

ABSTRACT

Title of thesis: MITIGATING COLORBLINDNESS: A
 PHYSIOLOGICALLY BASED MULTI-STAGED
 APPROACH

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Color vision deficiency, also known as colorblindness, is a widespread challenge for nearly 5% of the world's population. This condition has significant detrimental impacts on an individual's safety, education, career, and ability to perform tasks that rely on color discrimination. Current technologies aimed at addressing color vision deficiency (CVD) are neither effective nor affordable. They can cost several hundred dollars, are not personalized, and rely on filters with low light transmission, making them impractical for daily use. This research explored the process of creating accurate, personalized, and economically viable CVD mitigation solutions, as well as developing quantitative testing techniques. These objectives were carried out through three approaches: selective wavelength thin-film filtering, CVD simulation, and selective wavelength manipulation through additive application of light within a virtual space. Team Color successfully modeled a thin-film filter design aimed at addressing red-green CVD color confusion, while maintaining high light transmission. Finally, Team COLOR outlined an alternative exploratory approach for mitigating CVD in augmented reality environments using an adaptation of the designed simulation.

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1. Introduction

1.1. Description of Problem

Colorblindness, often referred to as color vision deficiency (CVD), is the inability to accurately differentiate between specific colors. There are two main forms of CVD, red-green deficiency and yellow-blue deficiency, which describe the color ranges that are most difficult for individuals with these conditions to distinguish. Red-green CVD is the most common form, affecting about 98% of the approximately 350 million people in the colorblind population. CVD predominantly affects men, occurring in approximately 1 in 12 men compared to about 1 in 200 women (Can Women Be Color Blind?, 2019).

Although colorblindness is often perceived as a minor visual limitation, its impacts can have a large impact on lifestyle. Professionally, individuals with CVD can face career limitations due to the safety risks associated with impaired vision. For example, color vision tests are required for pilots, police officers, electricians, engineering professionals, and certain military roles. Failing a color discrimination assessment can prohibit a candidate from a certain role or restrict their effectiveness in the role. For instance, individuals with CVD pursuing a career in aviation may be denied eligibility to fly at night, significantly limiting their ability to perform essential tasks (Can Pilots be Colorblind?, 2024). There are also daily safety risks, such as traffic lights, which use red, yellow, and green lights to signal drivers to stop, slow down, and proceed. Those with CVD may have difficulty distinguishing between a red and green light, therefore, placing themselves and other drivers at risk as they are more likely to run a red light.

There are several promising lenses and tools on the market designed to mitigate the effects of CVD, but significant room for improvement remains. Some current solutions aim to enhance color blind individuals' ability to differentiate colors using filtering lenses that block specific wavelengths of light responsible for CVD-related color confusion. However, these designs also block wavelengths outside the targeted range, reducing overall visual acuity while wearing the lenses, as seen in products like those produced by EnChroma. Additionally, many existing technologies are advertised as a universal treatment, despite the fact that CVD presents uniquely

in each individual. This limits the effectiveness of these designs and forces many individuals to rely on generalized solutions that do not meet their specific needs. Another significant issue is that current tools for mitigating red-green CVD lack effective testing methods by relying on anecdotal feedback from subjective user reports to guide design improvements. Therefore, there is a need for interventions that are customizable, preserve visual acuity, and can be evaluated using reliable, quantitative methods to accurately measure their effectiveness.

To achieve this goal, Team COLOR chose to pursue three objectives: (1) engineering a lens that filters out difficult to distinguish colors for individuals with CVD, without removing an excessive range amount of light transmittance, (2) developing a proof of concept exploring whether or not selective light manipulation can improve CVD vision, and (3) building a simulation program that can model what a colorblind individual would see after a corrective solution is applied, as a testing platform.

1.2. Research Questions

Based on the limitations of current CVD interventions and the objectives of this study, several research questions guide this investigation. With the objective of designing a new, high acuity filtering lens, the first question the team sought to answer was: Can the perception of color differentiation be enhanced through selective filtering? Addressing this question required a comprehensive understanding of the design characteristics of existing filters and the factors that limit their effectiveness as CVD mitigation interventions. Specifically, Team COLOR explored the use of thin-film interference as a targeted filtering approach to improve color differentiation while maintaining acuity.

In parallel, the team investigated an explorative approach to selective light manipulation as a potential method to enhance color distinction in CVD vision, leading to the question: Can the perception of color differentiation be enhanced by the addition of targeted wavelengths of light based on an individual's CVD profile? This question was examined as a proof of concept through a trial-and-error methodology, with validation supported by the development of a colorblind simulation and a complementary human study.

The creation of a quantitative colorblind simulation was essential to support the design and validate the effectiveness of both the filtering and light manipulation approaches. Two main questions guided this work: How can the genetic effects of CVD be mathematically interpreted and modeled? And, is it possible to link an individual's ability to discriminate colors to a quantifiable description of colorblindness?

Over the course of three years, these questions guided three unified research paths, each building on existing understandings of colorblindness and methods to mitigate its effects. Despite their distinct approaches, all efforts were aligned toward a single overarching question: How can the limitations of existing CVD mitigation technologies be addressed to develop solutions that enhance color perception for individuals with red-green colorblindness?

2. Literature Review

2.1. Overview

Color Vision Deficiency (CVD) is a condition characterized by an inability to distinguish between two or more colors. A thorough understanding of CVD requires first grasping the fundamentals of color vision. Color vision is a complex process involving interaction between the eyes and brain to perceive color and is significantly influenced by genetic factors. Since its initial discovery, various tests, technologies, and treatments have been developed to help diagnose and mitigate colorblindness. Many of these innovations hinge not only on understanding the biological elements of CVD, but also on comprehending how color can be represented from a mathematical perspective. This literature review introduces the biological and mathematical foundations of color vision necessary for understanding colorblindness. It examines historical and contemporary inventions developed to diagnose and mitigate CVD, analyzing the advancements achieved as well as the limitations that remain. Through this evaluation, this literature review establishes the conceptual foundation required to understand the models and design approaches implemented in this study.

2.2. Color Perception

Color recognition relies on the eyes' ability to capture light and convert it to signals that the brain can interpret. Light enters the eye through the dome-shaped cornea which focuses it on the pupil (see Figure 2). After passing through the iris and pupil, the light is further focused onto the retina, marking the beginning of the visual processing pathway (Baskin, 2021).

The retina contains two types of photoreceptors: rods and cones, which both convert light into electrical signals transmitted to the brain via the optic nerve. Rods, primarily concentrated in the peripheral regions of the retina, are highly sensitive to dim light, essential for night vision, and detect motion, but they do not detect color. Cones are concentrated in the central part of the retina, known as the fovea, and are responsible for high-acuity vision and color perception under well-lit conditions. There are three types of cones – long (L, or red), medium (M, or green), and short (S,

or blue) – which are categorized by the wavelengths of light that stimulate them, a concept known as spectral sensitivity. Spectral sensitivity functions (see Figure 1) show the extent to which each type of cone responds to different wavelengths across the visible spectrum. The overlap in the absorbance spectra of the cone types and how the brain interprets the signals sent from them enables the perception of a wide range of colors (Dr. Biology, 2010).

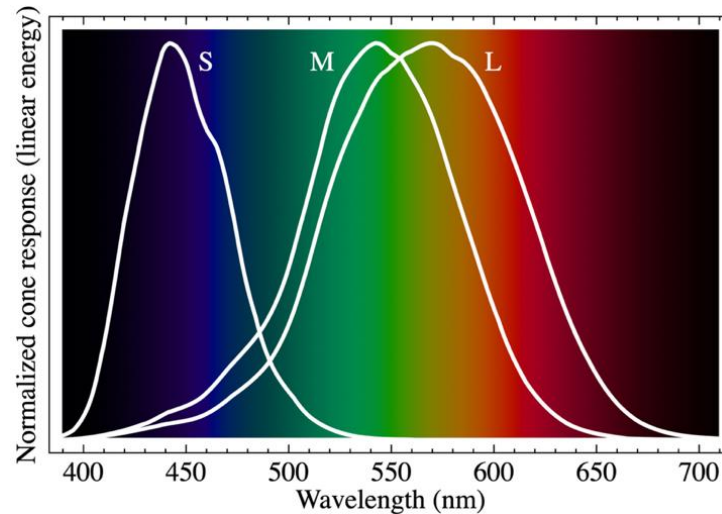


Figure 1. The absorbance spectra of red, green, and blue cones, otherwise known as the L, M, S cone spectral sensitivity functions. Red (L) cones are maximally stimulated at ~560 nm, green (M) cones at ~540 nm, and blue (S) cones at ~420 nm (Human Color Perception, n.d.).

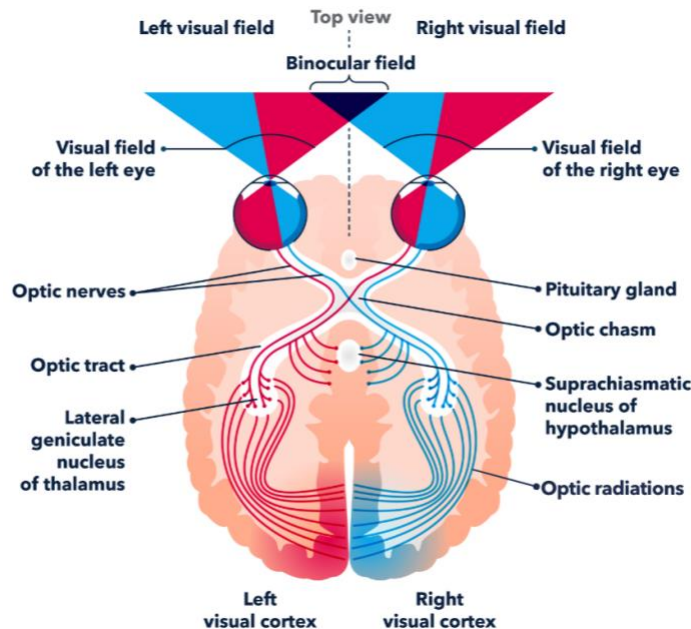


Figure 2. The visual processing pathway (Baskin, 2021).

2.2.1. Opponent Color Theory

The opponent color theory explains how signals from the retina are interpreted by the brain, resulting in color vision. When light stimulates the cones, each cone type produces an electrical signal (referred to as its response) whose strength depends on how much the wavelength(s) of the light overlap with the cone's spectral sensitivity range. These signals are then encoded into opponent signals, which represent differences between the responses of different photoreceptor types rather than independent signals for each one (Fairchild, 2005). The opponent color theory assumes the existence of six perceptual color categories: white, black, red, green, yellow, and blue (Machado, Oliveira, & Fernandes, 2009). Rods primarily contribute to the perception of white and black (luminance), while cones are responsible for color perception, with yellow arising from the combined stimulation of red (L) and green (M) cones. However, instead of six separate color signals, the brain interprets color through three opponent channels: red-green (RG), yellow-blue (YB), and white-black (WB) (Machado, Oliveira, & Fernandes, 2009).

A channel functions by comparing the opponent signals to determine which color is dominant (The Opponent Process (Neurological) Theory of Color, n.d.). For each opponent pair, only one of the two colors can be perceived at a time: red or green, yellow or blue, and white or black. If the signals are equal, they cancel each other out. For example, equal amounts of white and black produce the perception of gray, while equal amounts of red and green or blue and yellow result in the absence of perception for those opposing colors, as they cannot be simultaneously perceived (Machado, Oliveira, & Fernandes, 2009).

Specifically, when light of some frequency is observed, the RG channel compares the responses of L (red) and M (green) cones to determine red-green differences, identifying which color is more dominant and therefore perceived. The YB channel compares S (blue) cone responses against the combined L+M response – since yellow arises from the mixed L+M signal – to determine whether blue or yellow is more dominant and therefore perceived. The WB channel is similar but captures overall light intensity, producing achromatic contrasts (The Opponent Process (Neurological) Theory of Color, n.d.).

This differential process sharpens color distinctions and enables the brain to perceive a wide range of colors across the visible spectrum. Notably, the opponent color theory shows that color perception relies on cone responses. This is a key point because CVD arises from missing or modified photoreceptors that produce altered cone responses, which in turn change the signals available to the opponent channels and ultimately affect color perception (see [Section 2.3.3](#)).

2.2.2. Color Matching Tests

To quantitatively describe all light visible to humans in the electromagnetic spectrum, a series of color-matching tests were conducted in the late 1920s by William David Wright and John Guild. In these tests, observers were shown a light resultant from a combination of three wavelengths from the standard long, medium, and short range, respectively. Observers were then asked to recreate the color of the light by adjusting the intensities of the red (700 nm), green (546.1 nm), and blue (435.8 nm) lamps (Fairman, Michael, & Hemmendinger, 1998). Each color belonged to the spectral colors, a special class of colors in the RGB color space that are produced by a singular wavelength of visible light, rather than a mixture of wavelengths.

Figure 3 shows the experimental setup, and Figure 4 presents the results. Figure 4 illustrates a trichromat's RGB color matching functions across the visible spectrum (CIE 1931 color space, n.d.), while the Figure 5 shows normalized data from ten observers, with RGB values scaled to sum to one (Zhu, 2020). The results demonstrate individual variations in color perception, emphasizing the importance of accounting for perceptual differences in CVD modeling.

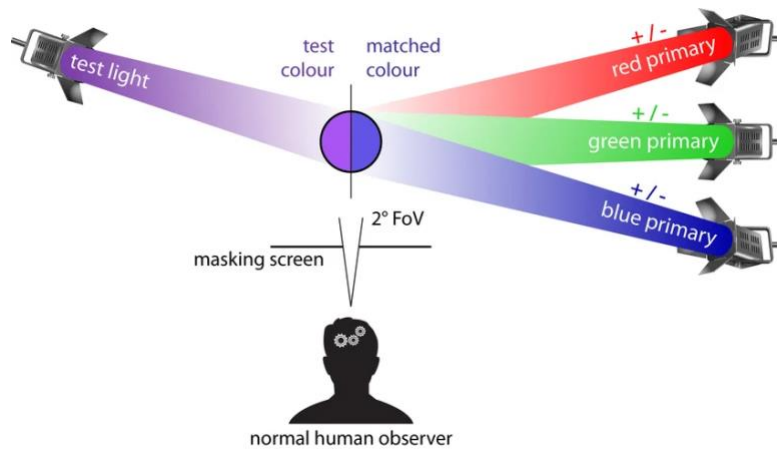


Figure 3. Experimental setup of the 1920s color matching test (Verhoeven, 2016).

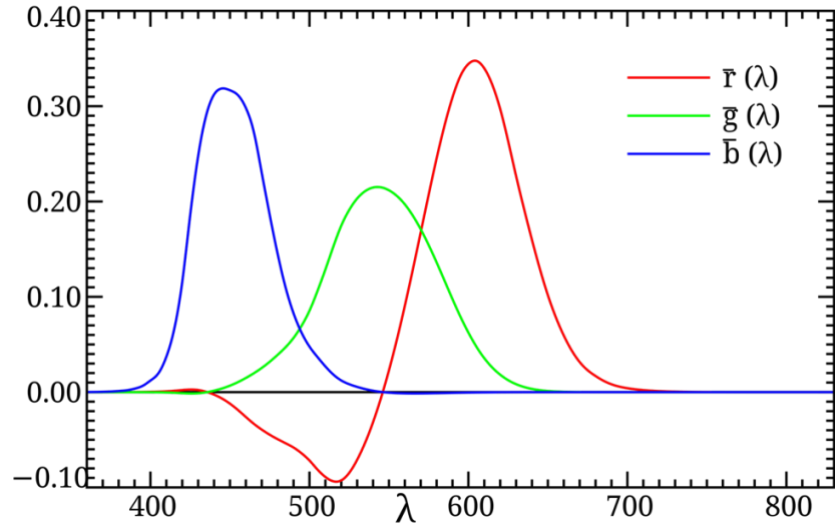


Figure 4. RGB tristimulus color matching functions of a trichromat, for every visible spectral wavelength (CIE 1931 color space, n.d.).

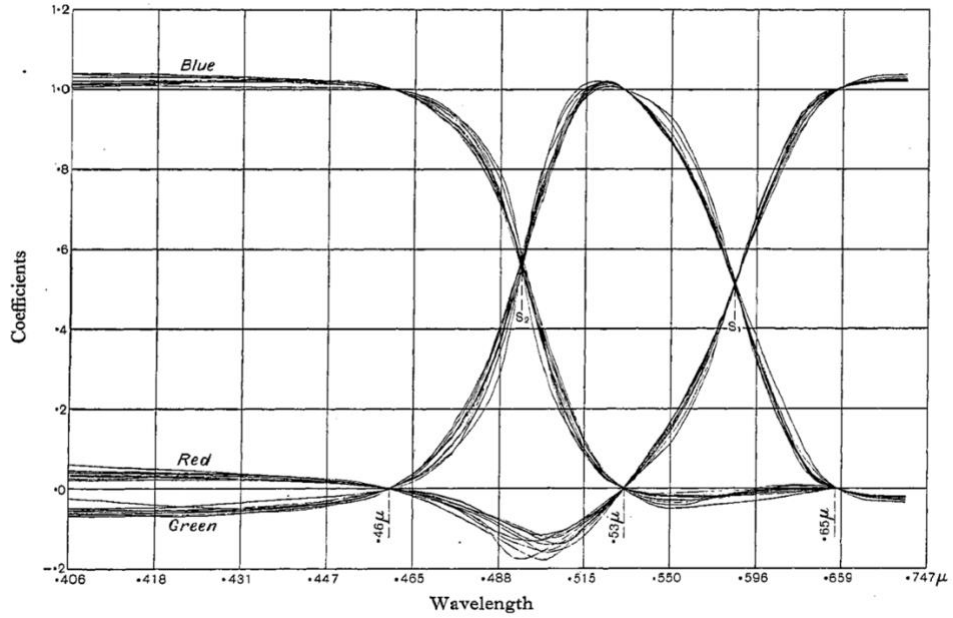


Figure 5. RGB color matching functions normalized for the red, green, and blue components to always sum to one for ten observers (Zhu, 2020).

Note that some target spectral wavelengths cannot be produced by combining varying amounts of red, green, and blue light alone. In other words, they cannot be matched using only positive amounts of the three primaries in a single mixture. For instance, cyan (~ 485 nm) cannot be matched through additive RGB combinations alone. Experimentally, a match is achieved by adding some

red light to the target field. In mathematical terms, this is equivalent to saying: $cyan \approx (green + blue) - red$. Because negative light cannot be physically added, this “ $- red$ ” is implemented by adding red to the target side of the comparison rather than subtracting it from the mixture (Chapter 7 Additive Color Mixing).

Although the additive nature of light is not inherently obvious, the results of these color-matching experiments provided important insight into the vectorial behavior of color. Specifically, they showed that any color can be described as a linear combination of other colors, even if this description involves negative coefficients – meaning that color cannot always be physically produced using only positive amounts of the primaries (Fairman, Michael, & Hemmendinger, 1998).

2.2.3. RGB Color Space and the CIE XY Chromaticity Diagram

Using the normalized results from the color matching tests (Figure 5), the International Commission on Illumination (CIE) plotted the data in a three-dimensional vector space (Figure 6). Each axis of the space corresponds to one of the three primary colors used in the color matching experiments, and the distance along each axis corresponds to the relative intensity of each primary color. Plotting the relative intensities of red, green, and blue light required to create every pure spectral color creates a curved line in the RGB color space referred to as the spectral locus (Fairman, Michael, & Hemmendinger, 1998).

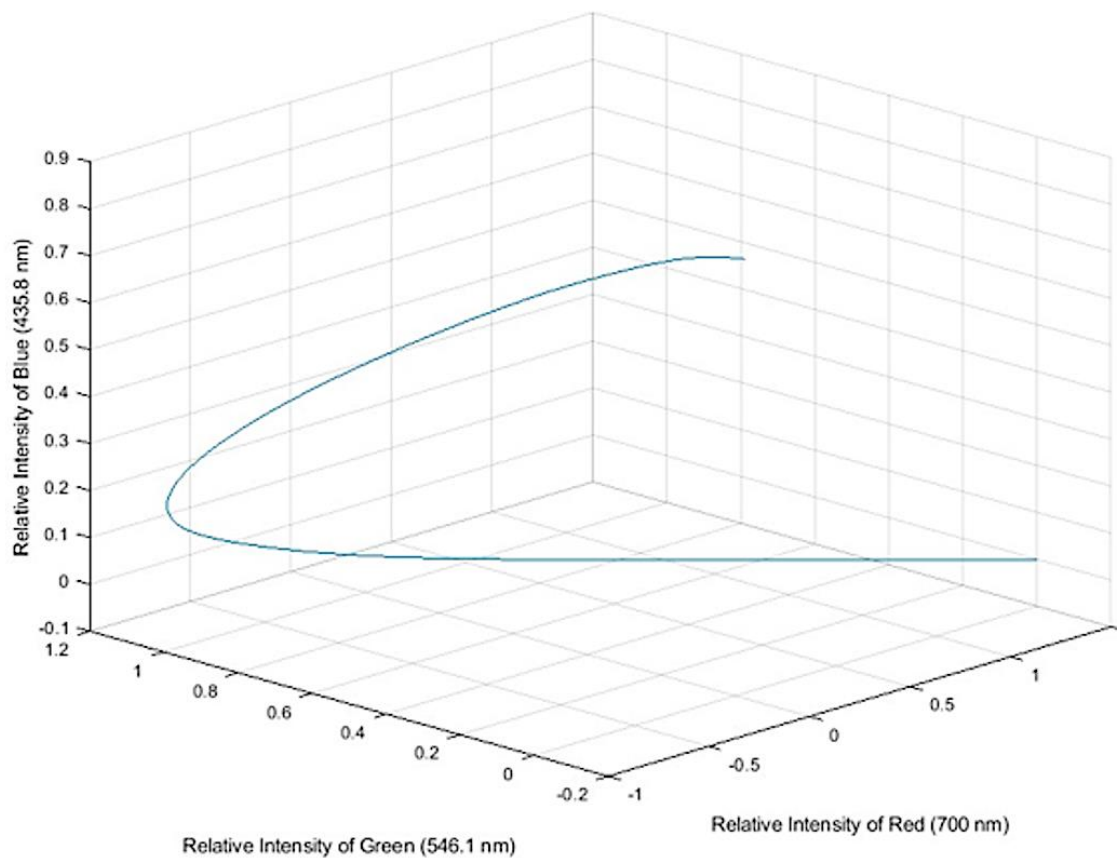


Figure 6. The spectral locus plotted in RGB color space using the CIE 1931 RGB normalized color matching functions. The area enclosed by the curve, if the two ends were connected by a straight vector, contains all color combinations visible to a trichromat.

Upon deciding that quantitatively describing chromaticity – the observable hue and saturation of a color – should be independent of luminosity, the CIE then projected the RGB three-dimensional color space with the spectral locus onto a two-dimensional red-green plane, creating the world’s first chromaticity diagram that could be used to quantify any visible color (Figure 7). The motivation behind this is that any cross-sectional area of the RGB color space contains amounts of all three primary colors, meaning that only two dimensions are required to fully describe the hue of any color. A third dimension would only convolute the description of color by introducing another variable for intensity or luminosity (Fairman, Michael, & Hemmendinger, 1998).

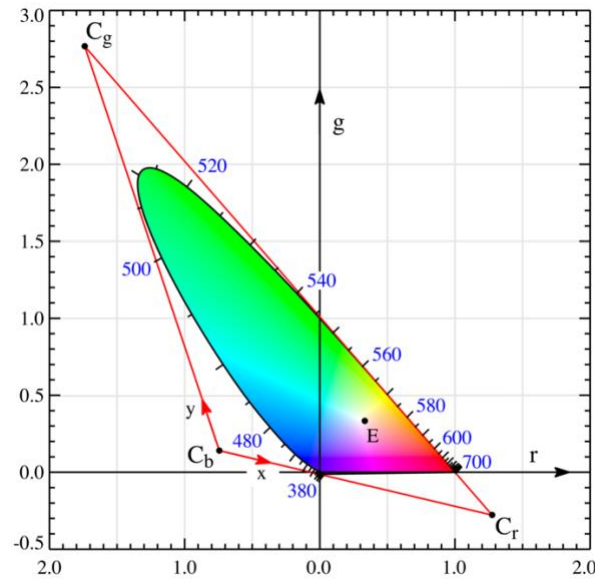


Figure 7. The CIE RG chromaticity diagram shows all colors visible to the human eye where red intensity is shown on the x -axis and green intensity on the y -axis. Equal energy white (equal relative intensities of red, green, and blue) is located at $(1/3, 1/3)$. The three primary colors used in the color-match experiment are respectively located at $(1,0)$, $(0,1)$, and $(0,0)$ (CIE 1931 color space, n.d.).

