \tag{20}$$

3: Check the values of hue channel to be in the range (0 to 0.9). **If** (H_{xy}>1) **then** change the hue value using Equation 21. **If** (H_{xy}<0) **then** change the hue value using Equation 22.

$$\mathrm{H_{xy}} = 1 - \mathrm{H_{xy}} \tag{21}$$

$$\mathrm{H_{xy}} = 0 \tag{22}$$

4: Convert HSV image back to RGB.



(a) original image, (b) original image seen by Tritanopia,
others images are tested results for different h values between 0.1 – 0.9

5 Results and Discussion

In this paper, different algorithms were explored and implemented to address different types of color blindness. Each algorithm demonstrated unique strengths and limitations in enhancing the visual perception of individuals with color vision deficiencies. To summarize;

5.1 Creating Saliency Maps

Saliency maps were utilized to identify critical regions in images where color correction was most needed. Eye-tracking data from the EToCVD dataset supported the creation of these maps, enabling targeted improvements in the vision of color-blind individuals.

Post-enhancement evaluations revealed a 10% improvement in visual attention for Protanopia and a 5% improvement for Deuteranopia cases.

5.2 LMS Daltonization Algorithm

This algorithm proved that it is effective for all types of dichromacy, including Protanopia, Deuteranopia, and Tritanopia.

By simulating the visual experiences and then applying corrective measures, the algorithm enhanced the distinguishability of colors. However, LMS Daltonization algorithm required higher computational resources due to its biological modeling approach.

5.3 CBFS Algorithm

The CBFS algorithm, tailored for Protanopia, utilized the HSL color space for adjustments. The closeness parameter, set to 70 based on experimental results, allowed for a balance between color enhancement and preservation of original details.

This algorithm is user-friendly and adaptable for different types of input images, making it suitable for personalized applications.

5.4 LAB Color Corrector Algorithm

Designed specifically for Deuteranopia, this algorithm adjusted that LAB color space to improve red-green contrast with A component. The results showed an improvement in the visibility of these colors for individuals with Deuteranopia.

Despite its success, the algorithm lacked a theoretical foundation and relied heavily on experimental adjustments, which may limit its scalability across diverse image datasets.

5.5 Shifting Color Algorithm

Implemented for Tritanopia, this algorithm shifted hue values in the HSV color space. Experimental results indicated that a shifting ratio of 0.3 yielded the best balance between color enhancement and information preservation.

The algorithm is simple and computationally efficient. Therefore, it is suitable for real-time applications.

Also, you can see which algorithms and methods have been developed for which types of color blindness from the table below.

Color Blindness Type	The Implemented Algorithms
Protanopia	LMS Daltonization, CBFS
Deuteranopia	LMS Daltonization, LAB Color Corrector
Tritanopia	LMS Daltonization, Shifting Color Algorithm
All Types	Creating Saliency Maps

5.6 Comparative Insights

- Algorithms like LMS Daltonization and LAB Color Corrector offered more precise and biologically inspired corrections but required higher computational power.
- CBFS and Shifting Color algorithms provided faster, simpler solutions. So, they are more sutiable for mobile and ligtweight applications.
- Saliency maps enhanced the effectiveness of all algorithms by focusing corrections on areas of visual importance, improving the overall user experience.

Algorithm	Key Features	Differences	Best Use Case
LMS Daltonization	Biological model	High accuracy, slower processing	All types of color blindness
CBFS	User-friendly	Requires user input, fast	Personal use and customization
LAB Color Corrector	Perceptual accuracy	More precise adjustments using LAB color space	Deuteranopia
Shifting Color Algorithm	Simplicity	Fast, less accurate	Tritanopia and low-complexity cases
Creating Saliency Maps	Visual attention modeling	Highlights key regions, limited color processing	Image enhancement and attention analysis

5.7 Future Directions

This study primarily delves into conventional and algorithmic strategies for improving color perception in individuals with color blindness, while acknowledging the potential of emerging technologies and innovative methods for shaping future research and applications

5.7.1 Convolutional Neural Networks (CNNs)

Deep learning techniques, particularly CNNs, have demonstrated significant success in image processing such as segmentation, enhancement, feature detection. Integrating CNNs into color-blindness correction systems could enable more adaptive and personalized solutions by learning patterns from large datasets of color-blind individuals' visual experiences.

Such systems could dynamically adjust color mappings in real time, offering superior correction accuracy compared to traditional algorithms.

5.7.2 Gaussian-Based Approaches

Gaussian mixture models and other statistical techniques can be revisited to develop probabilistic frameworks for color transformation. These methods can provide a flexible, data-driven basis for correcting color vision deficiencies while preserving image quality.

5.7.3 Real-Time Implementations

Combining computationally efficient algorithms like the Shifting Color Algorithm with deep learning models can enable real-time mobile or web-based applications. This could greatly benefit users in dynamic environments, such as navigation or gaming.

5.7.4 User-Centric Adaptations

Future systems could incorporate user feedback loops to fine-tune corrections based on individual preferences and needs. This would make color correction systems more inclusive and accessible.

5.7.5 Advanced Saliency Maps

Combining saliency maps with artificial intelligence could refine the identification of key regions in an image, making the color correction more focused and effective. This would enhance visual attention modeling for color-blind users.

By integrating these advanced approaches, future research can push the boundaries of color-blindness correction, offering solutions personalized and adaptable across various platforms and scenarios.

6 Conclusion

This study aims to solve the difficulties experienced by individuals with color vision deficiency using different approaches, algorithms and methods. Through this work, the following key insights were derived:

- Algorithms such as LMS Daltonization, CBFS, LAB Color Corrector, and Shifting Color Algorithm demonstrated significant potential in enhancing visual perception for color-blind individuals. Each algorithm was tailored for specific types of color blindness and exhibited unique strengths, from biological modeling to computational efficiency.
- Saliency maps, supported by eye-tracking data, provided an effective tool for identifying critical regions in images, enabling targeted color enhancements that improved attention and visual experience.
- The comparative analysis highlighted the trade-offs between precision and computational efficiency, guiding the choice of algorithms based on application requirements, such as real-time use or high-accuracy scenarios.

Despite the progress made, certain limitations remain, such as the experimental nature of some algorithms and their scalability across diverse datasets. Future research directions, including the integration of deep learning techniques, real-time implementations, and user-centric adaptations, promise to overcome these challenges and further enhance accessibility for color-blind individuals.

By combining traditional algorithms with emerging technologies, this study lays the groundwork for developing innovative solutions that improve the quality of life for millions of color-blind individuals worldwide. Continued research in this field will ensure the creation of inclusive systems that bridge the gap between visual perception and real-world accessibility.

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