Although the RG chromaticity diagram can adequately describe any visible color, it is non-intuitive, as a large portion of the diagram lies in the “negative red region”, which increases the difficulty and likelihood of error while performing calculations. The term “negative red region” refers to the fact that some colors require negative coefficients of the red primary to achieve a match within the RG coordinate system, meaning their representations fall into the negative portion of the red intensity (x -axis) in the RG chromaticity diagram. To resolve this, a linear transformation was applied to the RG chromaticity diagram, moving all parts of the diagram into the positive coordinate region while keeping equal energy white at the coordinates of $(1/3, 1/3)$ and bounding all visible colors by the triangle with vertices $(1, 0)$, $(0, 0)$, and $(0, 1)$ (Fairman, Michael, & Hemmendinger, 1998). The resulting xy coordinates at these vertices do not correspond to real spectral colors, as can be seen in Figure 8, and are therefore referred to as imaginary primaries. Transformations can be applied bidirectionally between the xy and RG chromaticity spaces, allowing any color to be equivalently represented in either system using its RGB components. In the xy space, the RGB values associated with the xy primaries define the

geometric structure of the triangular-like chromaticity region shown in Figure 8. This diagram is referred to as the 1931 CIE xy chromaticity diagram. Although it is over 90 years old, the CIE xy chromaticity diagram remains widely used today in color vision, color science, and computer graphics. Its lasting value lies in offering an intuitive, standardized way to represent all perceivable colors.

The study of color perception has a vast history, starting with the realization of color perception as a scientific phenomenon and then continuing to the discovery of color perception differences in humans through color matching assessments. Most recently is the creation of color spaces, that standardize the color visual experience, allowing stakeholders to differentiate clearly between discrete color values and explain the physiological process that is color perception.

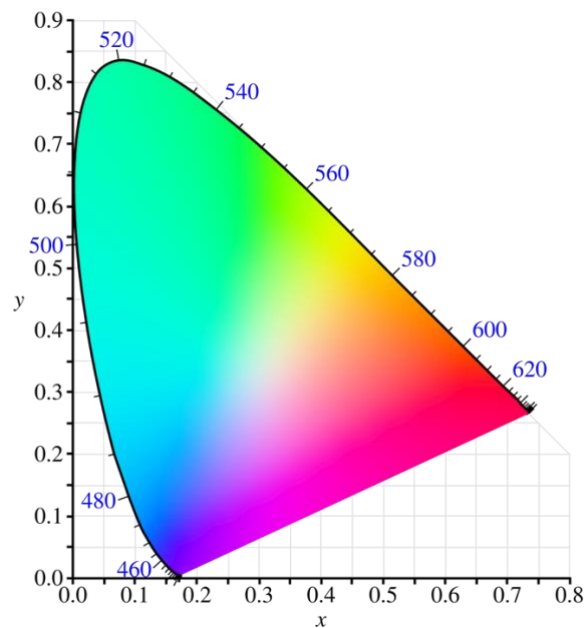


Figure 8. The 1931 CIE xy chromaticity diagram. Equal energy white still lies at $(1/3, 1/3)$, but all coordinates are positive, making the diagram easier to use and understand (CIE 1931 color space, n.d.).

2.3. Color Vision Deficiency (CVD)

Color vision deficiency, or colorblindness, is the reduced ability, or complete inability, to distinguish between certain colors in the visible electromagnetic spectrum. The condition manifests in a variety of ways, both biologically and visually, resulting in a range from mild difficulty differentiating specific colors to the complete inability to perceive color. Over the past

200 years, colorblindness has gone from being treated as an exploitable ‘defect’ to a well-studied condition that has led to the development of diagnostic tests and technologies designed to mitigate its effects for individuals with the condition (Hanaway-Oakley, 2019). To understand the challenges involved in creating and improving these technologies, it is first necessary to explore the history, causes, effects, and identification methods of CVD.

2.3.1. History of CVD

Historically, color vision deficiency has not been regarded as a significant safety concern or workplace hazard. Instead, an individual’s inability to distinguish between colors was believed to be a form of color ignorance resulting from a lack of effort or competence to identify color. In the late 1700s, John Dalton, driven by his and his brother’s own color-deficient vision, became the first scientist to take academic interest in the subject of colorblindness (Robertson, 2017). Dalton attributed his color vision deficiency, now known to have been deuteranopia, to a blue-tinted vitreous humor that he believed absorbed longer wavelengths of light (Robertson, 2017). Although this theory was later disproven by a post-mortem examination of his eyes in 1844, it reflects the limited early understanding of CVD and how the condition had yet to be recognized as a true physiological limitation that impacts everyday functionality.

Colorblindness became recognized as a potential threat to life in the mid to late 1800s with the rise of railways and commercial shipping (Hanaway-Oakley, 2019). In 1875, physiologist Frithiof Holmgren linked a fatal railway accident in Sweden to a railway worker's inability to distinguish between red and green signals. This finding propelled Holmgren to develop an early method of colorblind testing, which involved test subjects matching up skeins of colored wool, like those shown in Figure 9 (Hanaway-Oakley, 2019). As train accidents and shipping disasters were increasingly attributed to colorblind railway and ship workers, mass unease and fear permeated. Consequently, many workers who were discovered to be colorblind were forced to leave their jobs or exploited with the threat of disclosing their ‘defect’ (Hanaway-Oakley, 2019).

Anomalous Trichromacy. Anomalous trichromats have all three types of cones, but the spectral sensitivity of one or more cone types is altered, reducing their ability to accurately distinguish certain colors. The main types of anomalous trichromacy include *protanomaly* (a shift in the sensitivity of L-cones toward shorter wavelengths), *deuteranomaly* (a shift in the sensitivity of M-cones toward longer wavelengths), and *tritanomaly* (a shift in the sensitivity of S-cones toward longer wavelengths) (Color Blindness, 2025). Protanomaly and deuteranomaly are forms of red-green color vision deficiency, while tritanomaly affects blue-yellow discrimination.

Dichromacy. Dichromats are individuals who lack one type of cone photoreceptor, leaving them with only two functional cone types. As a result, their ability to distinguish between certain colors is significantly reduced. The three types of dichromacy are *protanopia* (absence of L-cones), *deuteranopia* (absence of M-cones), and *tritanopia* (absence of S-cones). Protanopia and deuteranopia primarily affect red-green color discrimination, while tritanopia affects blue-yellow discrimination (Color Blindness, 2025).

Monochromacy. Monochromacy is an extremely rare condition in which individuals possess only one type of cone cell – either L, M, or S cones. Monochromats are unable to distinguish between colors, perceiving the world in shades of gray despite having one functioning cone type. This inability arises because the lack of additional cone types prevents the introduction of any contrast necessary for color differentiation, as explained by the opponent color theory (Color Blindness, 2025).

Achromatopsia/Rod Monochromacy. Achromatopsia, also known as rod monochromacy, is considered the rarest form of color vision deficiency. It is characterized by the complete absence of all cone cells in the retina. Achromats experience a lack of true color perception, viewing everything in shades of gray. Additionally, achromats often suffer from poor visual acuity due to a lower density of rod cells compared to cones (Color Blindness, 2025).

Although unlikely, it is possible for a person to suffer from multiple types of color vision deficiencies. For example, an individual could have tritanopia while also having deuteranomaly,

resulting in the capability to perceive some reds and greens, with impaired differentiation between certain red-green combinations.

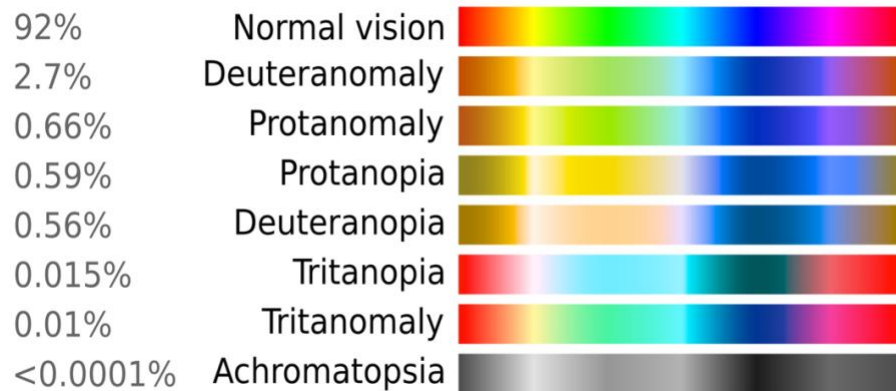


Figure 10. The most common types of color vision deficiencies and how they appear to individuals with CVD. Deficiencies that end in “-anomaly” are indicative of a mutated cone while those that end in “-opia” or “-opsia” are indicative of a missing cone type. The percentages refer to the portion of the colorblind population effected by each condition (Color blindness, 2025).

In contrast to the various types of color vision deficiencies described above, individuals with fully functioning three-cone color vision are known as *trichromats*. Trichromats can perceive the full range of colors in the visible spectrum. Trichromacy serves as the reference condition for the color vision standard and is used as the baseline for comparing differences in color perception caused by color vision deficiencies.

2.3.3. Genetic Causes of CVD

The majority of color vision deficiencies arise from inherited genetic mutations. The most prevalent form of colorblindness, red-green, is caused by an X-linked recessive chromosome mutation. The genes responsible for red (OPN1LW) and green (OPN1MW) cone pigmentation are located adjacent to one another in the Xq28 band of the X chromosome (Hughes & Maloy, 2013). Each of these long and medium cone photopigment genes contains six exons, which collectively determine the spectral absorbance of the corresponding cone type (Figure 11).

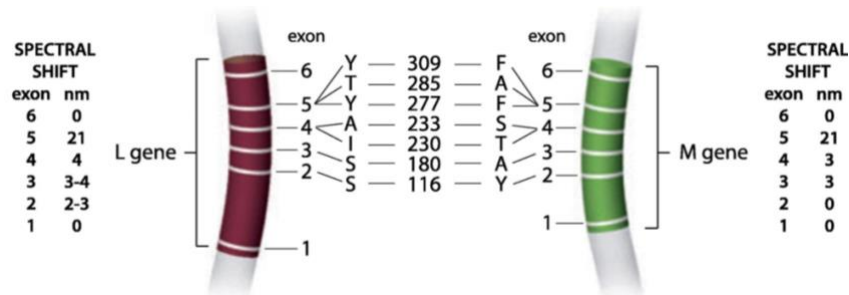


Figure 11. A diagram of the six exons present in photopigment determining genes. Exon mismatches between genes result in spectral absorbance shifts towards redder colors (in the case of mismatches in the M gene) or greener colors (in the case of mismatches in the L gene) (Neitz & Neitz, 2011).

Red-green color vision deficiencies can arise when misalignment during recombination and crossover of the X chromosomes affects the L and M cone pigmentation genes. In some cases (Figure 12), crossover occurs between misaligned L and M genes, which leads to exons from the M cone pigmentation genotype to exchange with those from the L cone pigmentation genotype, creating a hybrid photopigment gene. These hybrid photopigment genes exhibit a peak absorbance that falls between the standard spectral sensitivities of red and green cones, leading to anomalous trichromacy in the form of protanomaly or deuteranomaly (Neitz & Neitz, 2011).

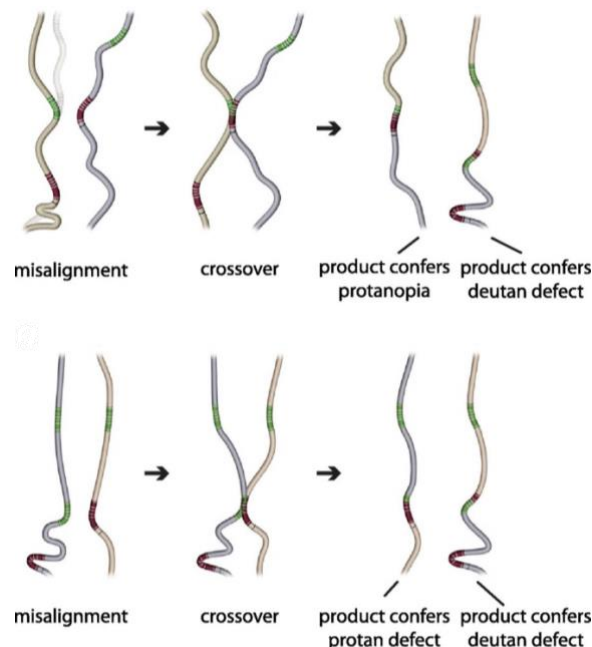


Figure 12. Misalignment of L and M cone pigmentation genes during crossover produces hybrid photopigment genes with mixed exons, resulting in intermediate spectral absorbance and anomalous trichromacy (protanomaly or deuteranomaly) (Neitz & Neitz, 2011).

Certain exon mismatches, such as between exons 1, 2, 3, 4, and 6, cause very small cone spectral absorbance shifts, leaving an individual with a near undetectable color vision deficiency (Neitz & Neitz, 2011). However, compounding several of these mismatches can exacerbate the issue, making an individual's color vision deficiency more severe. Exon mismatches with exon 5 create severe alterations in the absorbance spectra of red and green cones, effectively causing the red cones to function as green cones or the green cones to function as red cones. The genetic nature of red-green color vision deficiency leads to very distinct cone spectral absorbance shifts for every individual (Figure 13).

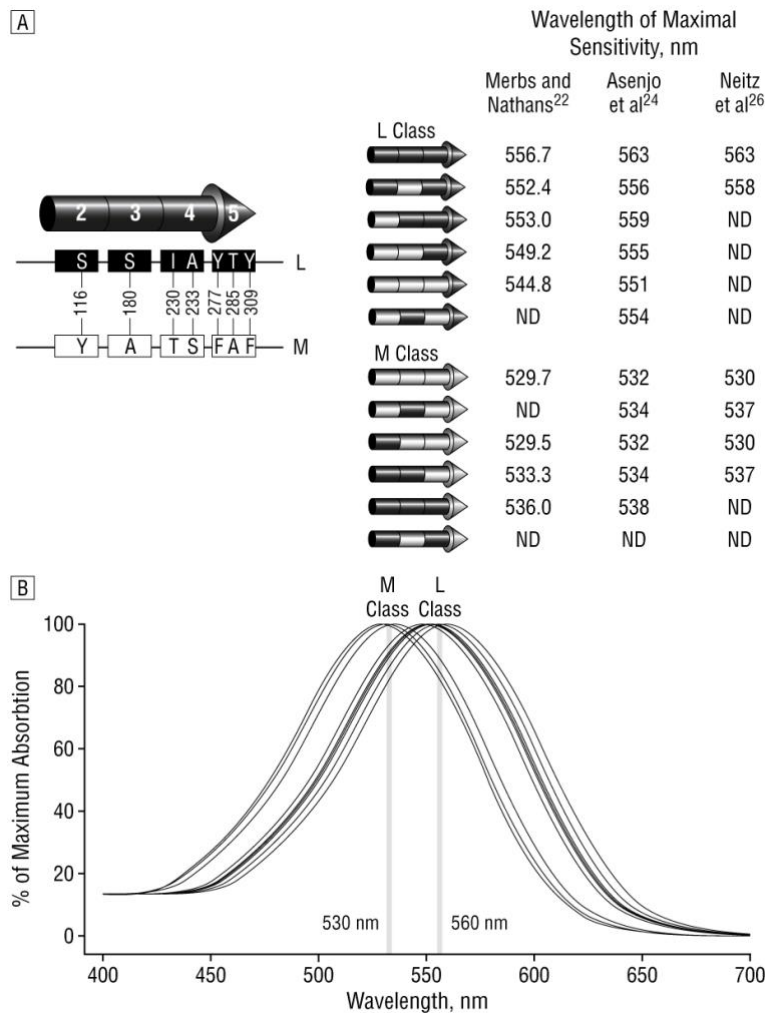


Figure 13. Part A (top) shows the maximal absorbance wavelengths of certain hybrid red-green cones as measured in various studies. Part B (bottom) is a graph of the absorbance spectra of hybrid red-green cones from multiple individuals. Red cone absorbance peaks are nominally centered at 560 nm and green absorbance peaks are nominally centered at 530 nm (Neitz & Neitz, 2000).

In addition to exon mismatches, it is possible that during the crossover and recombination phases of meiosis, the entirety of a red or green pigmentation gene is transferred to one X chromosome, leaving the other X chromosome without the information to create red or green pigmented cone cells. Offspring that inherit a chromosome with the extra pigmentation gene typically have full-spectrum trichromatic color vision, while the offspring who inherit the chromosome with the missing pigmentation gene will be a dichromat with either protanopia or deuteranopia (Neitz & Neitz, 2000).

Tritan defects (tritanomaly and tritanopia) are autosomal dominant mutations that occur on the OPN1SW gene of the 7q32 band on chromosome 7. These mutations lead to the premature destruction of blue cones and the production of dysfunctional blue cones. Tritan defects progressively worsen with age, making quantifying the spectral absorbance changes of a tritanope difficult. More research is needed to fully understand how inherited tritan defects manifest (Neitz & Neitz, 2011).

2.3.4. Implications of CVD on Perception

A compilation of early scientific findings into how individuals with CVD perceive color led to the discovery of confusion lines, a key concept in testing and modeling CVD. On the CIE xy chromaticity diagram, a confusion line is formed by connecting two colors that appear identical to a person with a specific type of CVD and extending that line across the diagram (Flück, 2007). Protan, deutan, and tritan forms of CVD are each associated with a distinct system of confusion lines, determined by a characteristic co-punctal point for each type. For each form, these confusion lines converge at a unique point in the CIE xy color space known as the co-punctal point (Flück, 2007). Therefore, for each type of CVD, any number of confusion lines can be drawn from the co-punctal point to different reference colors, with each line representing a range of colors that may be indistinguishable from one another to an individual with that deficiency, depending on the severity of their unique condition. Figure 14 and Figure 15 show examples of confusion lines for individuals with protan or deutan CVD, along with the co-punctal points for each deficiency.

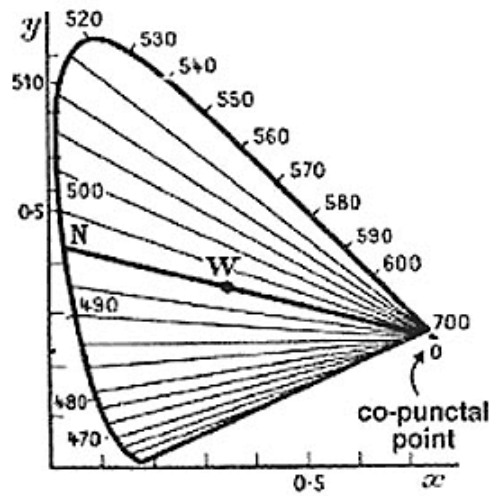


Figure 14. Example of some confusion lines for individuals with protan CVD, showing colors (i.e., wavelengths) that appear identical to a protanope and the co-punctal point where all lines converge (Flück, 2007).

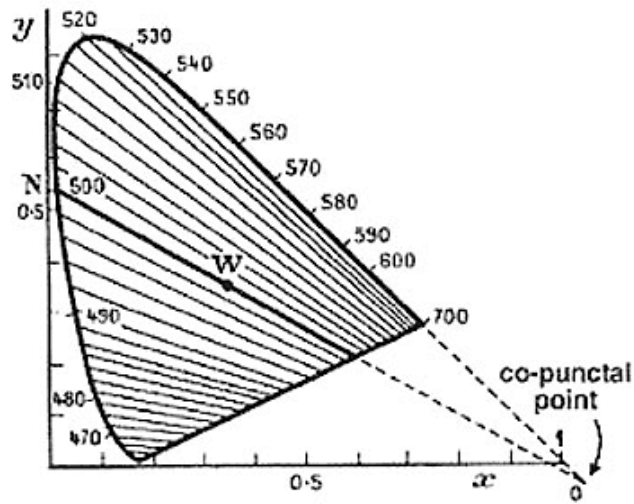


Figure 15. Example of some confusion lines for individuals with deutan CVD, showing colors (i.e., wavelengths) that appear identical to a deuteranope and the co-punctal point where all lines converge (Flück, 2007).

The protan and deutan co-punctal points are located near each other near the red region of the CIE xy color space (see Figure 14 and Figure 15). The similarly oriented sets of lines that radiate from these two points explain why both types of CVD are associated with red-green colorblindness (Flück, 2009). In contrast, tritan confusion lines converge to a co-punctal point near the blue region of the CIE xy color space, corresponding to blue-yellow color confusion. The closer that two colors

are along or near a confusion line, the more difficult they are to distinguish among individuals with CVD (Flück, 2007). This property makes confusion lines useful not only for understanding CVD perception but also for designing diagnostic tests that isolate and identify different types of CVD.

The discovery of confusion lines significantly advanced the understanding of color confusion and has informed the design of diagnostic tools as well as the development of color appearance models that simulate CVD perception. Tests, such as the Ishihara test, rely on the concept that protans, deuterans, and tritans each have distinct sets of confusion lines to diagnose the presence and type of CVD (National Research Council (US) Committee on Vision, 1981). These tests also make use of the principle that colors closer together on the same confusion line – or adjacent across different lines – are more difficult for CVD individuals to distinguish than colors further apart, which can help in estimating severity (National Research Council (US) Committee on Vision, 1981). Furthermore, understanding where color confusion occurs for each type of CVD has made it possible to develop models that simulate how colors may appear to protan, deutan, or tritan observers (Moreira, Álvaro, Melnikova, & Lillo, 2017). These models and tests are approximations due to individual variability in CVD type and severity. Nonetheless, they remain effective and widely used, often regarded as sufficiently accurate for practical purposes.

2.3.5. Testing for CVD

One of the most used methods to identify red-green colorblindness is the pseudoisochromatic plate test, commonly known as the Ishihara test. This test generally consists of 38 individual plates. It can be used to potentially determine if an individual has protanopia, protanomaly, deuteranopia, or deuteranomaly (Ishihara test, 2025).

Each plate depicts a circle made up of dots that vary in colors and sizes. Within this circle, some dots form a symbol, usually a number (Ishihara test, 2025). Examples of such plates are shown in Figure 16. The colors of these dots are carefully selected to exploit the perceptual limitations of individuals with red-green colorblindness. This is done by choosing color combinations based on the colors' position relative to protan and deutan confusion lines and their visibility to red-green colorblind individuals (National Research Council (US) Committee on

Vision, 1981). On the most common type of Ishihara plate, the color of the dots that form the symbol and the other surrounding dots, referred to as the background, will lie in close proximity to one another on either a protan or deutan confusion line. Therefore, to an observer with red-green colorblindness, the symbol and background may be indistinguishable, but to a trichromat, the symbol and background are easily distinguishable (National Research Council (US) Committee on Vision, 1981). Plates can also be designed so that the symbol is only visible to those with red-green colorblindness (Figure 16, right-most plate), while others may result in different symbols being seen by individuals with or without red-green colorblindness (Figure 16, middle plate) (Ishihara test, 2025). Table 1 summarizes how responses to fourteen individual Ishihara plates correspond to different classifications of red-green color vision deficiency.

The varied color combinations used on each of the 38 plates are designed to detect the presence of a color vision deficiency that causes red-green colorblindness. The choice of colors, with respect to chromaticity, helps to approximate the severity of an existing color vision deficiency. Overall, the Ishihara test is an excellent preliminary red-green diagnostic test, but it does have some significant limitations that are addressed later in this section.

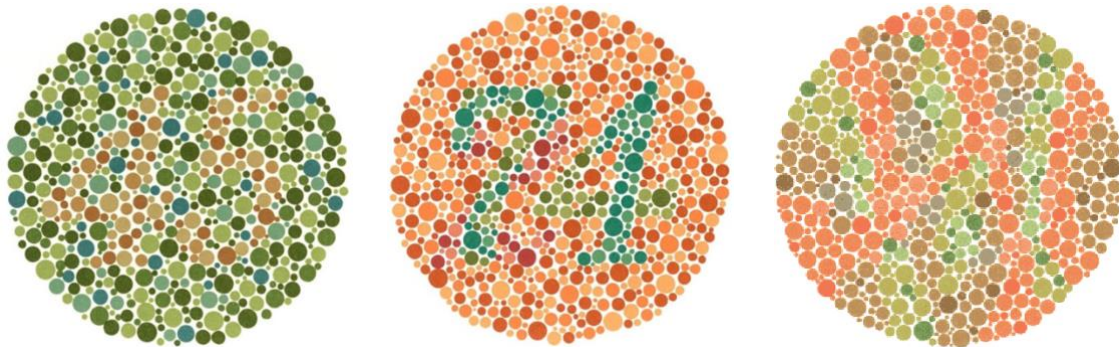


Figure 16. Ishihara color vision test plates. (Left) Trichromat observers see “45”; most individuals with CVD cannot see a number. (Middle) Trichromat observers see “74,” whereas those with red–green CVD typically see “21” (Károly, n.d.). (Right) Trichromat observers see no number, while red–green CVD observers should see “5” (Ishihara Charts).

Answers to each plate

Number of Plate	Normal Person	Person with Red-Green Deficiencies		Person with Total Colour Blindness and Weakness	
1	12	12		12	
2	8	3		x	
3	5	2		x	
4	29	70		x	
5	74	21		x	
6	7	x		x	
7	45	x		x	
8	2	x		x	
9	x	2		x	
10	16	x		x	
11	traceable	x		x	
		Protan		Deutan	
		Strong	Mild	Strong	Mild
12	35	5	(3) 5	3	3 (5)
13	96	6	(9) 6	9	9 (6)
14	can trace two lines	purple	purple (red)	red	red (purple)
					x

The mark x shows that the plate cannot be read. The numerals and winding lines in parenthesis show that they can be read or traced but they are comparatively unclear.

Table 1. Classification of responses to Ishihara color vision test plates. The table lists the numbers typically perceived by individuals with and without red–green color vision deficiencies and the corresponding diagnostic interpretations (Ishihara).

Another color vision deficiency testing technique is the arrangement test, which evaluates an individual's ability to discriminate between different colors. Two commonly used adaptations of the arrangement test, created by Dean Farnsworth, are the FM-100 hue test and the D15 panel test. The D15 Panel test was engineered to diagnose subjects along the lines of normal to mildly color deficient and medium to strong color deficient. The test includes 16 colors and shades, in total, represented by a reference cap and 15 test caps labeled one through fifteen on their underside, as shown in Figure 17. The subject places each color in sequential hue order to the best of their ability, with the reference cap acting as the first color in the sequence. Once the test concludes, the evaluator draws a line along the scoring plane that mirrors the order of the sample hues. If no inconsistencies appear in the graph, the subject is classified as a trichromat; as the number of inconsistencies increases – especially those crossing the center of the plane – the severity of the

subject's CVD correspondingly increases. Any lines that cross the center will be compared to the protan, deutan, and tritan confusion axes to determine the type of color vision deficiency present (D-15 Color Test Guide, n.d.).



Figure 17. D-15 arrangement test with 1 reference cap and 15 test caps (Farnsworth D-15 color blind test, n.d.).

Despite its name, the FM-100 hue test uses 88 unique color samples, 4 reference cap colors, and 84 movable cap colors to gauge how individuals with and without CVD distinguish color. The larger number of color samples allows identification of finer distinctions in hue discrimination, revealing subtle deficits that may not be detected by the D15 test. The testing procedure is the same as the D15's, except that the subject must arrange more samples in order. Once all the samples are arranged, the evaluator scores the sequence by comparing the order to the correct hue progression. These scores can be visualized as a circular graph, like the ones in Figure 18, showing the magnitude and location of hue errors. Spikes in the graph indicate regions of the color spectrum where the subject has difficulty discerning subtle hue differences (Farnsworth Munsell 100 Hue Test, n.d.).

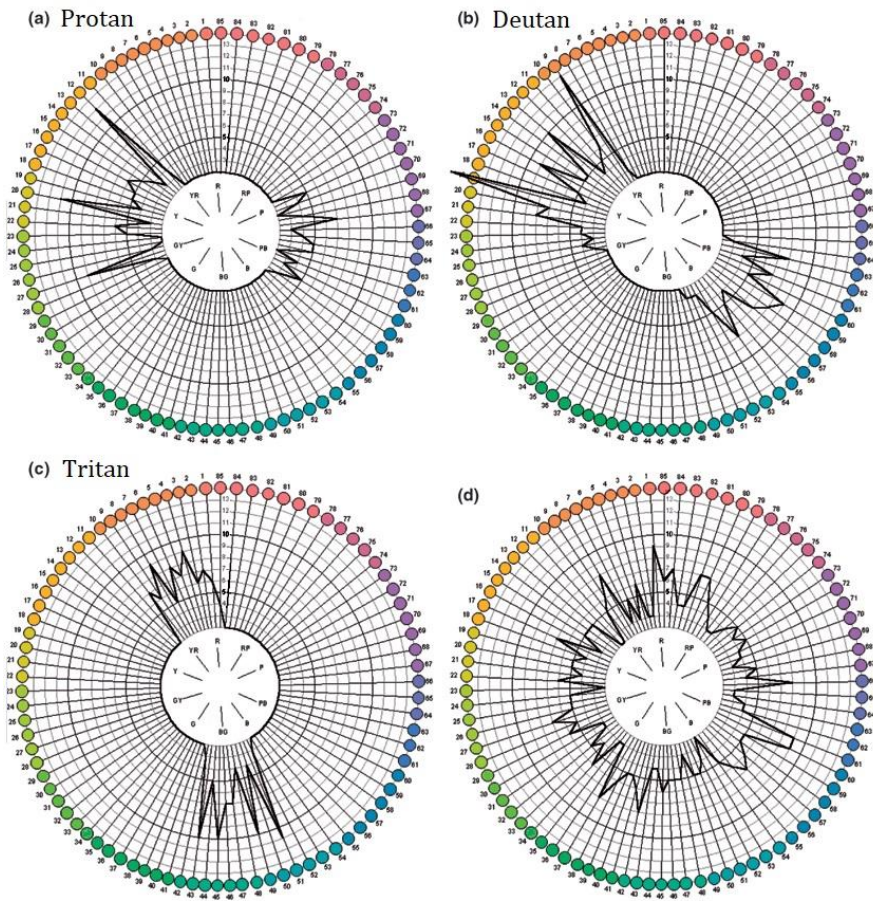


Figure 18. Results from the FM-hue 100 arrangement test showing scores of protan, deutan, tritan, and trichromatic (bottom right) color vision (Farnsworth Munsell 100 Hue Test, n.d.).

The traditional color vision tests assess different aspects of color perception, such as color recognition (Ishihara) and color arrangement (FM-100 and D15). These tests, while widely used and effective in providing generic diagnoses, still have limitations (Gómez-Robledo, Valero, Huertas, Martínez-Domingo, & Hernández-Andrés, 2018). The Ishihara test is widely used for CVD screening purposes, but it lacks the accuracy needed for a definitive CVD diagnosis. Arrangement-based tests use three severity designations, mild, moderate, and severe, but the scoring system used to make that determination still leaves room for ambiguity within each of these categories. The current approach to evaluating CVD mitigation technologies relies on having individuals with CVD take these tests while using an intervention. However, this method does not provide a precise way to measure the effectiveness of these technologies or to use the resulting data to refine and improve them. To address these limitations, Team COLOR developed a

simulation called Daltonis, designed to model perceptual differences between the most common form of CVD – red-green anomalous trichromacy – and trichromacy. The model operates within XYZ, LMS, and opponent process color spaces to produce a quantifiable measure of perceptual divergence.

2.4. Gaps in Existing Technologies

Many technologies claiming to mitigate the effects of CVD exist in today's market. Of particular interests to this research are filters, genetic therapies, and AR-enhanced technologies.

2.4.1. Filters

EnChroma Glasses. EnChroma glasses are one of the most well-known solutions for mitigating red-green color vision deficiency. In this condition, the wavelength ranges that stimulate the red-sensitivity in L-cones and those that stimulate the green-sensitivity in M-cones overlap significantly, making it difficult to distinguish between red and green hues (EnChroma, 2025). EnChroma addresses this by using notch-filter lenses that block light in the overlapping region, typically around 530–560 nm. This filtering enhances contrast between red and green signals perceived by the brain (EnChroma, 2025); (How Do EnChroma® Colorblind Glasses Work?, n.d.).

Figure 19 illustrates this concept with simplified LMS cone response curves for individuals, with and without CVD, wearing EnChroma glasses (“EnChroma Lenses”). These curves represent the specific wavelength ranges to which L, M, and S cones respond. Comparing the "Normal Vision" (i.e., trichromatic vision) and "Color Blindness" graphs shows the excessive overlap region between the L and M cones in individuals with red-green colorblindness. The "EnChroma Lenses" graph demonstrates how filtering this overlapping region increases the separation between cone responses, thereby improving color discrimination along the red-green axis (How Do EnChroma® Colorblind Glasses Work?, n.d.).

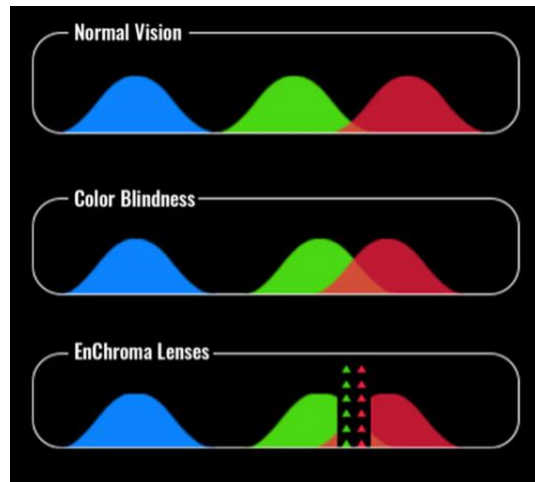


Figure 19. The confusion that is filtered through the EnChroma glasses (How Do EnChroma Color Blind Glasses Work, n.d.)

In 2018, researchers from the University of Granada conducted a 48-person study on the effectiveness of the EnChroma glasses for red-green CVD (Gómez-Robledo, Valero, Huertas, Martínez-Domingo, & Hernández-Andrés, 2018). Each participant completed two sessions – one with and one without the glasses – using Ishihara plates and the FM-100 to test color perception, and a subjective 21-color naming test based on the X-Rite Color Chart. The X-Rite Color Chart used 11 colors, each with a provided name, and was included to assess whether the glasses altered color perception without expanding the range of visible colors (Gómez-Robledo, Valero, Huertas, Martínez-Domingo, & Hernández-Andrés, 2018). Additionally, the researchers created a simulation, based on the known spectral transmittance of the EnChroma lenses, to model how scenes would appear to both CVD and trichromat observers, with and without the glasses (Gómez-Robledo, Valero, Huertas, Martínez-Domingo, & Hernández-Andrés, 2018).

When compared, the results of the two testing sessions showed that while EnChroma glasses helped some participants recognize certain colors they previously could not, this often came at the cost of misidentifying other colors they had been able to distinguish without the glasses. This suggests that EnChroma glasses alter color appearance but do not produce a diagnostic improvement (Gómez-Robledo, Valero, Huertas, Martínez-Domingo, & Hernández-Andrés, 2018). The simulation further confirmed that although the glasses may change the appearance of colors, they do not make color vision more similar to trichromatic color vision, as the overall range

of distinguishable colors remains limited (Gómez-Robledo, Valero, Huertas, Martínez-Domingo, & Hernández-Andrés, 2018). Notably, only one participant with mild deuteranomaly reported noticeable improvement in perceiving colors in their surroundings, indicating that the effect of the glasses varies by individual. Overall, EnChroma glasses may be useful to help some individuals with red-green CVD perceive certain colors differently, but they are not a reliable corrective tool for colorblindness (Gómez-Robledo, Valero, Huertas, Martínez-Domingo, & Hernández-Andrés, 2018).

Tinted Filters. ChromaGen filters, developed at the Corneal Laser Center for Color Blindness, offer a range of eight colored tinted filters, in the form of glasses and contacts. The tint in the contact lenses covers only the pupil area and comes in different sizes to accommodate various pupil sizes. The glasses work to alleviate the effects of CVD by changing the level of colors going into one or both eyes, which improves color discrimination and perception (Causes of Color Vision Deficiency, 2025). A study conducted by the National Institute of Health found that there was significant improvement in color vision (89.8%) and photosensitivity (87.5%) (Alkhudairy & Al Shamlan, 2022).

Another similar technology, hydro-tinted Lenses, which is a modified poly (hydroxyethyl) methacrylate resin (pHEMA resin) uses wavelength dyes Atto 565 and Atto 488 to construct contact lenses. This solution incorporates 3D-printing technology, which allows for the most ideal transparency for light and filtering capabilities (Alam, Salih, Elsherif, & Butt, 2022). These contact lenses were shown to be successful at their main goal of filtering specific target wavelengths of light.

However, further research has found that color filters such as ChromaGen filters and hydro-tinted lenses have mixed results. They show an improvement in recognition tests, such as the Ishihara test, but they have a negative effect on color arrangement tests, such as the FM-100 hue test. Consequently, there would be an inherent danger in using these filters in low-light environments while performing high risk activities like driving or flying, due to visual distortions and reduced visual acuity (Martínez-Domingo, et al., 2019).

Plasmonic Contacts. Gold and Silver Nanoparticles (NPs) have been used extensively in biomedical-related applications due to their attractive optical properties of absorption and scattering of light. Nanoparticles exhibit a high absorption band in the ultraviolet-visible light band that can be tuned to fit specific requirements, making them an ideal and flexible technology for filtering. Experimentation has found that the diameters of the NPs directly correlate with the absorption peak size, making contacts a natural fit for the technology (Roostaei & Hamidi, 2022). While this technology has shown promising results, nanoparticles are not fully understood in the scientific community. Plasmonic contact lenses result in issues such as non-biocompatibility, limited usability, low stability, and high cost. All of these raise a question of safety for use in plasmonic contacts (Roostaei & Hamidi, 2022).

2.4.2. Genetic Therapies

Gene Therapy is a medical approach that modifies a person's genes to cure illness or disease. However, it is not widely used for colorblindness due to the variety of mutations in specific genes that contribute to the manifestation of CVD. However, in recent years, gene therapy has been researched and tested on patients with achromatopsia, where individuals can only see black, white, and shades of gray. These individuals are extremely sensitive to light and have poor visual acuity (Kohl, Jägle, Wissinger, & Zobor, 2018). The most common underlying genetic mutations in this disorder are autosomal recessive changes in cone photoreceptor genes – CNGA3 and CNGB3 – that are essential for cone phototransduction, a process through which light triggers an electrical response (Naso, Tomkiewicz, Perry III, & Strohl, 2017). These photoreceptor genes encode proteins that are needed to create the environment required to deliver a nerve signal to the brain. When this environment fails to occur, cone cells are unable to reliably deliver nerve signals to the brain (Farahbakhsh, et al., 2021). Since the cone's cells are present, however, this dysfunction can be restarted using gene therapy.

Depending on which gene is mutated, gene therapy is done by delivering an intact copy of that gene to the retinal cells through an adeno-associated virus which tracks a gene into the cell's nucleus and then takes the role of the patient's own non-functioning gene. Delivery through adeno-

associated virus is the safest and most effective delivery mechanism. Although gene therapy has been tested on humans with CVD with promising results, Team COLOR did not focus on this topic due to limited resources and capabilities.

2.4.3. Augmented Reality Glasses

Augmented Reality (AR) Computational Glasses capture the environment, process the given image, and display a modified image to the user to provide real-time processing. For color vision deficient observers, AR glasses can be customized to the individual CVD observer using a color space matrix transformation, where they may be able to distinguish colors that they could not before. This process is described in Figure 20.

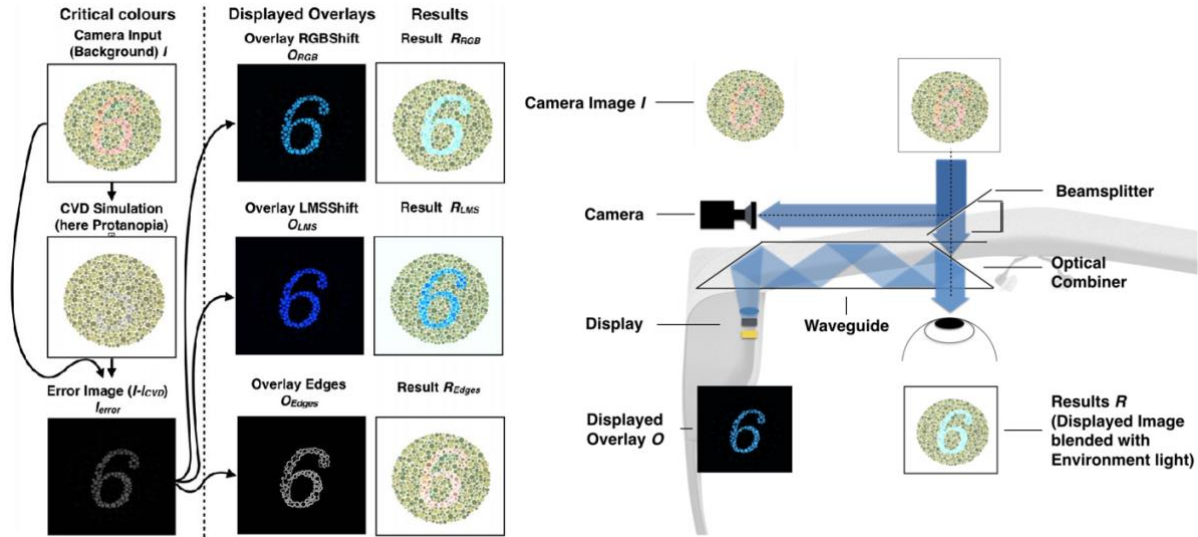


Figure 20. Diagram of how AR glasses manipulate RGB, LMS, and Edges Color Spaces (Sutton, Langlotz, & Itoh, 2019).

One study has shown that more advanced versions of AR glasses resulted in observers being able to better distinguish between colors. These advanced versions found that LMS color space transformation to be the most effective; however, they had mixed results when tested with natural images involving counting flowers or identifying fruits type tasks. In fact, no compensation technique proved more effective than having no glasses at all. This outcome is thought to be because all test subjects only had mild CVD, or that the subjects are accustomed to their type of

vision deficiency, so fruits and flowers were easily distinguishable in their field of view and not in a “corrected” view provided by the AR Glasses (Sutton, Langlotz, & Itoh, 2019).

One gap in this AR Glasses study is that testing was mostly done using Ishihara test plates, which have been proven to be extreme ways to generalize a person’s type of colorblindness. Additionally, all the participants of the study had mild red-green colorblindness, which leaves some unknown for how AR glasses will work for more severe cases of CVD. Despite the lack of research on AR glasses, existing literature on the technology is promising and leaves room for further exploration.

2.4.5. Problems with Current Solutions

Colorblindness affects a substantial portion of the population and has motivated the development of a variety of technologies and inclusive design initiatives intended to improve visual experiences for affected individuals. Gene therapy represents one potential area of intervention. However, research shows that its effectiveness remains limited, and application is constrained by ethical considerations and challenges related to data collection. Alternatively, existing technologies like EnChroma glasses, ChromaGen filters, hydro-tinted lenses, and plasmonic contact lenses attempt to isolate the overlapping wavelength range associated with red-green deficiencies. In their effort to isolate the target wavelength of 10 nm, they also filter out other wavelengths, reducing visual acuity and color perception. Additionally, the high cost of these devices and the lack of personalization present issues of accessibility and affordability. Their performance is typically assessed using the Ishihara test, which, as established in prior work, is not a comprehensive or reliable diagnostic tool for all forms of color vision deficiency. Collectively, these limitations highlight the need for further investigation into approaches that are effective, affordable, and customizable, with the potential to substantially improve the visual quality of life for individuals with color vision deficiencies.

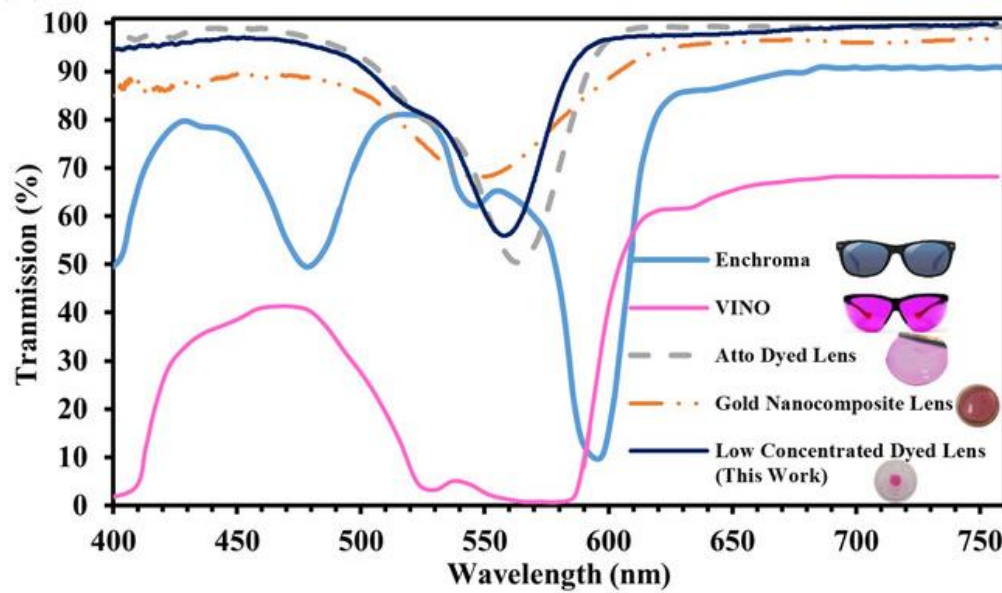


Figure 21. Amount of light transmitted with the use of each filter. Notice the significant loss of light transmission and therefore acuity associated with EnChroma (Salih, Alam, Elsherif, Hittini, & Butt, 2023).

2.5. Conclusion

This literature review examined existing research on CVD to understand the tools used to diagnose these conditions and the shortcomings of developed CVD mitigating technologies. Existing studies show that many prevailing diagnostic tools rely on subjective feedback from colorblind individuals. However, this does not provide a consistent metric to measure, altered color perception, or to evaluate the effectiveness of mitigation technologies that depend on these tests. Therefore, a research gap exists in the development of effective corrective CVD interventions, precise evaluation methods, and the ability to personalize these interventions to variations in CVD among different individuals.

There have been many technological developments to battle colorblindness, such as gene therapy, augmented reality glasses, and filter-based technology. While many of these have gained a lot of attention and popularity, they don't necessarily improve the quality of life for many colorblind individuals. Many current designs are tested using subjective diagnostic tools, which leads to ineffective technologies and, in some cases, worsens the color perception instead of improving it.

Several models for interpreting color perception have been explored, including the opponent color theory, RGB color space, and CIE xy chromaticity diagram. Of these, the chromaticity diagram is particularly valuable for aiding in the visualization and understanding of how CVD affects color perception through the concept of confusion lines. This concept led to the development of many colorblind tests that are effective for general diagnosis but remain limited in their ability to provide the quantitative data researchers need to evaluate and improve CVD mitigation technologies. As a result, assessing the efficacy of existing solutions and improving upon their designs remains a significant challenge.

This research explored several topics in an effort to address these issues and bridge the existing gap in colorblind technology. Three key objectives were undertaken: (1) the development of optimized notch filter lenses with high visual acuity; (2) an exploratory analysis of light manipulation and its effect on color perception, especially in CVD individuals; and (3) the creation of a quantitative CVD simulation. This simulation serves as a testing platform to support the incremental development and evaluation of the developed mitigating interventions, acting as an objective diagnostic tool.

3. Design & Validation of a Physiologically Based Color Vision Deficiency Simulation

3.1. Overview & Motivation

Current leading anomalous trichromacy mitigation tools, such as EnChroma glasses and Chromagen lenses, are primarily evaluated using subjective user reports, with relatively few standardized quantitative testing methods available. This reliance on anecdotal feedback limits the ability to systematically assess and improve the effectiveness of designed CVD interventions. One aim of this research was to design interventions that mitigate red-green color vision deficiencies without compromising overall visual acuity. To evaluate any design's effectiveness, there must exist a quantifiable method to model the relative difference between various forms of CVD. Relying solely on subjective user feedback is insufficient and limits the ability to iteratively design and improve upon these mitigating interventions.

Therefore, there existed a crucial need to develop a measurable method to model how interventions that physically alter light through filters, lenses, or other wavelength-selective manipulations affect the cone responses in the eye and the subsequent neural processing that produces color perception. Central to this effort was the creation of a physiologically-based simulation, called Daltonis, which links spectral stimulus information, photoreceptor responses in the human visual system, neural processing of cone responses, and representation of CVD in digital color spaces. Daltonis allows visualization and manipulation of how changes in red and green cone responses, caused by deuteranomalous or protanomalous color vision deficiencies, alter perceived color.

3.2. Daltonis CVD Simulation Design

Daltonis was designed to model both deuteranomaly and protanomaly, specifically varying severities of red-green color vision deficiency. The simulation accepts an uploaded image and applies a variable, user-specifiable wavelength shift – used to parameterize the degree and type of color vision deficiency – to generate a CVD-augmented version of the image. Figures 22 – 25 demonstrates the application of the simulation to a multi-colored butterfly image to illustrate the

perceived appearance of the image under both mild and mild-severe protanomaly and deuteranomaly conditions. This design supports the goal of creating a testing mechanism for physical red-green CVD mitigation devices by allowing images to be pre-modified by filters, lenses, or other wavelength-selective manipulating interventions and propagating these potential modifications through a physiologically based model of photoreceptor responses. In doing so, Daltonis enables systematic and quantitative evaluation of mitigation strategies beyond reliance on subjective user experience.

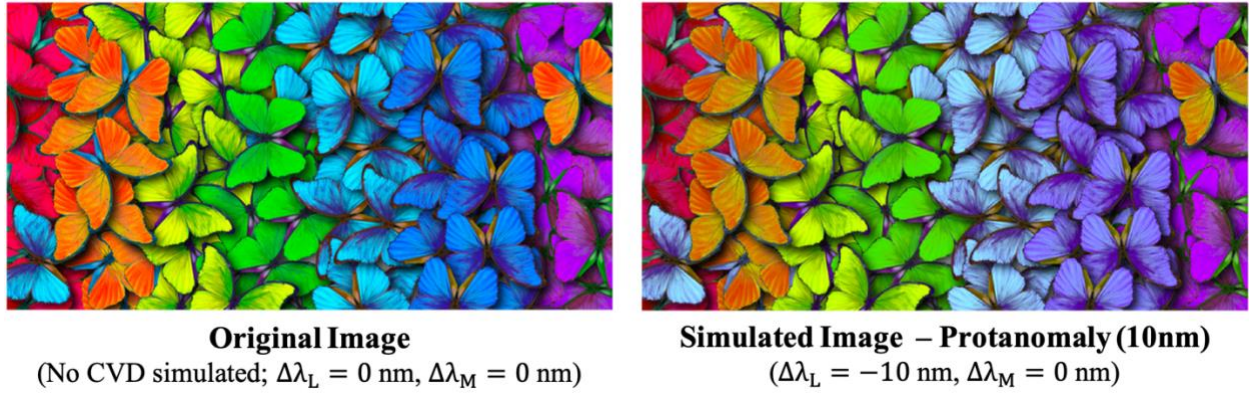


Figure 22. Demonstration of the Daltonis red-green anomalous trichromacy simulation applied to a multi-colored butterfly image spanning the visible spectrum. The left image shows the original input (no CVD simulated; $\Delta\lambda_L = 0 \text{ nm}$, $\Delta\lambda_M = 0 \text{ nm}$) and right image illustrates the visual effects of simulated protanomaly ($\Delta\lambda_L = -10 \text{ nm}$, $\Delta\lambda_M = 0 \text{ nm}$).

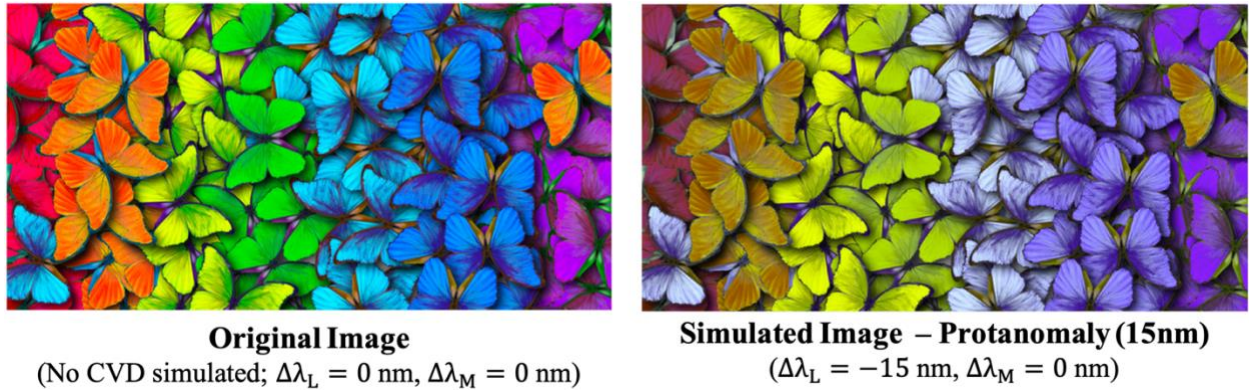


Figure 23. Demonstration of the Daltonis red-green anomalous trichromacy simulation applied to a multi-colored butterfly image spanning the visible spectrum. The left image shows the original input (no CVD simulated; $\Delta\lambda_L = 0 \text{ nm}$, $\Delta\lambda_M = 0 \text{ nm}$) and right image illustrates the visual effects of simulated protanomaly ($\Delta\lambda_L = -15 \text{ nm}$, $\Delta\lambda_M = 0 \text{ nm}$).



Original Image

(No CVD simulated; $\Delta\lambda_L = 0$ nm, $\Delta\lambda_M = 0$ nm)



Simulated Image – Deuteranomaly (10nm)

($\Delta\lambda_L = 0$ nm, $\Delta\lambda_M = 10$ nm)

Figure 24. Demonstration of the Daltonis red-green anomalous trichromacy simulation applied to a multi-colored butterfly image spanning the visible spectrum. The left image shows the original input (no CVD simulated; $\Delta\lambda_L = 0$ nm, $\Delta\lambda_M = 0$ nm) and right image illustrates the visual effects of simulated deuteranomaly ($\Delta\lambda_L = 0$ nm, $\Delta\lambda_M = 10$ nm).



Original Image

(No CVD simulated; $\Delta\lambda_L = 0$ nm, $\Delta\lambda_M = 0$ nm)



Simulated Image – Deuteranomaly (15nm)

($\Delta\lambda_L = 0$ nm, $\Delta\lambda_M = 15$ nm)

Figure 25. Demonstration of the Daltonis red-green anomalous trichromacy simulation applied to a multi-colored butterfly image spanning the visible spectrum. The left image shows the original input (no CVD simulated; $\Delta\lambda_L = 0$ nm, $\Delta\lambda_M = 0$ nm) and right image illustrates the visual effects of simulated deuteranomaly ($\Delta\lambda_L = 0$ nm, $\Delta\lambda_M = 15$ nm).

3.2.1. Daltonis: Physiologically Based Modeling Framework

Human color recognition is a complex process that involves both biological and neurological mechanisms within the visual system. Daltonis mathematically models this physiological process to simulate the effects of red-green anomalous trichromacy on images. To do so, the simulator relies on two foundational color theories: the Trichromatic Theory of Color and the opponent color theory. Together, these theories describe the color recognition pathway

that begins with light reflecting from a visual scene and entering the eye. This light stimulates the retinal photoreceptor cones, generating cone response signals that are transmitted to the brain and ultimately interpreted as specific perceived colors.

The Trichromatic Theory of Color, originally proposed by physicist Thomas Young, describes the trichromatic human color visual experience as arising from the combined activity of three types of cones in the retina. These cones are commonly referred to as red, green, and blue cones, though more precisely they correspond to the long (L), medium (M), and short (S) wavelength-sensitive cone photoreceptors, respectively. As shown in Figure 1 (in [Section 2.2](#)), each cone type has an associated spectral sensitivity function that defines how strongly the cone is stimulated by different wavelengths of light. For example, the peak sensitivity for red (L) cones sits at approximately 560 nm. When light enters the eye, it stimulates the cones according to these spectral sensitivity functions, producing cone response signals that are transmitted to the brain.

Color vision deficiency (CVD) originates at the level of the retinal cones (Machado, Oliveira, & Fernandes, 2009). As discussed in [Section 2.3.3](#) (Genetic Causes of CVD), the existence of hybrid red-green photoreceptors resulting from exon recombination are one source of diminished color discrimination, producing protanomaly or deuteranomaly. The scientifically accepted standard L, M, and S spectral sensitivity functions are based on average trichromats' cone sensitivities and exhibit distinctly defined peak responses. However, in individuals with red-green anomalous trichromacy, the affected anomalous cone exhibits a peak spectral sensitivity that lies between the standard L and M peaks. The distance, or delta, between the trichromat's canonical cone peak and the corresponding anomalous cone peak defines a CVD-induced spectral shift, representing the physiological effect a hybrid photopigment has on color perception.

Daltonis relies on the LMS color space, which represents an individual's L, M, and S cone spectral sensitivities. Using LMS allows spectral shifts to be applied to the LMS functions to model the impact of anomalous trichromacy on an individual's vision. This approach enables Daltonis to flexibly simulate a wide range of red-green anomalous trichromacy conditions.

Once cone response signals have been generated at the retinal level, they are transmitted to the brain for color processing. Following this physiological model, Daltonis uses a mathematical interpretation of the opponent color theory to combine the biological and neural mechanisms underlying color vision. The opponent color theory (see [Section 2.2.1](#)) suggests that the brain interprets color by comparing the relative activity of different cone types to form three opponent channels: white-black (WS), red-green (RG), and yellow-blue (YB) (Machado, Oliveira, & Fernandes, 2009). Opponent color space (OCS) therefore models the neural interpretation of these signals. While the opponent color process is the same for trichromats and anomalous trichromats, the differing cone response signals in individuals with red-green anomalous trichromacy are interpreted differently, resulting in an altered color perception. Representing color in OCS allows Daltonis to simulate how altered LMS cone signals are interpreted by the brain, producing physiologically based outputs for both trichromatic and red-green anomalous trichromatic vision (Machado, Oliveira, & Fernandes, 2009).

Daltonis is based on the physiological process that occurs in both trichromats and anomalous trichromats, providing a framework to accurately interpret how certain color vision deficiencies affect human color perception. To this point, Daltonis is a not complete CVD simulator, but rather focuses exclusively on deuteranomaly and protanomaly. It does not simulate tritanomaly, dichromatic CVD, monochromatic CVD, or CVD caused by injury. The simulator assumes that, aside from the photoreceptor cones, the rest of the visual system functions normally. This assumption is necessary because, in dichromatic, monochromatic, or achromatic vision, missing cone types provide no input for certain wavelengths, making it impossible to modify all three L, M, and S spectral sensitivities to simulate the full color perception, unlike anomalous trichromacy where all three cones are present. Furthermore, Daltonis' color assessment ability is intended to be used alongside technologies, such as glasses or contact lenses, that require the person to have all three cones, ensuring compatibility with these devices. Finally, tritanomaly is excluded because it is the rarest of the three main anomalous vision defects, and due to minimal research on it, as well as limited time and resources, it would be difficult to obtain a sufficient population and data

to validate the simulation. For these reasons, Daltonis focuses exclusively on red-green anomalous CVD.

3.2.2. Daltonis: Simulating Red-Green Anomalous Trichromacy

To develop Daltonis, the psychological color recognition pathway outlined in [Section 3.2.1](#) was interpreted from a mathematical perspective. The design of Daltonis closely follows the physiologically based methods proposed in the IEEE research paper *A Physiologically-based Model for Simulation of Color Vision Deficiency* (Machado, Oliveira, & Fernandes, 2009). The general design of Daltonis, a red-green anomalous trichromacy simulation, accepts a user-selected input image along with a user-defined spectral shift parameter that indicates both the type and severity of CVD to be simulated. The output of the simulation is a modified representation of the input image that exemplifies color perception under trichromatic, protanomalous, or deuteranomalous conditions.

Daltonis was implemented in MATLAB, leveraging the application's image processing, data visualization, and linear algebra capabilities. While some standard built-in MATLAB functions were used for image processing and color space conversions, all CVD transformations are implemented using custom matrix formulations derived from the model proposed by Machado et al. (Machado, Oliveira, & Fernandes, 2009).

The design of Daltonis is organized into two complementary components: (1) a matrix construction procedure and (2) the integration of that procedure into an image processing method that produces a final CVD-modified output image. The first component describes how RGB-to-OCS transformation matrices are constructed based on cone spectral sensitivities, user-specified spectral shifts, and the brain's physiological interpretation of cone response signals. The second component explains how the construction process is invoked during image processing to transform pixel color values and generate output images that reflect trichromatic or red-green anomalous color perception. Together, these components enable Daltonis to flexibly generate and apply custom RGB-to-OCS transformation matrices to simulate a range of CVD conditions through digital images.

RGB to Opponent Color Space Matrix Construction. To simulate red-green anomalous trichromacy in a physiologically based manner, following the IEEE model proposed by Machado et al., Daltonis relies on a procedure for constructing linear transformations that map RGB image data into an opponent color space representation derived from cone responses. These transformations are parameterized by a spectral shift that specifies the type and severity of the anomalous trichromacy, with a zero shift corresponding to trichromatic vision and non-zero shifts corresponding to either protanomalous or deuteranomalous vision. By applying the same construction procedure under different spectral shift parameters, transformation matrices can be generated for a wide range of anomalous trichromacy conditions. This construction method provides a mathematical interpretation of the biological visual processing system, incorporating the effects of anomalous trichromacy into each RGB-to-OCS matrix, which Daltonis applies during image processing to generate an anomalous trichromacy representation of a specified image.

The LMS color space serves as an intermediate transformation phase between RGB and opponent color spaces, modeling the spectral responses of the eye's L, M, and S cone photoreceptors. Incorporating the LMS color space into the matrix construction process allows the model to capture how signals generated at the retina are affected by variations in cone responses, such as those caused by red-green CVD. This also provides a foundation for linearly deriving opponent color channels from cone response signals, reflecting the physiological pathway by which light stimuli are sensed by the retina and subsequently interpreted by the brain.

An LMS color space representation is constructed using the spectral sensitivity functions $L(\lambda)$, $M(\lambda)$, and $S(\lambda)$, which define the functional characteristics of the L, M, and S cones. These functions are defined based on the spectral responses of average trichromats' cones and were obtained from LMS cone fundamental data published by the International Commission on Illumination (CIE 2006 LMS cone fundamentals for 2° field size in terms of energy, 2006). To obtain a continuous spectral representation suitable for wavelength-domain operations, such as

spectral shifting and integration, these functions were sampled and interpolated over a uniform wavelength grid.

Cone response deficiencies associated with red-green anomalous trichromacy are modeled as shifts in the spectral sensitivity function of the affected cone, with the magnitude of the shift corresponding to the severity of the anomaly. This is represented by the modified spectral sensitivity functions as shown in Eqs. 1 – 3,

$$L_a(\lambda) = L(\lambda + \Delta\lambda_L) \quad (1)$$

$$M_a(\lambda) = M(\lambda + \Delta\lambda_M) \quad (2)$$

$$S_a(\lambda) = S(\lambda + \Delta\lambda_S) \quad (3)$$

where $\Delta\lambda_L$, $\Delta\lambda_M$, and $\Delta\lambda_S$ range from 0 to 20 nm and represent the severity of the spectral shift applied to an anomalous L, M, or S cone (Machado, Oliveira, & Fernandes, 2009). However, a simple spectral shift does not fully capture the physiological changes in the L and M cone responses. In reality, increasing CVD severity cause the L and M cone sensitivity functions to not only shift, but also become more similar in shape as they increasingly overlap. Therefore, to accurately capture this transformation, Eqs. 5 and 6 should be used instead to account for the blending of $L(\lambda)$ and $M(\lambda)$ as the severity of the shift increases. This blending is controlled by $\alpha = (20 - \Delta\lambda)/20$, for $\Delta\lambda \in [0, 20]$ (Machado, Oliveira, & Fernandes, 2009).

$$L_a(\lambda) = \alpha L(\lambda) + (1 - \alpha) 0.96 \frac{\text{Area}_L}{\text{Area}_M} M(\lambda) \quad (4)$$

$$M_a(\lambda) = \alpha M(\lambda) + (1 - \alpha) \frac{1}{0.96} \frac{\text{Area}_M}{\text{Area}_L} L(\lambda) \quad (5)$$

Figures 26 – 28 demonstrate the effect of spectral sensitivity shifts on the $L(\lambda)$ and $M(\lambda)$ sensitivity functions. Figure 26 shows the canonical LMS space with functions $L(\lambda)$, $M(\lambda)$, and $S(\lambda)$, where $\Delta\lambda_L = \Delta\lambda_M = \Delta\lambda_S = 0$ nm. Figure 27 illustrates the spectral sensitivity functions for mild protanomaly ($\Delta\lambda_L = -10$ nm), demonstrating the negative wavelength shift applied to the L cone function $L(\lambda)$, while the M and S cone sensitivity functions remain unmodified. Figure 28 illustrates the spectral sensitivity functions for mild deuteranomaly ($\Delta\lambda_M = 10$ nm), showing the positive wavelength shift applied to the M cone function $M(\lambda)$, while the L and S cone sensitivity

functions remain unchanged. Notably, when either a $\Delta\lambda_L$ or $\Delta\lambda_M$ shift is applied, the L (red) and M (green) cone sensitivity functions overlap more, corresponding to the increased difficulty individuals with red-green CVD have in distinguishing these colors. Daltonis models protanomaly or deuteranomaly by specifying either a negative $\Delta\lambda_L$ or positive $\Delta\lambda_M$ value. The magnitude of this shift determines the severity of the condition, with 20 nm represents a severe case of either condition. This shift is then used to compute the transformation matrix corresponding to the specified form of anomalous trichromacy.

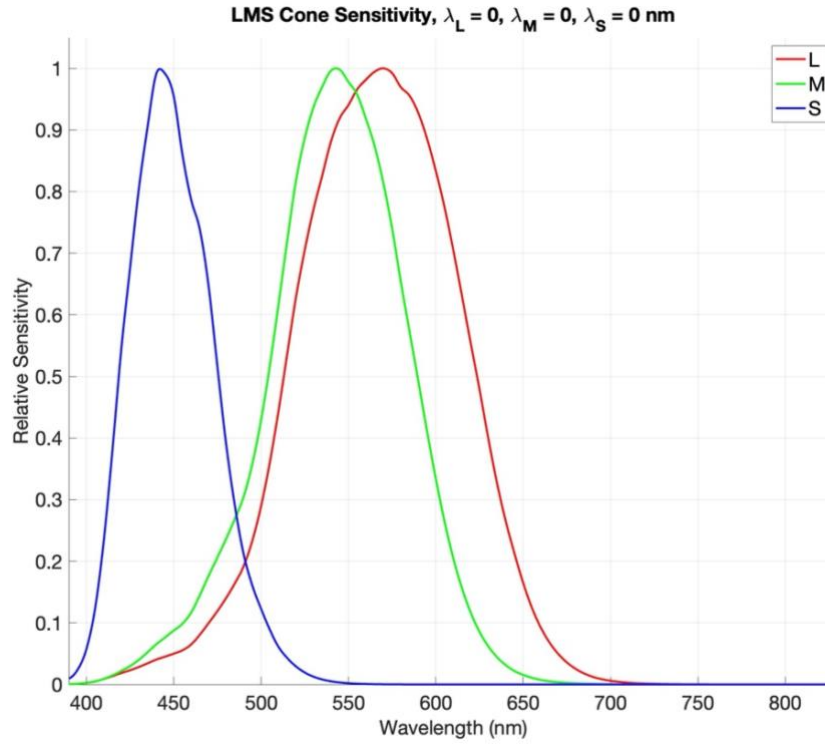


Figure 26. Canonical LMS cone spectral sensitivity functions $L(\lambda)$, $M(\lambda)$, and $S(\lambda)$ with no spectral shift ($\Delta\lambda_L = \Delta\lambda_M = \Delta\lambda_S = 0$ nm).

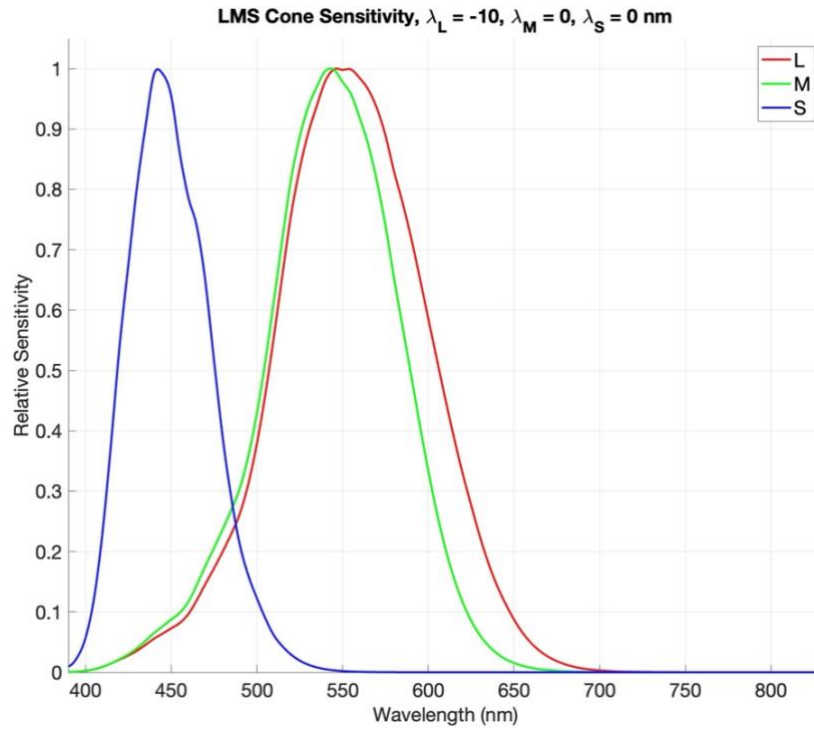


Figure 27. Spectral sensitivity functions for mild protanomaly ($\Delta\lambda_L = -10$ nm), showing a negative wavelength shift in the L cone function $L(\lambda)$, increasing overlap with the M cone.

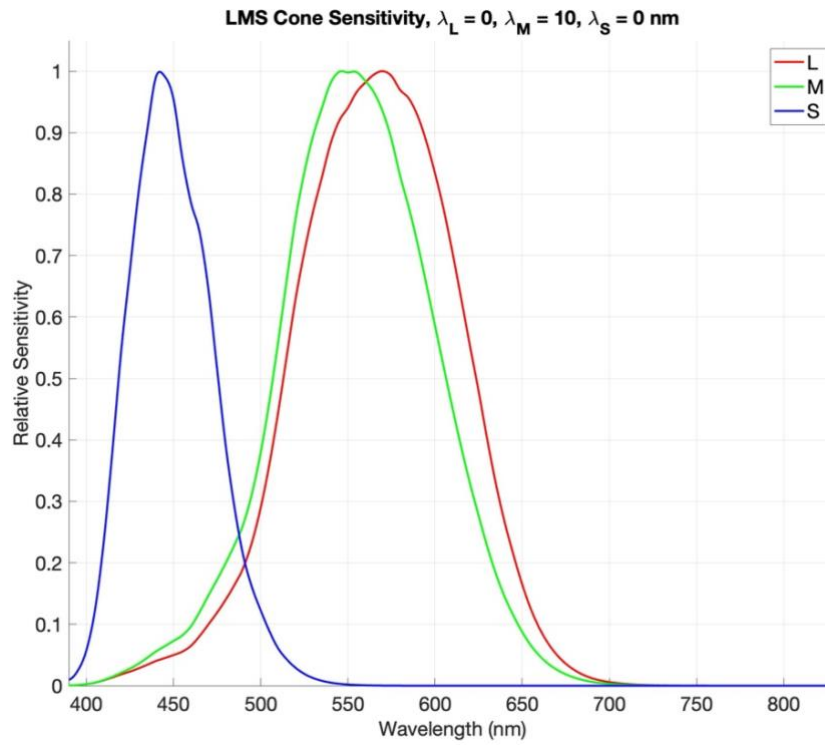


Figure 28. Spectral sensitivity functions for mild deuteranomaly ($\Delta\lambda_M = 10$ nm), showing a positive wavelength shift in the M cone function $M(\lambda)$, increasing overlap with the L cone.

Although Machado et al. indicate that tritanomaly may be simulated by shifting the S-cone spectral sensitivity function, Daltonis focusses exclusively on protanomaly and deuteranomaly and therefore restricts $\Delta\lambda_S$ to 0 nm. Trichromatic vision is modeled when both $\Delta\lambda_L$ and $\Delta\lambda_M$ are also set to 0 nm, such that no anomalous shift is applied during the matrix construction process, as colorblindness is not being simulated. Additionally, because Daltonis simulates only one form of red-green anomalous trichromacy at a time, a non-zero shift implies that either $\Delta\lambda_L$ or $\Delta\lambda_M$ is specified while the other remains zero; both parameters are never simultaneously non-zero in the simulation.

Following the biological and neurological mechanisms of color recognition, signals generated by cone responses at the retinal level are transmitted to the central nervous system, where they are ultimately perceived as color. The post-retinal interpretation of these signals can be modeled using opponent color theory (see [Section 2.2.1](#)), which represents how the brain combines L, M, and S cone responses into three opponent channels: white-black (WS), red-green (RG), and yellow-blue (YB) (Machado, Oliveira, & Fernandes, 2009). Within the Daltonis matrix construction process, this mapping from LMS cone responses to opponent channels is implemented as a linear transformation using the matrix T_{LMS_2Opp} (Eq. 6), originally introduced by Ingling and Tsou and adopted by Machado et al. (Machado, Oliveira, & Fernandes, 2009).

$$T_{LMS_2Opp} = \begin{bmatrix} 0.600 & 0.400 & 0.000 \\ 0.240 & 0.105 & -0.700 \\ 1.200 & -1.600 & 0.400 \end{bmatrix} \quad (6)$$

Applying T_{LMS_2Opp} to LMS cone spectral sensitivity functions produces a set of opponent channel response functions $WS(\lambda)$, $YB(\lambda)$, and $RG(\lambda)$ that define the corresponding opponent color space (Machado, Oliveira, & Fernandes, 2009). For trichromatic vision, these functions define the canonical opponent color space (Figure 29) based on the cone sensitivities of an average trichromat. When LMS inputs are modified to account for anomalous trichromacy using Eqs. 3 – 5, T_{LMS_2Opp} generates a correspondingly altered opponent color space reflecting protanomalous, deuteranomalous, and tritanomalous perception, as seen in Figure 30. In Daltonis, applying T_{LMS_2Opp} after specifying any anomalous shift, using Eqs. 4 or 5, ensures that the resulting

opponent channel responses correctly represent either trichromatic vision (when $\Delta\lambda_L = \Delta\lambda_M = 0$ nm) or red-green anomalous color perception (when a non-zero shift is applied). Eqs. 7 – 9 illustrate this transformation process for trichromatic (*tri*), protanomalous (*pa*), and deuteranomalous (*da*) conditions.

$$\begin{bmatrix} WS(\lambda) \\ YB(\lambda) \\ RG(\lambda) \end{bmatrix}_{tri} = T_{LMS_2Opp} \begin{bmatrix} L(\lambda) \\ M(\lambda) \\ S(\lambda) \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} WS(\lambda) \\ YB(\lambda) \\ RG(\lambda) \end{bmatrix}_{pa} = T_{LMS_2Opp} \begin{bmatrix} L_a(\lambda) \\ M(\lambda) \\ S(\lambda) \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} WS(\lambda) \\ YB(\lambda) \\ RG(\lambda) \end{bmatrix}_{da} = T_{LMS_2Opp} \begin{bmatrix} L(\lambda) \\ M_a(\lambda) \\ S(\lambda) \end{bmatrix} \quad (9)$$

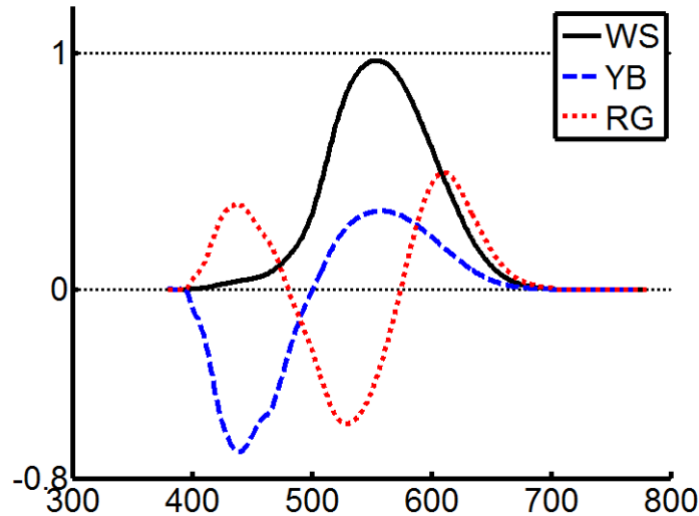


Figure 29. Opponent channel response functions $WS(\lambda)$, $YB(\lambda)$, and $RG(\lambda)$ that define the canonical opponent color space. The x-axis represents wavelength (nm) and the y-axis corresponds to chromatic response. (Machado, Oliveira, & Fernandes, 2009)

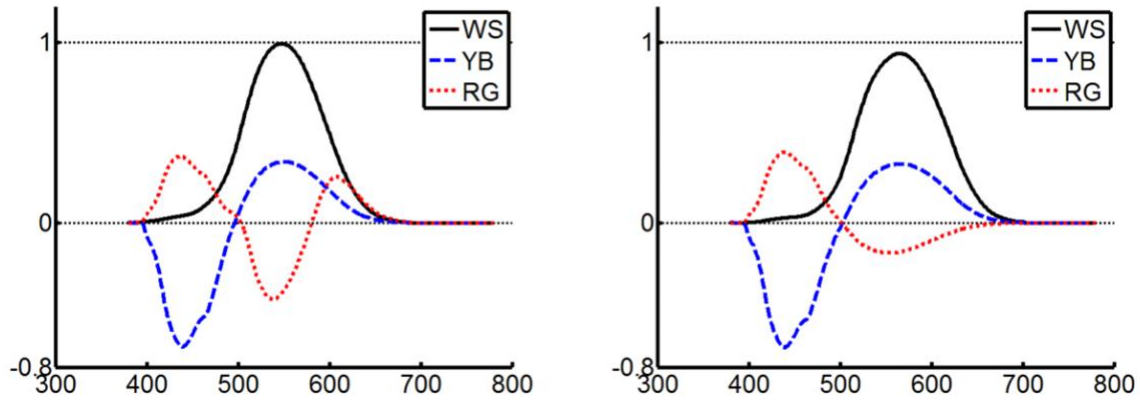


Figure 30. CVD altered opponent channel response functions for anomalous trichromats. (left) Protanomaly ($\Delta\lambda_L = -15$ nm). (right) Deuteranomaly ($\Delta\lambda_M = 19$ nm). Axes correspond to wavelength in nm (x-axis) and chromatic response (y-axis) (Machado, Oliveira, & Fernandes, 2009).

The final step in constructing a transformation matrix from RGB to opponent color space, which accounts for red-green anomalous trichromacy, is using the calculated opponent channel spectral response functions to define how RGB triples are transformed into opponent colors. As proposed by Machado et al., this is done by projecting the spectral power distributions of each RGB primary $\phi_R(\lambda)$, $\phi_G(\lambda)$, and $\phi_B(\lambda)$ onto the opponent channel spectral response functions $WS(\lambda)$, $YB(\lambda)$, and $RG(\lambda)$, as defined by the appropriate opponent color space formulation in Eqs. 7 – 9 (Machado, Oliveira, & Fernandes, 2009). Mathematically, this projection is expressed as an integral over wavelength. Eq. 10 shows how each RGB spectral power distribution is paired with the opponent channel functions and integrated, with the results multiplied by the normalization factors ρ_{WS} , ρ_{YB} , and ρ_{RG} .

$$\begin{aligned}
 WS_R &= \rho_{WS} \int \phi_R(\lambda) WS(\lambda) d\lambda, \\
 WS_G &= \rho_{WS} \int \phi_G(\lambda) WS(\lambda) d\lambda, \\
 WS_B &= \rho_{WS} \int \phi_B(\lambda) WS(\lambda) d\lambda, \\
 YB_R &= \rho_{YB} \int \phi_R(\lambda) YB(\lambda) d\lambda, \\
 YB_G &= \rho_{YB} \int \phi_G(\lambda) YB(\lambda) d\lambda, \\
 YB_B &= \rho_{YB} \int \phi_B(\lambda) YB(\lambda) d\lambda, \\
 RG_R &= \rho_{RG} \int \phi_R(\lambda) RG(\lambda) d\lambda, \\
 RG_G &= \rho_{RG} \int \phi_G(\lambda) RG(\lambda) d\lambda, \\
 RG_B &= \rho_{RG} \int \phi_B(\lambda) RG(\lambda) d\lambda
 \end{aligned} \tag{10}$$

The normalization factors are determined by the constraints in Eq. 11, which ensure the RGB weights for each opponent channel to sum to one:

$$\begin{aligned} WS_R + WS_G + WS_B &= 1, \\ YB_R + YB_G + YB_B &= 1, \\ RG_R + RG_G + RG_B &= 1 \end{aligned} \quad (11)$$

When the transformation defined by Eq. 10 is applied to an achromatic (gray shade) RGB triplet ($R = G = B = k$), the normalization factors specified in Eq. 11 ensure that each opponent channel's weighted sum evaluates to k . By forcing the RGB weights for each opponent channel to sum to one, the normalization constraints guarantee that gray colors remain gray in the OCS, preventing unintended shifts in color and brightness.

Therefore, Eq. 10 produces nine elements that describe how each RGB primary contributes to the WS, YB, and RG opponent channels. These elements are arranged into the transformation matrix T (Eq. 12), which maps linear RGB values into an opponent color space that represents trichromatic or red-green anomalous vision, with the type and severity determined by the spectral shift specified (Machado, Oliveira, & Fernandes, 2009).

$$T = \begin{bmatrix} WS_R & WS_G & WS_B \\ YB_R & YB_G & YB_B \\ RG_R & RG_G & RG_B \end{bmatrix} \quad (12)$$

This matrix construction process provides Daltonis with a physiologically grounded and flexible method for generating transformation matrices that map RGB values into opponent color spaces corresponding to trichromatic or red-green anomalous vision. By specifying different spectral shifts, unique matrices can be produced to represent a range of color perception conditions, forming the foundation for the image processing component of Daltonis.

Matrix Application to Simulate Red-Green Anomalous Trichromacy. Daltonis simulates red-green anomalous trichromacy by applying the matrix construction process to generate transformation matrices that are then used to modify an input image. These matrices are applied to each pixel, producing a visualization that reflects altered cone responses and the resulting physiological interpretation of color. This process can be used to simulate either deuteranomalous

or protanomalous vision, specifiable by the user-inputted shift that indicates the type and severity of the anomaly.

Integral to this image alteration process is the creation of two linear transformation matrices using the RGB-to-OCS matrix construction procedure. One matrix is constructed using the user-specified spectral shift to produce an RGB-to-OCS mapping matrix that accounts for red-green anomalous trichromacy. This matrix is denoted as T_S , where S indicates a “shifted” (CVD-modified) condition. The second matrix is constructed with no spectral shift applied, such that $\Delta\lambda_L$ and $\Delta\lambda_M$ (with $\Delta\lambda_S$ fixed at zero) are both set to zero. This matrix is denoted as T_{NS} , where NS indicates “no shift”, and represents the canonical RGB-to-OCS transformation corresponding to trichromatic vision. Figure 31 shows the general application of these matrices within Daltonis to generate a red-green anomalous trichromacy representation of an inputted image (Machado, Oliveira, & Fernandes, 2009).

$$Image_C = T_{NS}^{-1} \times T_S \times Image$$

T = conversion matrix, S = shifted, NS = no shift

Figure 31. Daltonis image processing procedure for simulating red-green anomalous trichromacy, corresponding to the RGB-to-OCS transformation method summarized by Eq. 11 of the IEEE research paper “A Physiologically-based Model for Simulation of Color Vision Deficiency” (Machado, Oliveira, & Fernandes, 2009).

In more detail, each image is treated as a collection of pixel-wise color vectors that are sequentially represented and transformed between color spaces throughout the simulation. Input images are initially represented in the standard sRGB color space and are converted into linear RGB, since sRGB is a non-linear encoding and linear color space is required for the application of linear transformation matrices. Each linear RGB pixel is then mapped into OCS using the shifted transformation matrix T_S . Since the desired type and severity of color vision deficiency are incorporated during the construction of this matrix through the user-specified spectral shift, this transformation produces an OCS representation that accounts for the anomalous cone sensitivities associated with the specified anomalous trichromacy.

To generate a displayable image after CVD has been applied to each pixel color vector, the inverse of the non-shifted matrix, T_{NS}^{-1} , is used to map the CVD-modified opponent color vectors back into linear RGB space. This inverse transformation preserves the perceptual anomalous trichromacy distortions introduced by the T_S mapping into OCS, resulting in RGB that reflect the simulated color vision deficiency. Finally, the modified linear RGB image pixels are converted back into sRGB for visualization on standard digital display devices, as sRGB's non-linear encoding is designed to more accurately match human luminance perception, completing the Daltonis anomalous trichromacy simulation process.

3.3. Experimental Evaluation of Daltonis Anomalous Trichromacy Simulation

As mentioned in [Section 3.2](#) the Daltonis physiologically based simulation was designed to model the effect of red-green colorblindness on visual perception. Initial functionality testing, which compared Daltonis-generated red-green CVD images with reference images known to represent red-green CVD, confirmed that the simulation could reproduce expected red-green CVD color transformations. However, more rigorous evaluation was required to determine the accuracy and validity of the Daltonis simulation. To address this need, an IRB-sanctioned study was conducted to investigate two primary objectives:

1. The simulation's ability to successfully alter the color of an image, and
2. The simulation's ability to accurately model the visual experience of a person with red-green anomalous trichromacy.

Within the study, individuals that genetically have full-spectrum color vision remained designated as "trichromats". Participants with inherent, genetically caused red-green CVD were classified as having "genetic CVD." Trichromats who viewed imagery processed through the Daltonis simulation – making the colors appear as they would to someone with red-green CVD – were classified as having "simulated CVD." Overall, this study aimed to collect data for a comparative analysis of the color differentiation ability between individuals with genetic CVD and

those with simulated CVD. This analysis served as the basis to validate the accuracy of the Daltonis.

3.3.1. Pallor-40: Custom Hue Arrangement Test

Although many CVD diagnostic tools exist, as discussed in [Section 2.3.5](#), they do not provide quantitative data measurements of a participant's color perception suitable for analysis. To validate Daltonis, such measurements were needed to compare performance between participants with genetic CVD and simulated CVD. While the Ishihara test design is useful for rapid preliminary screening for red-green CVD, arrangement tests offer a more detailed assessment of fine hue discrimination. With the goal of assessing subtle differences in color recognition across participant groups, an arrangement test, which tests color differentiation ability, was determined to be the most appropriate method for data collection that represented an individual's color perception.

Daltonis operates entirely within a digital environment, so the arrangement test needed to be implemented and administrable on a computer. Ideally, the FM-100 hue test would be used, as it is one of the most reliable tests available for assessing color discrimination ability, or an adaptation of it. However, this was not feasible for several reasons. First, the specific colors and design details of the FM-100 test are proprietary, and purchasing the physical test is expensive, costing around \$800. With the limited funding, neither the test itself nor the specifications required to reproduce it were accessible. Additionally, existing free online versions of the test, or adaptations of it, did not support integration with Daltonis, meaning the colors could not be modified. The ability to perform color modification was essential for testing a trichromat's color differentiation ability under simulated CVD conditions. Also, online tests provide limited data output, restricting the ability to conduct detailed performance analysis. These limitations necessitated the development of a custom digital hue arrangement test, called Pallor-40, that used colors transformed by the Daltonis simulation. The Pallor-40 hue test operates through a Graphical User Interface (GUI) to facilitate participant interaction and data collection, and it produces scoring metrics suitable for the comparative analysis central to validating the accuracy of Daltonis.

Hue Test Color Selection. The first step in designing the custom hue arrangement test, called Pallor-40, was selecting a set of colors spanning the full hue spectrum to assess participants' ability to distinguish subtle differences across the entire visible range. These colors were then later processed through the simulation to replicate the perceptual effects that different types and severities of colorblindness have on color appearance. The Munsell color system was used for selecting these colors, as it represents color in a three-dimensional cylindrical space defined by the three independent properties: hue, chroma, and value. Figure 32 illustrates the structure of the Munsell system, showing the ranges and visual changes that occur as each variable – hue, chroma, and value – are altered. Figure 33 provides a more extensive three-dimensional representation of how the many colors within the Munsell system are organized throughout the color space according to these defining variables. Hue arrangement tests, such as FM-100 hue and D15, use the Munsell system to select colors, keeping value and chroma constant while allowing hue to vary; the same approach was used with Pallor-40. This design allows for assessing an individual's ability to isolate and arrange subtle differences between colors spanning the full range of visible hues (Farnsworth–Munsell 100 hue test, 2025). Typically, hue arrangement tests select midrange values of about 5 or 6 for both value and chroma for optimal hue discrimination. To create a palette – a set of colors – that covers the full visible hue spectrum, the hue for each color in the set is determined by sampling at equal intervals along the hue dimension. The number of samples taken determines both the total number of colors in the palette and the degree of similarity between adjacent hues; a larger palette contains more colors, so there is a smaller degree of difference between the colors, increasing the difficulty for any individual to differentiate between them, regardless of their color vision type.

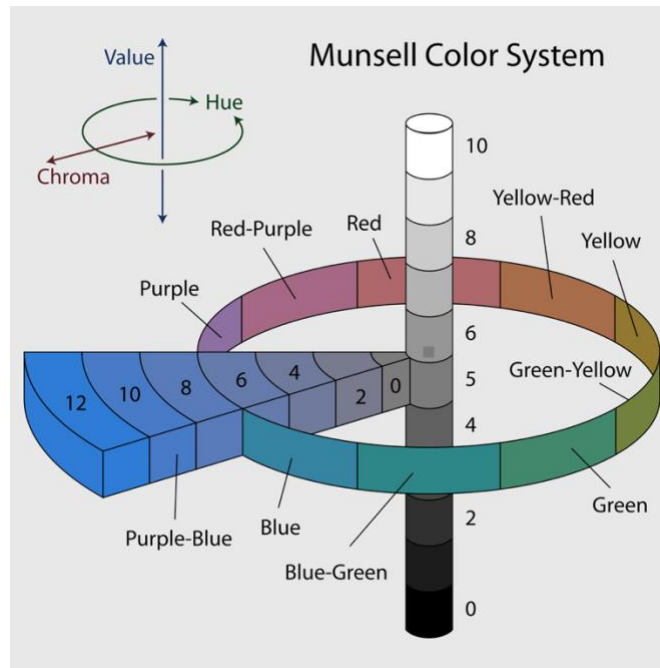


Figure 32. Cylindrical structure of the Munsell color system showing the ranges and visual changes that occur with variations in hue, chroma, and value (Munsell color system, 2025).

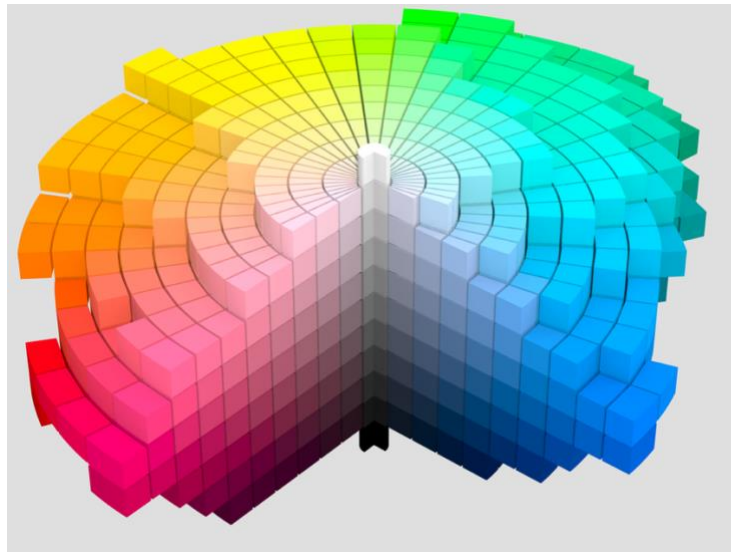


Figure 33. Three-dimensional representation of the Munsell color system (1943 renovations), illustrating how colors are organized within the color space according to hue, chroma, and value (Munsell color system, 2025).

For the Pallor-40 test, forty Munsell colors were first selected to cover the full hue spectrum. Consistent with standard hue arrangement test designs, a value of 6 and chroma of 6 were chosen to optimize visibility. The Munsell hue dimension was divided among forty equally spaced hue

samples, producing forty distinct colors: four fixed reference block colors and thirty-six movable block colors for the arrangement test. Figure 34 shows all forty hue identifiers that were selected. These colors were converted into hexadecimal (hex) codes using the Munsell-to-Hex translator from *Encycolorpedia*, producing a dataset suitable for use in the arrangement test and readable by the Daltonis simulation to generate CVD-altered versions of the standard color set (Encycolorpedia, n.d.). The human study that Pallor-40 was designed for, emphasizes comparative trend analysis rather than precise data point analysis, forty color samples – compared to the FM-100 hue test’s eighty-four or D15 test’s fifteen – were deemed sufficient to support meaningful comparisons between the study’s two populations: trichromats who viewed the Daltonis CVD-altered colors and those with genetic CVD that viewed the standard colors.

Figure 34. Hue identifiers for the forty colors selected from the Munsell color system for the custom hue arrangement test. The figure shows the hue positions across the spectrum; value and chroma were standardized to 6 for the custom test but may not be accurately represented in this figure (Clamp, 2023).

Integrating Daltonis. To integrate the Daltonis simulation into the study – using Pallor-40 to evaluate its accuracy in replicating colorblindness – the forty selected Munsell colors were converted into simulated CVD versions so the arrangement test could be run under different color-vision conditions. Each hex-coded color was converted into a single-pixel RGB image, processed through Daltonis with the specified CVD type and severity, outputted as a CVD-altered pixel, and then converted back into a hex value. This process was used to produce forty-color datasets that represent how the test colors would appear to an individual with the specified form of the simulated colorblindness. Pallor-40 can load either the standard or CVD-simulated datasets (specified using the $\Delta\lambda_L$ and $\Delta\lambda_M$ Daltonis spectral shift parameters), allowing participants to perform the same arrangement task while effectively viewing the colors through the applied CVD model.

Graphical User Interface. Using either the original hex-coded 40-color dataset or a version modified by the simulation to replicate the effects of a specific type and severity of color vision deficiency, Pallor-40 displays the colors on a GUI. Figure 35 shows the GUI study participants interacted with. The two outermost separated columns on the left and right serve as the eight fixed reference end blocks, composed of four distinct colors. The rows between these end blocks contain the thirty-six movable colors that participants were tasked with arranging. Participants could swap any two colors within a row, excluding the fixed end blocks with the goal of arranging the colors into a sequential hue progression across each row, guided by the end block colors; Figure 36 illustrates the correctly ordered arrangement corresponding to a perfect score. This straightforward interface provided an intuitive and user-friendly method for collecting data on individual's ability to distinguish between similar colors.

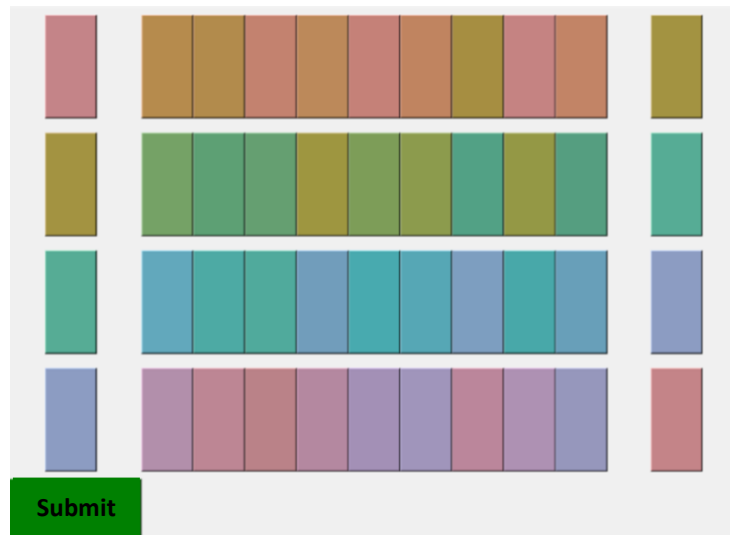


Figure 35. Initial view of the Pallor-40 graphical user interface. The 40 movable color blocks – drawn from one of the test’s predefined color datasets – are randomly arranged within their rows, while the leftmost and rightmost columns display the fixed reference end blocks.

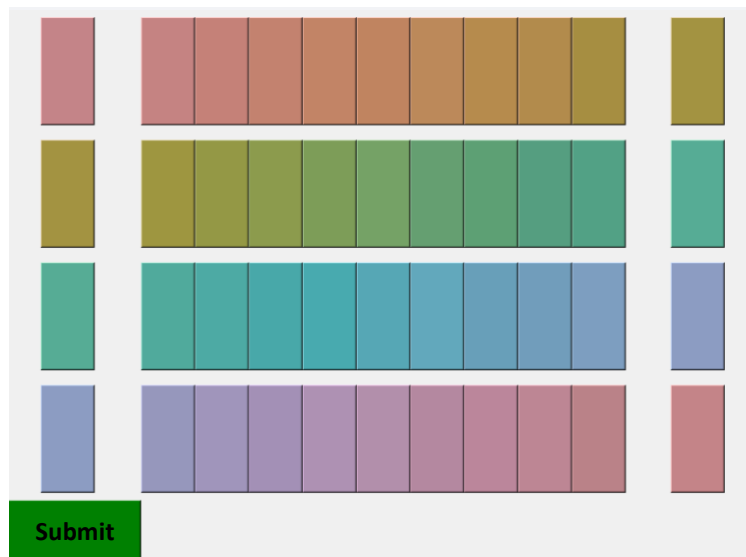


Figure 36. Correct (adjusted score of 0) arrangement of the Pallor-40 color blocks. All 36 movable colors are ordered in proper sequential hue progression within each row, guided by the fixed reference end blocks.

Scoring Results. Each color block in Pallor-40 was assigned a fixed index based on its position in the true sequential hue order taken directly from the Munsell color set before any shuffling occurred. These indices represent the correct ordering of the colors in hue space and serve as the scoring reference. The movable blocks were then randomly scrambled for presentation to the participant.

After a participant rearranged the color blocks and submitted their final layout, placement error was calculated for each movable block by summing the absolute differences between that block's index and the indices of its two neighboring color blocks in the participant's arrangement. The individual errors across all rows were summed to produce a total Raw Error Score (RES). Since each correctly placed block always differs by at least one index value from each of its two neighbors, a minimum error of 2 is unavoidable even in a perfect sequence. Therefore, the RES is then normalized by subtracting this baseline value across all movable blocks, and the result is reported as the adjusted score. This adjustment ensures that an adjusted score of 0 corresponds to a perfectly ordered hue sequence, with larger values indicating greater deviation from the correct chromatic progression.

To clarify the scoring process, the following example in Table 2 presents a single row with eight color blocks, showing how placement error is derived from a participant's arrangement relative to the correct hue sequence, as well as the process to calculate the Raw Error Score and adjusted score:

Correct Arrangement Assigned indices	1 (end cap)	2	3	4	5	6	7	8 (end cap)
Original Arrangement Random	1	7	3	6	5	2	4	8
Participant's Arrangement	1	3	2	4	7	5	6	8
Placement Error		3	3	5	5	3	3	
Deriving Placement Error Sum of differences of adjacent cap index values		(2+1)	(1+2)	(2+3)	(3+2)	(2+1)	(1+2)	

$$\text{Raw Error Score (RES)} = 3 + 3 + 5 + 5 + 3 + 3 = 22$$

$$\begin{aligned} \text{Adjusted Score} &= \text{RES} - ((\text{caps_per_row} - \text{num_end_caps}) * \text{num_rows} * \text{neighbors_per_cap}) \\ &= 22 - ((8 - 2) * 1 * 2) \\ &= 10 \end{aligned}$$

Table 2. Example of the Pallor-40 scoring procedures applied to a single row with eight color blocks (note Pallor-40 has four rows with ten color blocks each). The table shows the correct hue order (when indices are assigned), the randomized initial arrangement presented to a study participant, the participant's final arrangement, the resulting placement errors for each block, and the placement error derivation process. Also shown is the process to calculate the Raw Error Score (RES) from the individual placement errors and the normalization of the RES to produce the adjusted score.

Altogether, the Munsell color selection, Daltonis integration, GUI, and scoring mechanism were essential components in constructing Pallor-40 to provide a simple tool for quantitative assessment of hue discrimination in the study.

3.3.2. Study Procedure

To evaluate the Daltonis simulation's ability to accurately model red-green colorblindness. To ensure reliable data, participant selection included a few specific restrictions. Individuals with eye diseases, tritanomalous, or total blindness were excluded, as they would not have been able to perform the study's Pallor-40 arrangement test accurately. No constraints were placed on sex, age, type of colorblindness, or other non-vision-related characteristics. Additionally, it was imperative to have an approximately equal number of participants with trichromatic color vision and red-green colorblindness to ensure roughly equal amounts of data collected from each group for comparative analysis. Although participants with all types of CVD were eligible, those with red-green colorblindness were especially sought out as Daltonis is designed to simulate this visual condition. Within the study, individuals that genetically have full-spectrum color vision remained designated as "trichromats". Participants with inherent, genetically caused red-green CVD were classified as having "genetic CVD." Trichromats who viewed imagery processed through the Daltonis simulation – making the colors appear as they would to someone with red-green CVD – were classified as having "simulated CVD." Recruitment was conducted through flyers disseminated around the University of Maryland campus, social media outreach, and word-of-mouth. Participant eligibility was confirmed through a preliminary screening survey administered prior to enrollment in the study.

All testing was conducted on the same computer, as Pallor-40 and the Ishihara Plate test are computer-based tests. The Ishihara test was used for preliminary screening of CVD because of its simple design and proven effectiveness in classifying participants as either trichromats or colorblind. This screening process determined the subsequent steps for each participant in the study. Upon completing the Ishihara test, each participant received a designation of either trichromatic color vision or one of two CVD classifications: deuteranomalous or protanomalous.

After receiving a designation, participants were instructed to complete several predetermined rounds of the Pallor-40 hue test. In each round, the 40 hues are arranged in sequential order across each row, aiming to produce a final arrangement matching the correct sequence illustrated in Figure 36. The test was conducted in a dark room with no artificial or ambient lighting to reduce screen reflections and allow participants to distinguish the intentionally subtle differences between block colors as clearly as possible. Participants were encouraged to finish only when they felt confident that the color order was correct.

Participants with trichromatic color vision completed the Pallor-40 test five times, each using one of the test's pre-created Munsell color sets (see [Section 3.3.1](#) for details on color selection and color dataset creation). One set was the standard color set, used to assess baseline performance with unaltered trichromatic color vision, while the others had shifts applied via the Daltonis simulation to represent varying types and severities of red-green CVD. The five color datasets, and their corresponding simulated color vision conditions, were: $\Delta\lambda_L = \Delta\lambda_M = 0$ nm spectral shift (no applied CVD), $\Delta\lambda_M = -10$ nm shift (mild protan), $\Delta\lambda_M = -15$ nm shift (moderate protan), $\Delta\lambda_L = +10$ nm shift (mild deutan), and $\Delta\lambda_L = +15$ nm shift (moderate deutan). Each participant's scores were recorded in a table unassociated with any personal identifiable information. Deuteranomalous and protanomalous identified participants were only required to complete the Pallor-40 test once, using the unmodified standard color set. This was done to establish reference data showing how individuals with deuteranomalous or protanomalous red-green color vision deficiency are expected to perform on the standard test.

The Pallor-40 performance scores were recorded in a de-identified manner to maintain participant privacy, and participants were given the opportunity to discuss the study and ask questions at any point. Upon completion, participants were compensated with a \$10 Amazon gift card.

3.4. Analysis of Daltonis Evaluation Study

The study procedure described in [Section 3.3.2](#) was performed to collect data addressing two primary questions:

1. Is Daltonis capable of simulating a measurable effect of red-green anomalous trichromacy?
2. If Daltonis can simulate this effect, does the simulation accurately represent how genetic protanomaly or deuteranomaly affect an individual's vision?

The observed study procedure involved administering the Pallor-40 hue arrangement test and recording a performance metric, the adjusted score, for each round the test was conducted under different experimental conditions. Score values were collected from two populations, which were distinguished using the Ishihara test: (1) participants with trichromatic vision and (2) participants with either protanomaly or deuteranomaly. Participants without CVD completed five rounds of the Pallor-40 test to evaluate baseline hue arrangement performance without Daltonis applied (no simulated CVD) and performance with Daltonis applied for four different simulated CVD conditions. Score values were also collected from participants in the colorblind group after performing the Pallor-40 test without Daltonis applied to establish reference performance values representing how individuals with these color vision deficiencies perform on the standard test.

To address Question 1, several paired t-tests were conducted to evaluate whether Daltonis produces a statistically detectable change in Pallor-40 scores – and thus color perception – for trichromat participants. Each test included all participants who completed both the baseline round (no simulated CVD) and the specific simulated CVD round being analyzed. The pairings within each test were defined between each participant's baseline score and their score from one of the four simulated rounds: Deuteranomaly 10 nm, Deuteranomaly 15 nm, Protanomaly 10 nm, or Protanomaly 15 nm. The number of participants varied between tests depending on which rounds they had been administered. Some participants did not complete the two 15 nm shift rounds as the protocol was expanded during the study to include the two additional Pallor-40 testing rounds for trichromats, allowing for a wider assessment of Daltonis's ability to simulate CVD in a range of severities. The null and alternative hypotheses for these tests were defined as follows:

- **Null Hypothesis:** The application of Daltonis does not produce a change in Pallor-40 scores for trichromat participants and therefore does not induce any effect of red-green anomalous trichromacy.
- **Alternative Hypothesis:** The application of Daltonis produces a statistically significant change in Pallor-40 scores for trichromat participants and therefore induces some effect of red-green anomalous trichromacy.

Paired t-tests require the differences between paired observations to be normally distributed. The Shapiro-Wilk test was conducted to assess whether this assumption held true for the data collected. The results indicated no deviation from normality, satisfying this condition. Additionally, prior to performing statistical computations, several decisions were made regarding the selection of paired t-test parameters:

Inclusion and Exclusion Criteria. In addition to excluding participants who lacked data for a testing round, further requirements were defined for the trichromat population. Only participants who obtained an adjusted score of 0 in the baseline round (no simulated CVD) were included in data collection for statistical analysis. A baseline score of 0 corresponds to a perfectly ordered Pallor-40 hue sequence and is intended to represent an individual without a color vision deficiency. This assumption was considered reasonable because the Pallor-40 test uses only 40 distinct hues, meaning the perceptual difference between adjacent colors is larger than in other, more traditional tests with a greater number of hues, such as the FM-100 hue test. Consequently, it was reasoned that individuals without CVD should be able to reliably distinguish between and correctly arrange the Pallor-40 colors to get a perfect score of 0, unlike in the tests with finer hue gradations. This expectation further limited the overall trichromat population size; the final sample size values for each paired t-test can be seen in Table 3.

Power Calculations. The significance level is the threshold probability of rejecting a null hypothesis. Power is the probability of rejecting the null hypothesis when the alternative hypothesis is true. Following standard practice, a significance level of 0.05 and a power value of 0.8 were chosen. For each paired t-test pairing, the standard deviation is calculated from the

differences between paired scores for each participant. Specifically, for a given simulated round, each participant's baseline score is subtracted from their score in the simulated round to obtain the difference. The standard deviation is then computed from these differences across all participants included in that test. For example, to calculate the standard deviation of differences for the paired t-test comparing the baseline scores to the deuteranomaly 10 nm scores, the difference for each participant was calculated, and the standard deviation of those differences were used in the paired t-test.

Under these constraints, the final parameter values for each paired t-test can be seen listed in Table 3.

Paired T-Tests Setup				
Paired Comparison Condition	Baseline vs. Deuteranomaly 10 nm	Baseline vs. Deuteranomaly 15 nm	Baseline vs. Protanomaly 10 nm	Baseline vs. Protanomaly 15 nm
Significance Level	0.05	0.05	0.05	0.05
Power	0.8	0.8	0.8	0.8
Sample Size	15	11	15	11
Standard Deviation of Differences	5.164	8.912	4.240	4.763
Minimum Detectable Difference	3.5	8.349	3.298	4.462

Table 3. Paired t-test parameters, based on inclusion criteria, including sample sizes, significance level, statistical power, standard deviation of differences, and minimal detectable differences for each baseline versus simulated CVD comparison.

3.4.1. Experiment Study Results

Although 21 participants were classified as having trichromatic color vision according to the Ishihara test, only 15 trichromat participants met the inclusion criteria to be considered in the paired t-test analysis of the two CVD conditions defined by 10 nm spectral shifts, and 11 participants met the criteria for both the paired t-test analyses of the 15 nm spectral shift conditions. Figures 37 – 40 display histograms of the differences in the adjusted score results between each simulated CVD condition and the baseline no-CVD condition. Because all included participants had baseline scores of 0, these histograms are effectively equivalent to the distributions of adjusted

scores for each simulated CVD condition. From each paired t-test, the minimal detectable difference was calculated using the specified test parameters from Table 3. The minimal detectable difference represents the smallest difference between paired observations that the study can detect as statistically significant. Additionally for each test, the standard deviation of differences and the mean difference (d) were computed from the differences between matched participant scores.

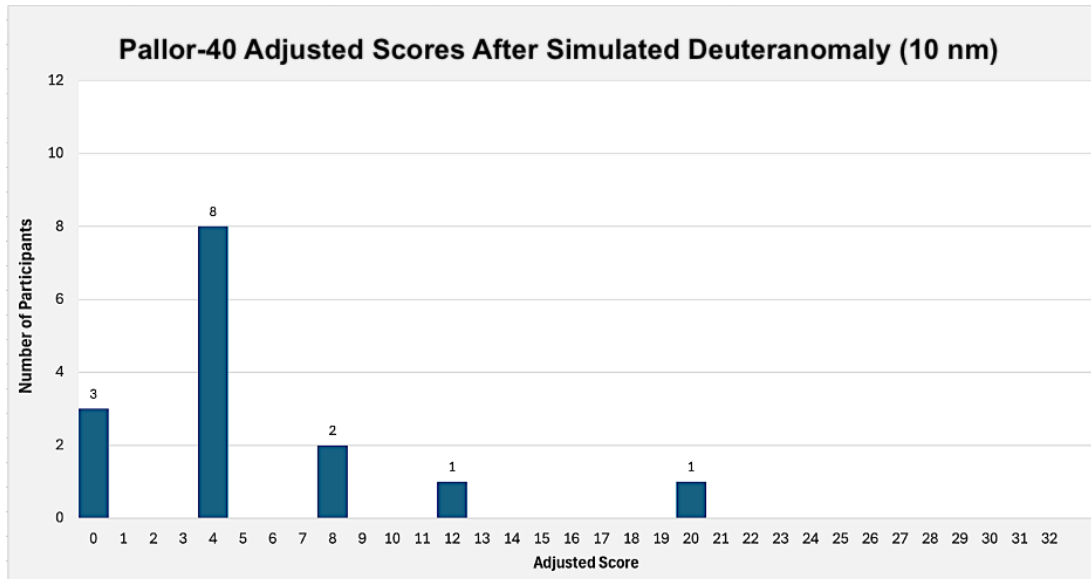


Figure 37. Distribution of adjusted score differences between baseline (no simulated CVD) and Deuteranomaly (10 nm) conditions for trichromatic participants.

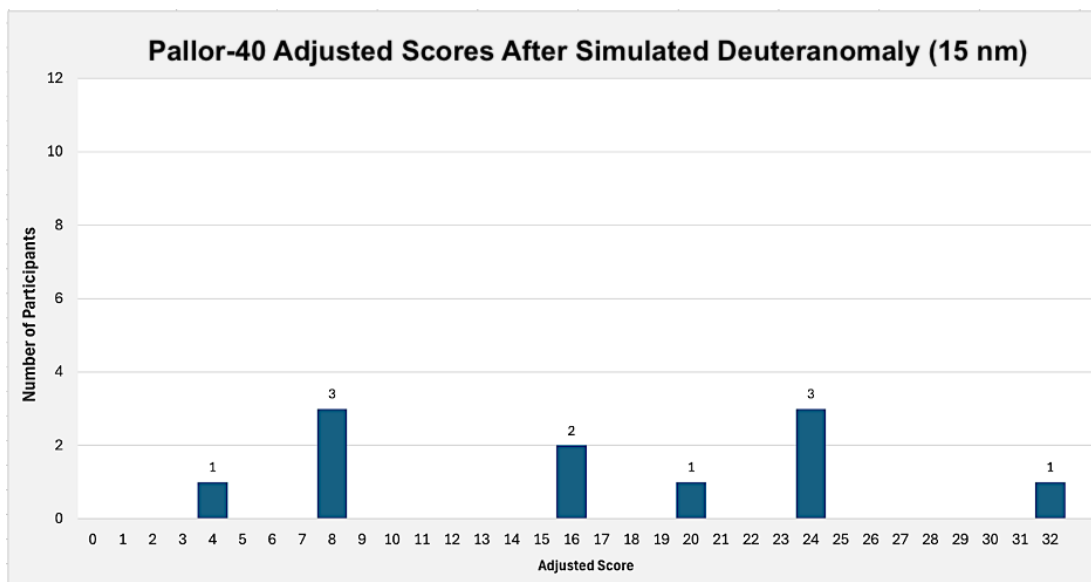


Figure 38. Distribution of adjusted score differences between baseline (no simulated CVD) and Deuteranomaly (15 nm) conditions for trichromatic participants.

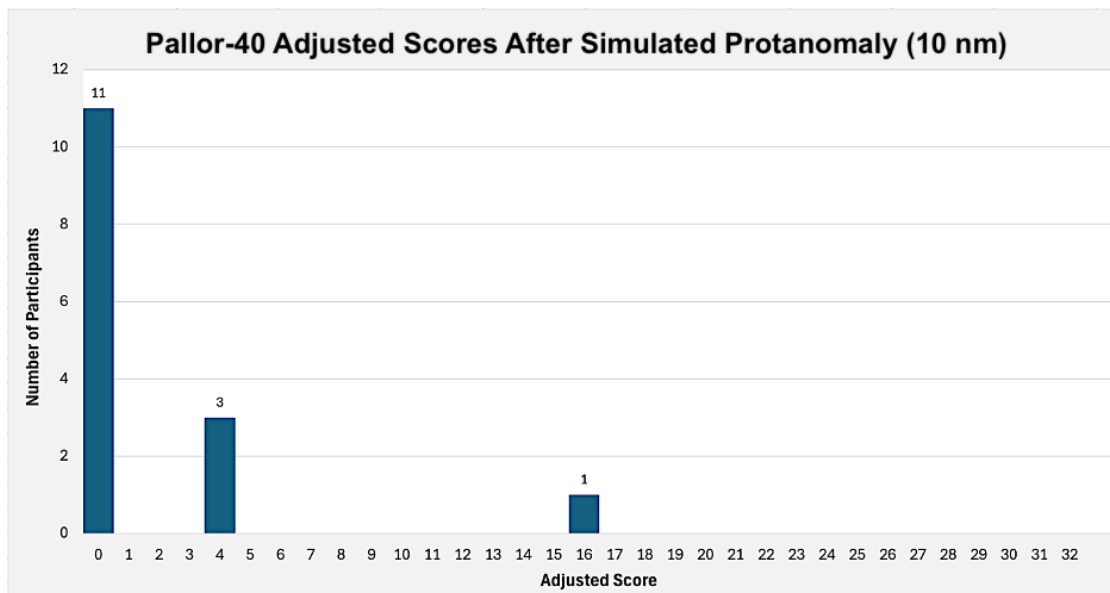


Figure 39. Distribution of adjusted score differences between baseline (no simulated CVD) and Protanomaly (10 nm) conditions for trichromatic participants.

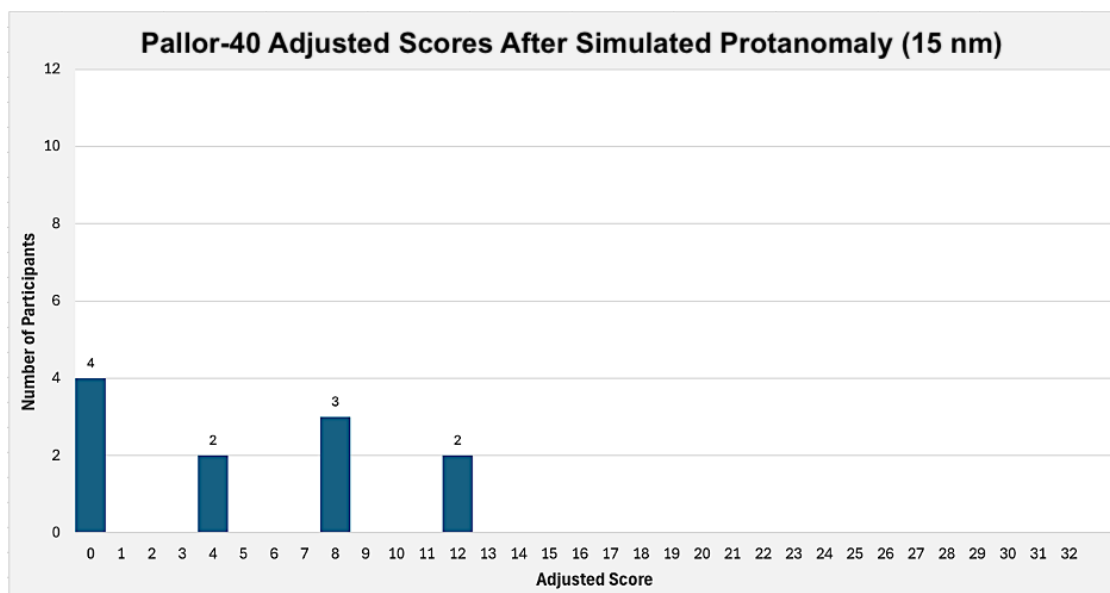


Figure 40. Distribution of adjusted score differences between baseline (no simulated CVD) and Protanomaly (15 nm) conditions for trichromatic participants.

Table 4 displays the adjusted score results of participants classified by the Ishihara test as having either deutan or protan colorblindness. These individuals performed the Pallor-40 test once using the standard (no simulated CVD) color dataset. Since the colorblind population consisted of only four participants, all of whom were deutans, the sample size was deemed too small to support

meaningful statistical analysis as a performance reference for either deutan or protan populations. Consequently, Team COLOR could not reliably answer Question 2: If Daltonis can simulate the effects of red-green anomalous trichromacy, how accurately does that simulation match the color perception of individuals with those genetic conditions? However, Question 1 – Is Daltonis capable of inducing a measurable effect consistent with red-green anomalous trichromacy? – remained achievable with the collected data.

	Ishihara Results	No CVD simulated
Participant	(Deutan or Protan)	$\Delta\lambda_L = 0 \text{ nm}, \Delta\lambda_M = 0 \text{ nm}$
1	Deutan	20
2	Deutan	60
3	Deutan	12
4	Deutan	12

Table 4. Pallor-40 adjusted scores for participants classified as having deutan or protan CVD based on the Ishihara test. Pallor-40 test was conducted using the standard color dataset (no simulated CVD).

Visually, Figures 37 – 40 reflect some correspondence to the expected trend. The Pallor-40 tests using a simulated CVD color dataset show fewer participants with adjusted scores of 0 compared to the baseline round, in which all participants, by requirement, scored 0. Additionally, comparing the results of the 15 nm CVD conditions to their corresponding 10 nm forms shows that even fewer participants scored 0 under the more severe 15 nm spectral shift conditions. Also, adjusted scores under these conditions generally shifted to higher values compared to the 10 nm conditions. Logically, these patterns correspond with what would be expected from individuals with these types of CVD taking the standard Pallor-40 test. Participants with more severe forms of anomalous trichromacy (larger spectral shifts) would generally perform worse at correctly sorting the baseline color dataset, resulting in higher adjusted score values.

3.4.2. Statistical Analysis

To determine whether the visually observable data trends were statistically significant and to address Question 1, paired t-tests were performed on the data collected from the trichromat population, producing a p-value for each comparison (see Table 5). These p-values were compared

against the pre-established significance level of 0.05. A p-value falling below this threshold was considered statistically significant, indicating that the observed differences between the simulated CVD and unchanged trichromatic conditions were unlikely to have occurred by chance under the null hypothesis. Therefore, the occurrence of statistical significance would suggest that Daltonis can induce an effect consistent with red-green anomalous trichromacy.

Paired Comparison Condition	Baseline vs. Deuteranomaly 10 nm	Baseline vs. Deuteranomaly 15 nm	Baseline vs. Protanomaly 10 nm	Baseline vs. Protanomaly 15 nm
Significance Level (α)	0.05	0.05	0.05	0.05
Sample Size	15	11	15	11
Standard Deviation of Differences	5.164	8.912	4.24	4.763
Mean Difference (d)	5.333	16.727	1.867	5.091
p-value	0.000658	0.000049	0.055144	0.002658
p-value < α	Reject Null	Reject Null	Fail to Reject Null	Reject Null

Table 5. Results of paired t-tests comparing baseline (no simulated CVD) scores with simulated CVD conditions for trichromatic participants. Bottom row “Reject Null” values indicate statistical significance .

As shown by the computed p-values in Table 5, three of the four paired t-tests indicated a statistically significant effect. For the protanomaly 10 nm spectral shift condition, the null hypothesis could not be rejected. Comparing the mean difference ($d = 1.867$) to the previously calculated minimal detectable difference (3.298) for this condition, showed that d fell below this threshold. These findings indicate that there is insufficient evidence to reject the null hypothesis, suggesting more extensive testing with a larger trichromat population is required to form stronger conclusions regarding Daltonis’ ability to simulate mild protanomaly. For the other simulated conditions – mild and severe deuteranomaly, and severe protanomaly – statistically significant results were found, suggesting that Daltonis can simulate measurable effects of these conditions.

A larger population would also help reduce the influence of natural variability. One issue encountered during the study was that some participants’ scores improved with successive rounds, likely due to increased familiarity with the testing procedure and expectations of the task. This effect was partially mitigated by altering the order in which each trichromatic participant completed the Pallor-40 tests. However, this approach did not completely eliminate potential

learning effects in the trichromat results, especially in a small sample set, nor did it address similar effects within the CVD participant group, who completed only a single Pallor-40 test.

Overall, these findings provide strong evidence supporting Daltonis' ability to simulate red-green anomalous trichromacy. While the results for the protanomaly 10 nm condition were not statistically significant, they do not necessarily contradict this conclusion but instead suggest that additional testing is needed to draw a stronger conclusion regarding the simulation of mild protanomaly. Expanding the participant pool and performing Pallor-40 testing on a wider range of CVD conditions with more spectral shift variations would enable a more robust statistical analysis and allow the study to more definitively address analytical Questions 1 and 2. Enlarging the CVD population size and ensuring a more balanced representation of deutan and protan individuals would further support evaluation of how accurately Daltonis simulates the full range of red-green anomalous trichromacy. Despite the limitations of this study, these results demonstrate that Daltonis is capable of simulating an effect consistent with, at the very least, mild and severe deuteranomaly as well as severe protanomaly. Overall, this study establishes a procedural framework for the evaluation of Daltonis's ability to simulate CVD using Pallor-40 testing, providing a strong foundation for future work aimed at more rigorously assessing the accuracy, functionality, and application of Daltonis. Additionally, the statistically significant findings validate the methodological approach implemented in the design of Daltonis. They also demonstrate that this research and the construction of Daltonis contribute to a clearer understanding of how anomalous trichromacy can be modeled mathematically, physiologically, and visually.

3.5. Future Directions and Lessons Learned

While conducting this study, Team COLOR became aware of some limitations that impacted the trajectory of this research. These limitations were primarily caused by a lack of preexisting literature and data, or time and resource constraints, which impeded the achievement of some of the research objectives. Still, many avenues of exploration exist to further the study of CVD,

relying on the development of Daltonis. Below, a select few of the future applications and directions are examined.

3.5.1. ICVDS: Daltonis Adaptation for CVD Corrective Augmented Reality

In addition to the Daltonis experimental evaluation study outlined in [Section 3.3.2](#), an exploratory adjacent procedure was conducted to investigate the effects of simulating the inverse of CVD. Rather than focusing solely on mitigating the visual limitations of CVD, this approach seeks to recognize the individual's unique physiological variation to model and optimize alternative pathways for color differentiation. Daltonis modifies an image to replicate how it would appear to an individual with a specific form of red-green anomalous trichromacy, allowing a trichromatic viewer to experience the perceptual effects of that color vision deficiency. In contrast, this adaptation of Daltonis – referred to as the inverse CVD simulation (ICVDS) – assumes the viewer has a specific type of red-green anomalous trichromacy. It applies a transformation to the image designed to mathematically offset the individual's cone-response overlap. By simulating the additive application of light to shift wavelengths within a virtual environment, ICVDS provides a targeted, pre-processed visual field that maximizes color discriminability for the affected individual. This is achieved by using the inverse of the CVD transformation ($T_{NS}^{-1} * T_S$) shown in Figure 31.

Any participant classified, using the Ishihara test, as having either protan or deutan CVD in the original study was asked, in addition to completing their single round of Pallor-40 hue test, to identify a series of custom Ishihara test plates designed using the ICVDS. This inverse simulation is based on the premise that individuals with CVD perceive color through the following process: (1) light from an image is projected onto the retina, (2) anomalous photoreceptors – corresponding to the individual's specific type of CVD – produce anomalous spectral cone responses, and (3) the resulting cone response signals are processed by the brain, producing an CVD-altered perception of the image. From a mathematical perspective, simulating this involves transforming the RGB values of each image pixel as shown in Eq. 13,

$$\begin{bmatrix} r_{cvd} \\ g_{cvd} \\ b_{cvd} \end{bmatrix} = G_{cvd} * \begin{bmatrix} r \\ g \\ b \end{bmatrix} \quad (13)$$

where the vector $[r; g; b]$ represents the original RGB values of a pixel and $[r_{cvd}; g_{cvd}; b_{cvd}]$ denotes the transformed RGB vector as perceived by an individual with CVD. G_{cvd} represents the transformation induced by genetic CVD, modeling the perceptual distortion applied to an image pixel.

The ICVDS builds on the Daltonis simulation framework as a proposed adaptation for future applications in augmented reality environments. This adaptation applies an inverse CVD transformation to the image prior to observation by an individual with CVD, effectively simulating the effect of targeted light manipulation. Referring back to the general color processing pipeline, the resulting perceptual sequence for a CVD observer becomes: (1) the image is modified using the inverse of the Daltonis CVD transformation matrix, (2) the modified image is projected onto the retina, (3) the anomalous photoreceptors alter the incoming spectral signals in a way that produces cone responses similar to those that would be generated in a trichromatic observer viewing the unmodified image, and (4) the resulting cone response signals are processed by the brain, producing a more normalized perceptual experience that closely aligns with that of a trichromatic observer viewing the original image.

The algorithmic interpretation of the ICVDS for color correction expressed as:

$$\begin{bmatrix} r_{seen} \\ g_{seen} \\ b_{seen} \end{bmatrix} = G_{cvd} * G_{cvd}^{-1} \begin{bmatrix} r \\ g \\ b \end{bmatrix} \quad (14)$$

where G_{cvd}^{-1} represents the inverse CVD transformation matrix equivalent to $(T_{NS}^{-1} * T_S)^{-1}$. The expression $T_{NS}^{-1} * T_S$ denotes Daltonis's simulated CVD transformation defined in Figure 31. Eq. 14 simplifies to:

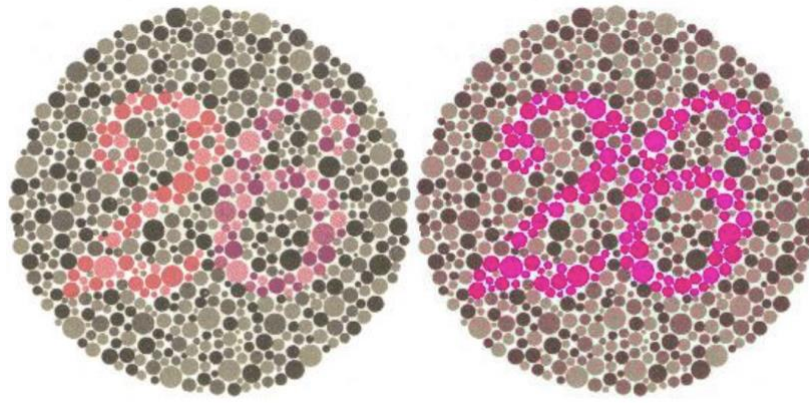
$$\begin{bmatrix} r_{seen} \\ g_{seen} \\ b_{seen} \end{bmatrix} = \begin{bmatrix} r \\ g \\ b \end{bmatrix} \quad (15)$$

Therefore, Eqs. 14 and 15 demonstrate that by preemptively applying an inverse CVD transformation to an image, the genetically induced CVD transformation is approximately

cancelled. As a result, the resulting RGB values for each pixel perceived by an anomalous trichromat (as well as the corresponding LMS and OCS space values) closely mirror those perceived by a trichromatic observer viewing the original unmodified image. Ideally, this process corresponds to introducing additive light in physical (non-digital) environment, where the added light would act in a manner to the inverse CVD matrix, G_{cva}^{-1} .

3.5.1.1. ICVDS Evaluation: Study Procedure

As mentioned, to test the effectiveness of the ICVDS, in complement to the Daltonis experimental evaluation study procedure, participants in the CVD group were sequentially presented with a constructed set of ICVDS-modified Ishihara test plates with varying intensity levels. These intensity levels refer to the strength of the inverse CVD transformation applied to each plate, with higher intensity corresponding to stronger compensation for more severe cases of red-green anomalous trichromacy. Two separate plate sets were generated: one targeting protan CVD and the other targeting deutan CVD. Participants were assigned to the corresponding set based on their Ishihara test classification (protan or deutan). The original Ishihara plates were selected from those designed to be unidentifiable to individuals with red-green CVD prior to modification. Figure 41 shows an example of an ICVDS-treated plate. The left plate is the original Ishihara plate, which is difficult for individuals with red-green CVD to identify, while the right plate shows the modified version that is part of the deutan plate set and has a 14 nm green shift ($\Delta\lambda_M = 10$ nm). To create each set of plates, an Ishihara plate generator was used to create 10 different Ishihara plates, each containing a different number (Boyle, 2025). Using the original, official Ishihara plates as reference, the generator's eye-dropper tool was used to modify plate colors while maintaining a consistent color palette, resulting in a set of ten Ishihara plate images with a resolution of 400x400 pixels.



Example of Treatment: G14

Figure 41. Example of an ICVDS treatment. Left: Standard Ishihara Plate of the number 26, with no modification applied. Right: Same plate as the left, but with a 14nm green shift (G14).

Participants viewed the modified plates in order of increasing intensity until the previously indistinguishable number on the plate became identifiable, indicating the compensation level at which the inverse transformation effectively counteracted the participant's color vision deficiency; the intensity level of the first identifiable plate was recorded for each participant. This identified plate corresponded to a specific protanomaly or deuteranomaly spectral shift associated with the participant's CVD profile. Using this individualized spectral shift, the ICVDS was applied to generate an inverse color dataset, which was then used in another administration of the Pallor-40 hue test.

Therefore, in this way, each participant's baseline performance was established with the first administered Pallor-40 test on the standard, unmodified color dataset. The ICVDS-modified Ishihara plates were then used to determine the compensation level required to overcome the effects of the participant's CVD. This compensation level corresponded to identifying the spectral shift value characteristic of the participant's genetic CVD condition. The shift value was then used by the ICVDS to produce an adjusted color dataset for a second Pallor-40 test, allowing the resulting adjusted score to be compared with the baseline adjusted score value. This procedure was developed to enable comparison-based evaluation of whether the ICVDS produced a measurable inverse CVD effect for each CVD participant.

3.5.1.2. ICVDS Evaluation: Study Results

Figure 42 shows the Pallor-40 hue test results for each participant, with baseline scores represented in blue and ICVDS-adjusted scores in red. This data was collected to support the assessment of the ICVDS's effect on colorblind individuals (protan/deutan). However, due to the limited sample size ($n = 4$), the study lacked sufficient statistical power to perform an inferential analysis and draw generalized conclusions regarding the efficacy of the ICVDS's performance in its application on the Pallor-40 hue test. Comparing the observations indicated that only one participant demonstrated a notable improvement in adjusted scores, while the remaining three study participants showed negligible variance in score value.

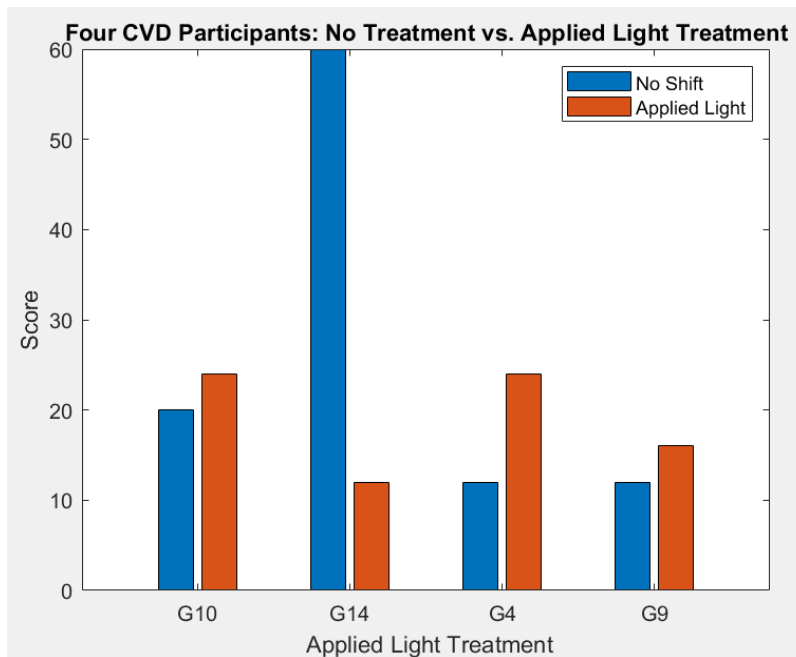


Figure 42. Pallor-40 hue test results for four colorblind participants. Blue bars represent baseline scores with no shift applied, and red bars represent scores after applying the minimum ICVDS shift each participant required to identify a sample Ishihara plate.

Furthermore, potential confirmation bias was identified as a concern, as repeated exposure to the same Ishihara plate modified at different intensity levels could allow participants to infer the plate's embedded number at lower intensity levels due to familiarity and predictability. To mitigate this effect, both hue intensity and the embedded number were varied across plates within each set.

However, all plates within a set maintained a consistent color palette to preserve experimental control.

With a larger participant cohort and these refined controls, future studies could apply paired t-tests or ANOVA to determine whether the ICVDS treatment produces statistically significant improvements in chromatic acuity. While the current results are limited, this research establishes a foundation for exploring how selective spectral modifications can enhance color differentiation in individuals with CVD. In particular, it supports further investigation into additive light as a potential physical mitigation strategy and the exploration of whether color perception can be improved through the introduction of targeted wavelength manipulation, based on an individual's CVD profile. Additionally, this framework highlights the potential for implementation in augmented reality environments, where selective spectral adjustments could provide individualized chromatic enhancements for users with anomalous trichromacy.

3.5.4. Additional Future Directions for Daltonis

One significant limitation was a lack of access to colorblind individuals interested in participating in the simulation assessment study. It was the express goal of Team COLOR to prove that Daltonis was able to create some colorblind effect on images viewed by standard trichromats. Furthermore, it was imperative that this visual effect was actually comparable to that of the average red-green color vision deficient observer. Due to a lack of participants from the red-green colorblind population, this team was unable to test if Daltonis simulate CVD conditions that accurately correspond to the color perceptions experienced by those with genetic CVD.

Another limitation of Daltonis is its inability to simulate tritanomaly. The focus on protanomalous and deuteranomalous users was driven by the high prevalence of red-green anomalous trichromacy. While Daltonis was not developed or tested for tritanomaly, the underlying methodology implemented in the construction of Daltonis could be extended to simulate blue-yellow CVD. With population of individuals with tritanomaly, a similar study could be conducted to validate Daltonis's ability to simulate tritanomalous vision, creating a more inclusive and accessible simulation.

As mentioned previously, Daltonis is intended to supplement technologies that treat and mitigate CVD. Its primary benefit comes from being able to provide quantitative feedback on how close to standard color vision a technology is able to make the vision of a CVD user. This feedback can be employed to make incremental improvements that are not exclusively founded on the subjective color vision experience of the users. To demonstrate this capability, Daltonis intended to simulate the thin-film lens designed as part of this research, to see if this type of lens could create a more color-standard image when given a color-altered image as input. With more resources and time, Daltonis could be expanded to simulate a vast array of technologies and used in the efficacy assessment of these products. Not only would this benefit color vision research, but it would also provide color blind individuals with an objective tool that could serve as a companion or aide in their color vision treatment journey.

3.6. Conclusion

The development of Daltonis was motivated by the need for a quantitative, adaptable tool to evaluate how variations in CVD affect perception. Such a tool is essential for assessing whether CVD interventions provide effective mitigation treatment. Two central questions guided this research:

1. How can the genetic effects of CVD be mathematically interpreted and modeled?
2. And, is it possible to link an individual's ability to discriminate colors to a quantifiable description of colorblindness?

To address these questions, Daltonis, a red-green anomalous trichromacy simulation, was created. Central to its development was the understanding that anomalous trichromacy affects vision at a cone response level, resulting in altered color perception after neural processing. In this way, the genetic effects of CVD can be mathematically represented as spectral shifts in the LMS color space, capturing the alterations CVD induces on cone responses. Daltonis uses these spectral shift values as a quantifiable metric to generate a range of red-green anomalous trichromacy conditions.

Following the development of Daltonis, a human study was conducted using a custom arrangement test to validate the simulation's ability to produce the effects of CVD in a digital environment. The results of the study demonstrated statistical significance, confirming that Daltonis can simulate mild deuteranomaly, severe deuteranomaly, and severe protanomaly. Repeating the procedure with larger populations of trichromats and red-green anomalous trichromats would allow for more definitive conclusions regarding Daltonis's accuracy across the whole range of red-green anomalous trichromacy conditions.

These findings reaffirm the physiological interpretations of anomalous trichromacy made in the design of Daltonis and indicate the potential for it to be further developed into a complete anomalous trichromacy simulation, inclusive of tritanomaly. Additionally, an adaptation of Daltonis was explored for CVD corrective augmented reality through inverse CVD simulation. This exploratory approach tested whether preemptively modifying visual input in a digital landscape and using an individual's measured CVD profile could enhance color differentiation for that individual. This work provides a foundation for personalized AR-based interventions for anomalous trichromats.

Therefore, Daltonis has shown to be a promising tool that can be extended beyond red-green anomalous trichromacy simulation to support testing of CVD mitigation interventions that rely on wavelength-selective manipulation, as well as exploration of innovative approaches to correcting the effects of anomalous trichromacy.

4. Design and Validation of a Thin-Film Interference Based Filter Model

4.1. Overview and Motivation

Existing designs for wearable optical solutions for red-green CVD, including notch filtering spectacles and contact lenses, face significant limitations. Red-green color vision deficiency arises from increased overlapping of the spectral sensitivities of the L and M photoreceptors, creating a narrow confusion region in which certain wavelengths cannot be easily distinguished. This confusion region is a narrowband spanning approximately 10 nm between 545 and 555 nm, causing difficulty for individuals with this condition to differentiate between reds and greens. To address this ambiguity, current designs rely on broad-spectrum filtering, which lacks the spectral precision required to isolate this narrow band. As a result, these approaches often cause excessive reductions in light transmission, impairing visual acuity, particularly in low-light conditions. These limitations highlight the need for an optical filter capable of precisely targeting a select range of wavelengths. This design could then be applied to selectively filter out the wavelength within the confusion region associated with red-green CVD to improve differentiation between red and green colors. To address this need, this research investigates thin-film interference as a targeted filtering approach for red-green CVD, in contrast to conventional broad-spectrum methods. Unlike traditional broad-spectrum filters, this proposed method selectively blocks only the wavelengths contributing to red-green confusion. By narrowing the filtered range, thin-film interference minimizes unnecessary light loss while providing a more precise and scientifically grounded approach for improving color discrimination. Accordingly, the objective of this research was to develop a filter concept that overcomes the limitations of existing designs, offering a practical and effective aid for individuals with red-green CVD.

4.2. Process and Design

The development of an effective thin-film optical filter requires careful consideration of both physical design principles and predictive modeling. The desired spectral response is achieved by systematically integrating material properties, multi-layer architectures, and optical interactions.

The following sections outline the computational and experimental approach used to translate these theoretical principles into a functional, high-performance filter design.

4.2.1. Thin-Film Interference in Red-Green CVD Filtering

Thin-film interference is an optimal approach due to its predictability, ease of development, and design flexibility (Hinczewski, Hinczewski, Tepehan, & Tepehan, 2005). Based on established fabrication methods, these filters are constructed using sol-gel coating techniques that alternate between a high refractive index material, Titanium Dioxide (TiO_2), and a low refractive index material, Silicone Dioxide (SiO_2). This alteration between high and low index materials ensures high reflectance by causing reflected waves from each layer to interfere constructively at the surface of the substrate. The optical response of the filter can be tuned by adjusting the number of layers, material type, and thickness of each thin film layer. A quarter-wavelength thickness for each thin-film layer serves as the foundation for effective thin-film filters, and is commonly used in longwave-pass filters, band stop filters, and laser mirrors (Technical Introduction to Thin-Film Filters, 2026). Additionally, sol-gels are adaptable for industry-scale mass production and offer a cost-effective manufacturing approach. Titanium dioxide and silicon dioxide were specifically selected for their chemical stability and resistance to corrosion, an important feature for use in an optical device (Hinczewski, Hinczewski, Tepehan, & Tepehan, 2005). A primary limitation of this approach is that high reflectance typically occurs only over a narrow wavelength range (about 540 – 580 nm), limiting effectiveness across varying types and severities of color vision deficiency beyond red-green CVD.

4.2.2. Theoretical Model for Thin-Film Filter Design

The theoretical model outlined by Hinczewski et al. calculates the total reflectance and transmission as a function of wavelength, based on parameters such as the thin-film layers' thickness, refractive index, and extinction coefficient of the chosen materials. The modeled filter consisted of coatings applied on both sides of the substrate. The reflectance and transmission coefficients for light passing through the coating layers are determined using the standard transfer

matrix method, ensuring that these coefficients depend on the thickness and extinction coefficient of each layer (Hinczewski, Hinczewski, Tepehan, & Tepehan, 2005). Further considerations were made to account for the reduction in intensity of light as it passes through the substrate, modeled as a function of the substrate's absorption coefficient and thickness. Additionally, reflectance and transmission were adjusted to account for this loss of intensity. As each layer is coated, the early layers of the design are subjected to more heat treatment, causing them to become thinner than the calculated design thickness. This occurs because the heat removes residuals, condenses the gel network, and reduces porosity, which in turn alters the refractive index and the extinction coefficient. To account for this densification of the material, the model introduces a densification factor, which compares the density of each layer to a single-layer sample (Hinczewski, Hinczewski, Tepehan, & Tepehan, 2005).

With these constraints in place, the remaining four free parameters are the sol-gel layer thicknesses and the densification factors of both the high index and low index materials. All other parameters are fixed based on measurements from a single layer reference sample. A Levenberg-Marquardt multivariate-regression algorithm is implemented to compute a non-linear least-squares fit of the experimental multilayer reflectance and transmission coefficient data. S- and P-polarization data sets are fitted simultaneously to adjust thickness and extract the refractive index dispersion for each layer in the stack (Hinczewski, Hinczewski, Tepehan, & Tepehan, 2005).

4.2.3. Idealized Spectra Model for Thin-Film Filter Design

The Hinczewski et al. model incorporates multiple physical effects, including double-sided multi-layer coatings, substrate absorption, and densification of sol-gel materials due to prolonged heat exposure. The additions to the theoretical model enable accurate fitting of experimental measurements for fabricated filters. In contrast, the Spectra model developed focuses exclusively on the optical interference design using the transfer matrix method for a single-sided multilayer coating. It is further simplified by neglecting substrate absorption, extinction coefficients, and material densification effects in order to isolate the ideal behavior of the thin film filter. This simplification is appropriate for the objective of designing a filter that provides a more direct

mapping between design parameters and optical performance, enabling optimization of the notch filter geometry to achieve nearly 100% transmission outside the target wavelength range.

The Spectra model is therefore intended to predict the ideal spectral response of the filter based on its designed layer parameters. In contrast, the Hinczewski model is structured to characterize fabricated filters, incorporate post-fabrication effects, and fit experimental data. This approach produced a filter design that achieved the desired target wavelength. However, the uniform layer thickness and abrupt index transitions caused excessive ringing, resulting in significant light loss in areas outside the target range (Figure 43). The final design utilizes TiO_2 (high refractive index, $n = 2.7$) and SiO_2 (low refractive index, $n = 1.46$) following an alternating pattern of TiO_2 and SiO_2 repeated 20 times, resulting in 40 individual layers.

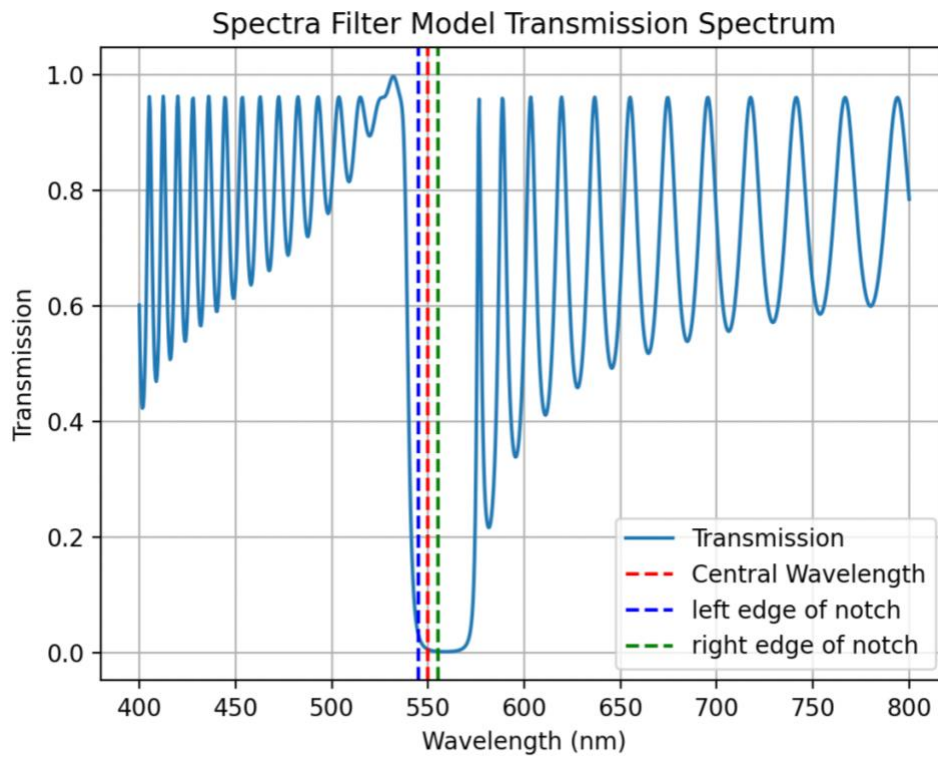


Figure 43. Spectral response of the 40 layer TiO_2 and SiO_2 alternating layer thin-film filter. The solid blue line represents the transmission percentage at each wavelength. Blue, red, and green dashed lines represent the left margin wavelength (545 nm), the central target wavelength (550 nm), and right margin wavelength (555 nm), defining a 10 nm notch filter range for selective wavelength blocking. As can be seen, transmission drops to 0 % within the notch, but with excessive ringing outside this range.

Using Light Machinery's Thin Film Cloud, a filter optimization tool, the layer stack of the initial design was optimized. The resulting filter incorporated varying thicknesses, producing a more effective spectral response. Although the design consisted of the same alternating pattern of TiO_2 and SiO_2 with 40 individual layers, each individual layer thickness was adjusted in order to reduce the ringing outside the target wavelength range, as can be seen in Figure 44 in comparison to the spectral response of the initial design in Figure 43.

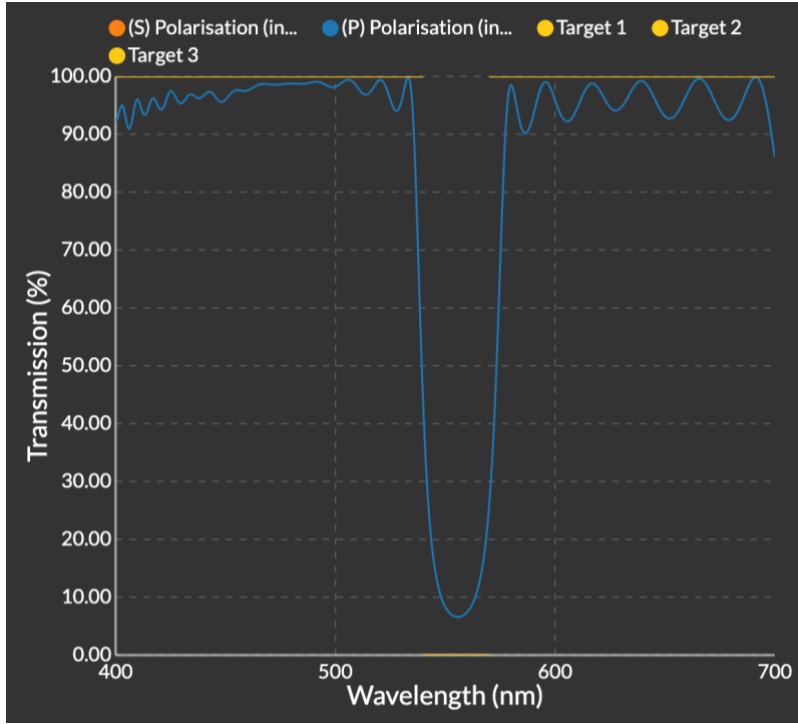


Figure 44. Spectral response of the layer-optimized version of the initial thin-film filter design. The blue solid line represents the transmission percentage at each given wavelength. Compared to the initial filter design in Figure 43, there is significantly less ringing in regions outside the targeted filtering range.

4.3. Proof of Concept Evaluation

Having established a multilayer thin-film interference filter design, experimental fabrication and testing were required for validation of the proposed filter. However, the specialized deposition equipment, materials, and processing are costly. Manufacturing of the 40-layer filter with varying thicknesses was estimated to cost over \$7,000 dollars. Due to the financial and resource constraints, experimental fabrication of the proposed filter was not feasible within the scope of this research. Therefore, a scaled model and simulation-based evaluations were implemented to

support assessment of the filter's performance and provide insight into its predicted optical and perceptual effects.

4.3.1. Scaled Spectra Model Experimentation

Scaled Model Configuration. To enable preliminary validation and gain insight into the effectiveness of the Spectra model, a scaled model configuration was constructed. The scaled design used 8 layers instead of 40, with a central target wavelength of 550 nm. To address material constraints, alternative materials with similar refractive indices were used as substitutes. The scaled model consists of 4 layers of alternating SiC (high refractive index, $n = 2.5$) and SiO₂ (low refractive index, $n = 1.46$) layers with uniform thicknesses of 198 nm for SiC and 16 nm of SiO₂, resulting in a total of 8 individual layers. The predicted transmission graph (Figure 45) for this scaled design shows that there is excessive loss of light due to the low number of layers.

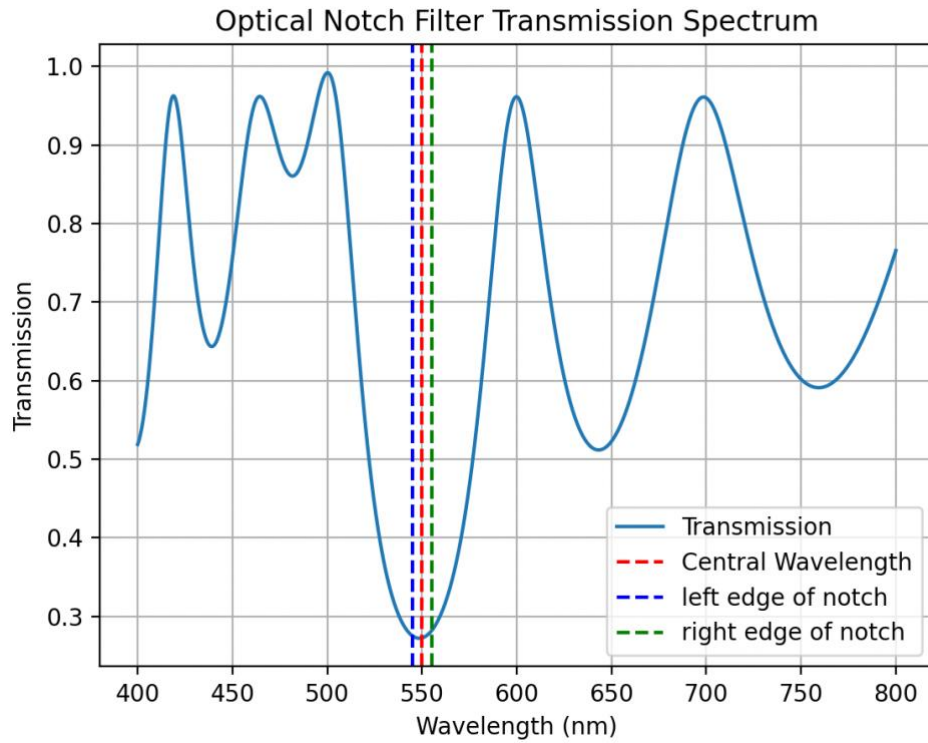


Figure 45. The predicted transmission curve for the scaled Spectra model. Blue, red, and green dashed lines represent the left margin wavelength (545 nm), the central target wavelength (550 nm), and right margin wavelength (555 nm) that define the 10 nm notch filter range for selective blocking.

Scaled Model Experimentation Results. The scaled filter model was manufactured with the assistance of the University of Maryland NanoCenter. After fabrication, the filter underwent white-light testing in order to evaluate its effectiveness.

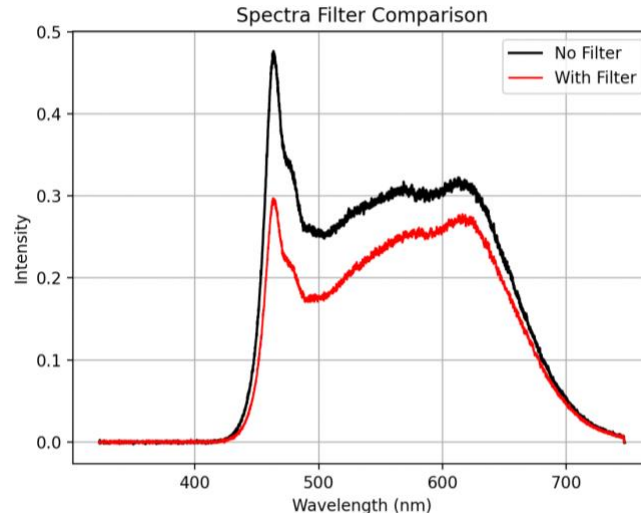


Figure 46. White-light intensity measured with and without the scaled filter positioned between the light source and the detector. The overall intensity decreases when the filter is applied, but the shape of the spectrum remains largely unchanged, indicating minimal selective attenuation in this scaled model.

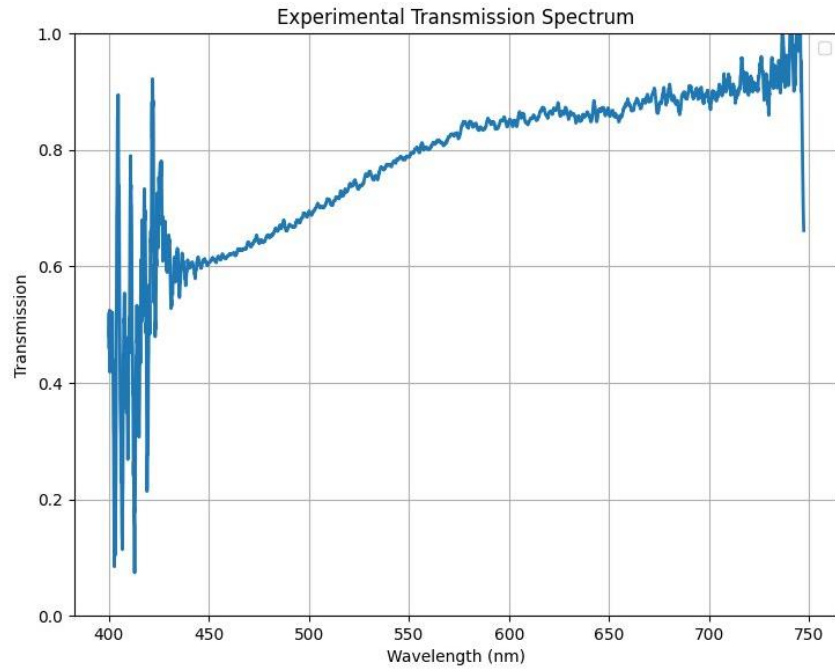


Figure 47. Transmission of light with the scaled filter applied. The transmission does not align closely with the predicted scaled Spectra model from Figure 45. This highlights the limitations in the fabricated scaled filter's ability to reproduce the intended notch.

Figure 46 shows that the scaled Spectra filter produced little observable effect on the white-light intensity compared to when no filter is used. Only a small overall reduction in intensity can be observed, and there is no significant change in the spectral shape. Ideally, the results in Figure 47 should match the predicted transmission shown in Figure 45, which as can be seen, does not. These results are due to several factors such as fabrication tolerances, material property variations, and measurement noise inherent in the white light setup. As the first layers of the thin-film filter get further heat exposure while the other layers are being deposited, they start to become denser, introducing what is known as the densification factor. Additionally, human error during the manufacturing and testing processes could have contributed to a lack of any significant effect from the scaled filter.

To provide an alternative evaluation technique of Team COLOR's proposed optimized 40-layer filter, a simulation-based evaluation was conducted that assessed the performance and perceptual impact of existing and designed filters. This approach applied spectral transmission characteristics predicted by filter models to image data, approximating how the filters would influence perceived color and brightness.

4.3.2. Simulation-Based Evaluation of Filter Performance

To evaluate the 40-layer filter designed by Team COLOR, an image-based simulation using an RGB approximation of spectral filtering was implemented. Transmission properties were obtained for three filters: EnChroma filters, the thin-film interference filter optimized using Light Machinery, and the scaled Spectra model. Transmission data was extracted from published transmission graphs using the *WebPlotDigitizer* tool (Extract Data From Charts, n.d.). The spectral response of each filter was approximated using central wavelengths of 620 nm, 540 nm, and 460 nm for red, green, and blue, respectively (Politis, Margounakis, & Karatsoris, 2008). Transmission values at these wavelengths were interpolated from the extracted curves and applied independently to each color channel of the sample image. All three filters were evaluated to gain insight into the performance of the proposed 40-layer design. The transmission curves for all three filter models are overlaid on top of the ideal notch are shown in Figure 48.

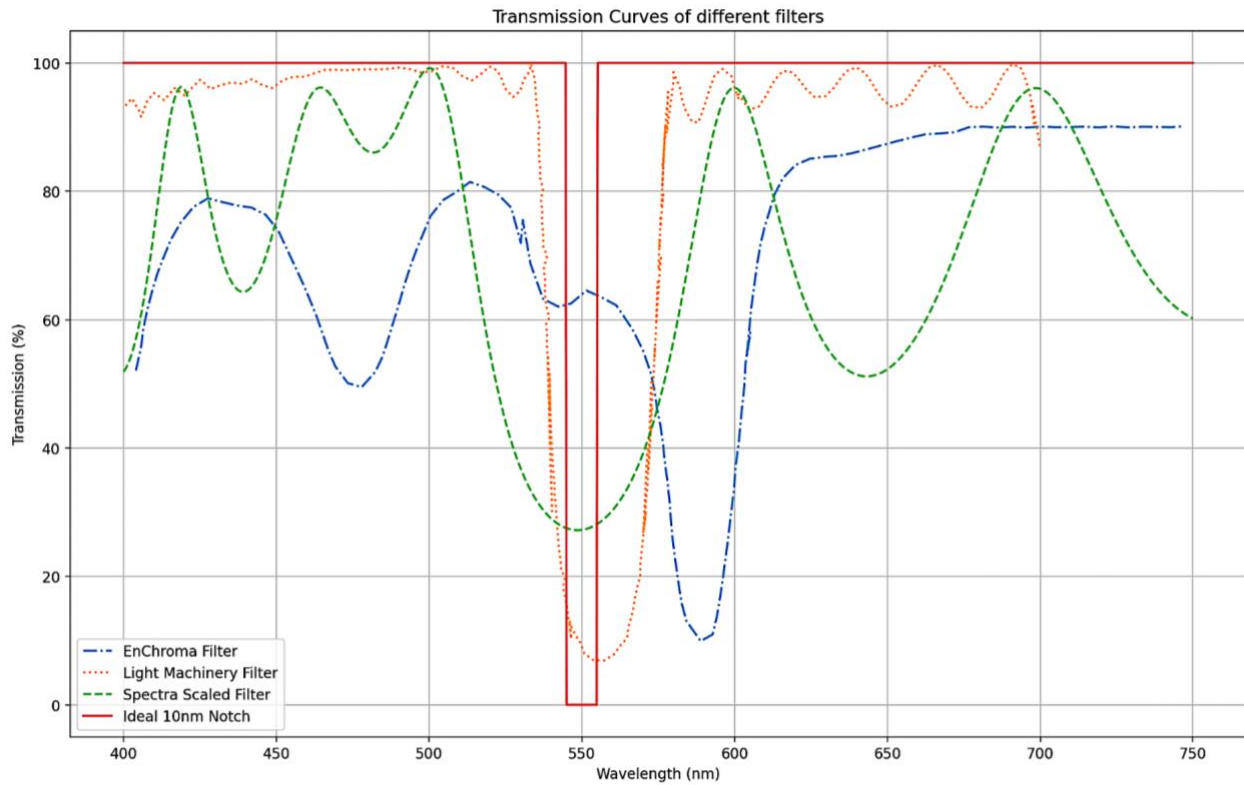


Figure 48. Transmission curves for EnChroma filter, Team COLOR's proposed thin-film optimized filter, scaled Spectra filter, and an ideal 10 nm notch filter.

Average transmission across the visible wavelength range was calculated for each filter. The positive control, an ideal 10 nm notch filter, exhibited 97.5% overall transmission with 0% transmission within the target notch region. In comparison, overall transmission achieved by the EnChroma filter was 63.73%, the Team COLOR's optimized thin-film filter reached 73.62%, and the scaled proof-of-concept Spectra model produced an intermediate overall transmission of 69.25%.

Average transmission within the target wavelength band (545–555 nm) was evaluated to assess each filter's ability to suppress the desired spectral region. The EnChroma filter exhibited a relatively high notch transmission of 63.53%, indicating limited attenuation within the targeted band. The scaled model reduced transmission in this region to 27.46%, demonstrating improved spectral suppression. The optimized thin-film design achieved the strongest attenuation, with a notch transmission of 10.64%.

Overall, the optimized filter proposed by Team COLOR demonstrates the best balance between spectral selectivity and overall light transmission, most closely mirroring an ideal 10 nm notch filter. By reducing transmission within the target wavelength band to 10.64% while maintaining an overall transmission of 73.62%, the design effectively attenuates the desired region of the visible spectrum while preserving sufficient light throughput to support visual clarity. To further visualize the impact of these filters, each transmission profile was applied to a sample image using the RGB approximation described previously. The results are shown in Figure 49.

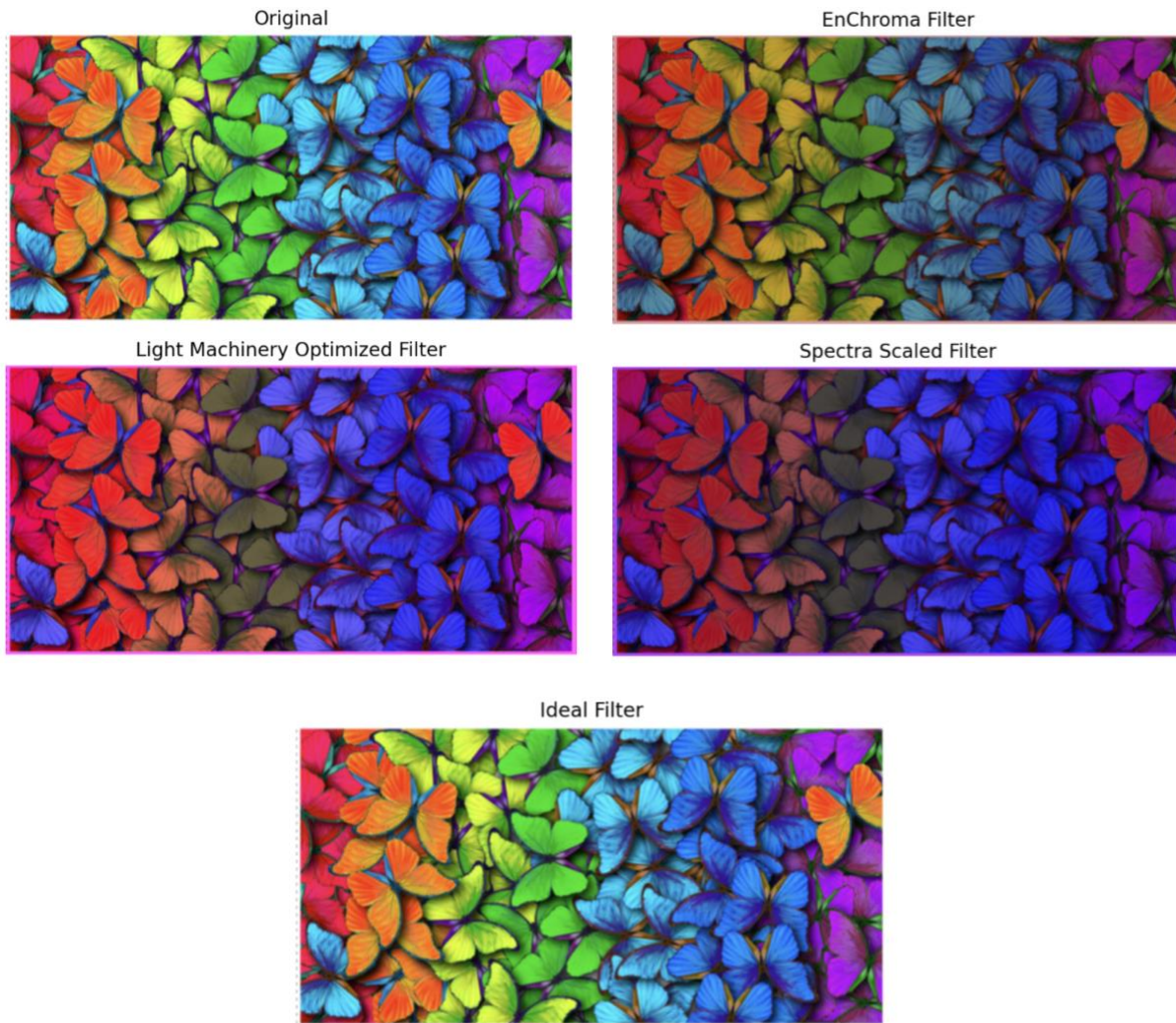


Figure 49. Image outputs with each of the filter transmission profiles applied to the original image. The EnChroma filter appears noticeably dimmer. The Team COLOR filter excessively suppresses the green portion causing a purple tint. The scaled Spectra filter suppresses the green and also appears noticeably dimmer. The ideal filter shows the desirable image, which visually is nearly identical to the original image, as expected.

The simulation-based evaluation of the different filter types showed that the EnChroma filter noticeably reduces image brightness due to its lower overall transmission. In contrast, the designed thin-film model preserves higher brightness levels. However, the thin-film filter exhibits a wider suppression region, which results in a visible color shift caused by excessive attenuation in the green portion of the spectrum. The scale filter produces similar visible distortion relative to the optimized 40-layer design, while also demonstrating low brightness due to the loss of light in other regions outside the target notch.

4.4. Future Design Considerations for Red-Green Thin-Film Filters

The 40-layer filter developed by Team COLOR was optimized to maximize notch depth within the 10 nm red-green confusion region. While this approach successfully produced strong attenuation within the targeted spectral range, it also resulted in a suppression band wider than intended. Because the multilayer thin-film design parameters were tuned primarily to increase notch depth, the resulting filter introduced excessive attenuation in the green region of the spectrum. This effect was observed in the image-based simulation, where the filter output exhibited a noticeable color shift.

Our current design consists of 40 individual layers coated on a substrate. Due to this complexity, manufacturing a single set of lenses would cost thousands of dollars. However, thin-film interference filters are well-established and can be manufactured at a large scale using vacuum deposition techniques such as sputtering. These techniques enable precision control over layer thickness and refractive index. The cost of such filters is dependent on layer count, material selection, and fabrication tolerances. Titanium Dioxide and Silicon Dioxide are both materials with low costs. Large scale manufacturing of such filter significantly reduces costs. Industry estimates suggest that multilayer dielectric filters can be produced in the range of \$100-\$400 per unit at moderate to high production volumes (Piegari & Flory, 2018).

The simulation-based evaluation highlighted a key tradeoff between notch depth, spectral bandwidth, and perceptual quality. Commercial color vision correction filters often balance these competing factors by optimizing both spectral shaping and total transmission rather than

maximizing attenuation alone. Future work on the proposed thin-film filter design should therefore focus on optimization strategies that constrain the bandwidth of the suppression region while maintaining high transmission. Additional improvements could include refining layer thickness parameters, enhancing perceptual modeling beyond RGB approximation, and investigating the effects of angle dependence. These refinements could produce a more balanced filter that better aligns with the desired visual outcomes, allowing individuals with red-green anomalous trichromacy to better distinguish colors without losing light.

4.4.1. Angular Dependence Considerations for Selective Filtering

To fully understand the real-world performance of the designed filter, it is necessary to consider the effect of angular dependence. In thin-film interference, the spectral response of a filter is determined by the distance that light travels through each layer. While the theoretical model calculates transmission based on a set thickness for the TiO_2 and SiO_2 layers, this distance only remains constant for light at normal incidence. When light strikes the filter at an angle, it travels a longer path through the layers, which causes the notch to shift to shorter wavelengths – a phenomenon known as blue shift (Mischok, et al., 2024).

This effect introduces a significant limitation for real-world applications. Wearable devices, such as glasses or contact lenses, receive light from a wide range of incidence angles. While ideal filter performance is based on normal incidence (0°), light typically enters the lens at moderate angles ($\sim 15^\circ$) during typical viewing and at larger angles ($\sim 30^\circ$) during peripheral viewing. As a result, the notch region may shift away from the intended 10 nm target wavelength region centered at 550 nm, reducing the filter's effectiveness at suppressing the red-green confusion region. Using the thin-film angular shift relation and an estimated effective refractive index of the TiO_2 and SiO_2 layer stack (TiO_2 $n \approx 2.5 - 2.7$ and SiO_2 $n \approx 1.45 - 1.46$, with average $n \approx 2.0$), the notch at 550 nm is expected to shift by approximately 4 to 6 nm at 15° and up to about 17 to 22 nm at 30° , potentially moving the notch to roughly 528 – 533 nm at larger viewing angles (Mischok, et al., 2024).

Recent research has shown that conventional thin-film filters can shift by around 100 nm over large angle ranges, which reduces their ability to selectively filter specific wavelengths. More advanced designs using strong light-matter coupling, where light interacts with the material inside the filter to stabilize its optical response, have been shown to reduce this effect, with shifts below 15 nm even at extreme angles (Mischok, et al., 2024). While these methods are beyond the scope of this design, they highlight the importance of considering angular effects in future filter optimization.

4.5. Conclusion

Team COLOR successfully developed and evaluated a thin-film interference filter for potential application in red–green color vision correction. The proposed design achieved an average transmission of approximately 73.62%, exceeding that of existing commercial filters such as EnChroma, while also demonstrating strong attenuation within the targeted confusion region. These results indicate that selective spectral filtering through thin-film interference can improve the separation of wavelengths associated with red–green color confusion. However, the results also revealed limitations related to the bandwidth of the suppression region, highlighting the challenges associated with achieving precise spectral selectivity while maintaining high overall transmission. This finding emphasizes the importance of balancing notch depth with spectral precision when designing thin-film filters intended for perceptual applications. In addition, the results suggest that targeted thin-film interference filtering is a viable approach for improving spectral separation within the visible spectrum. While additional optimization is required to refine the bandwidth and perceptual performance of the filter, this work demonstrates the feasibility of thin-film interference as a strategy for addressing limitations in current color vision deficiency mitigation technologies and supports further development of spectrally selective optical solutions.

5. Final Discussion

5.1. Equity Impact Report

Colorblindness is often perceived as a “minor inconvenience”; however, it can hinder the performance of everyday tasks (e.g. food safety), creates safety risks (e.g. traffic signaling), and can prevent individuals from pursuing certain occupations (e.g. aviation, electrical work). Nearly 5% of the population is susceptible to these limitations with no absolute solution available. Therefore, to address this issue, this research aims to support an underrecognized group by contributing to the field of physiological optics to explore methods of improving their quality of life through a comprehensive approach.

One method explored involves the design of a lens that can selectively filter wavelengths to improve color differentiation for individuals with CVD while preserving visual acuity. The proposed design demonstrates a feasible, relatively inexpensive, customizable solution that is flexible and intended to accommodate multiple forms of CVD. Pre-existing products, such as EnChroma lenses, only offer a single standardized solution when CVD is not a general matter. Furthermore, these lenses are costly, creating a socioeconomic barrier to something as fundamental as vision. Therefore, Team COLOR is providing a framework to a low-cost design that upholds the standards of quality to reduce the barrier of obtaining access to a solution for CVD. The second method explored was the development of the Daltonis simulation, designed to model a wide range of severity levels of CVD, enabling the testing of solutions across diverse presentations of red-green anomalous trichromacy. This flexibility supports a more inclusive and comprehensive study of the condition, while also facilitating the development of targeted mitigation interventions. In doing so, it moves away from a ‘one size fits all’ medical model and towards a person-centered design approach that addresses individuals’ physiological variations.

To maximize impact within a limited three-year timeframe with constrained resources – including funding and access to a large demographic of colorblind individuals – this research focused specifically on red-green anomalous trichromacy; the most common form of colorblindness. While this focus did exclude the rare yellow-blue form of anomalous trichromacy

(tritanomaly), the methodology, experimentation, and analysis developed in this study could be extended to include this condition. This research also did not address dichromacy, monochromacy, or achromatopsia (rod monochromacy), as these forms of CVD result from the absence of one or more cone types. The approaches presented here rely on modifying or modeling differences in cone responses when all cone types are present but altered due to red-green anomalous trichromacy. Therefore, these methods are not directly applicable to these cone-absent conditions. However, the underlying framework may still inform future work exploring alternative strategies for these affected populations. For instance, severe cases of protanomaly and deuteranomaly can produce visual experiences that closely resemble those of dichromatic conditions, specifically protanopia and deuteranopia. Despite differences in underlying genetic causes, the methods developed in this research – which build upon existing mitigation strategies, introduce new approaches for simulating the effects of red-green anomalous trichromacy, and its removal through inverse color vision deficiency simulation (ICVDS) – may provide a foundation for future efforts to better understand, model, and design interventions for these related forms of CVD. In this way, this research provides an open and adaptable framework that seeks to lower the research debt for future studies that may incorporate rarer forms of CVD, serving as a catalyst for complete inclusivity within the field of physiological optics.

5.2. Final Conclusion

The red-green anomalous trichromacy simulation, the augmented reality CVD correction approach, and the selective filtering lens framework developed in this research represent a significant step forward in addressing color vision deficiencies. Further work building on these contributions is essential to advancing definitive CVD mitigation technologies, as the findings provide a strong foundation for improving CVD mitigation interventions. With additional time and resources, the work from this research could be used to produce publicly accessible improvements in colorblindness interventions. Ultimately, Team COLOR has successfully demonstrated a three-pronged approach to addressing the visual limitations experienced by individuals with red-green anomalous trichromacy.

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