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# Evaluating the Influence of Eyewear on Perception of Small Color Difference in Reflective Samples

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## Abstract

*Tinted eyewear is increasingly utilized in outdoor environments to protect against ultraviolet radiation and manage luminance levels reaching the human visual system. While these protective functions are well-established, these modifications can also affect color perception. This research investigates how different tinted eyewear affects observers' ability to distinguish small color differences in reflective samples, with implications for understanding how specific eyewear transmittance properties influence color discrimination ability in different environments. Two sets of stimuli are used: (1) six adjacent Munsell sample pairs varying only in hue, and (2) seven parameric pairs generated through Kubelka-Munk theory modeling of 16 pigments. Six eyewear with different transmittance properties were examined in this study under normalized lighting conditions. Color differences ($\Delta E_{2000}$) were predicted using spectral data and validated through psychophysical experiments with 27 observers using a scaling method. Results demonstrate that tinted eyewear can alter color discrimination ability compared to neutral eyewear, with effects varying based on the interaction between the eyewear's spectral transmittance and the stimuli's spectral reflectance. For example, one foliage pair showed a $\Delta E_{2000}$ of 2.37 under neutral eyewear that increased to 5.21 under a tinted eyewear, with corresponding mean observed visual differences of 2.79 and 5.51, respectively. Overall, the observed color difference evaluations aligned with predictions, with correlation coefficients (r) of 0.816. This research enhances the understanding of how tinted eyewear affects color perception and supports the development of eyewear optimized for specific outdoor environments.*

## Introduction

Color vision plays a crucial role in daily life, as it not only affects aesthetic experiences but also assists us in accurately identifying objects within our environment [1]. In outdoor environments with high light intensity, tinted eyewear protects the human visual system through its spectral transmittance properties, which block ultraviolet radiation and reduce the total luminance reaching the eye [2]. Different tinted eyewear reduces light differently across the visible spectrum, altering multiple aspects of visual perception, including visual acuity, contrast sensitivity, and color discrimination ability [3]. Therefore, understanding how the spectral transmittance characteristics of tinted eyewear influence visual performance is crucial for optimizing eyewear design. Numerous studies have investigated the impact of eyewear's tinted color on specific aspects of visual performance. For instance, Graham et al. [4] evaluated the effect of amber and Gray-Green tinted eyewear on visual acuity using a Bailey-Lovie chart and the Haynes Distance Rock test. The results indicate that the tinted eyewear examined in the study can provide better contrast discrimination and better speed of visual recovery in bright sunlight compared with neutral eyewear. In another study, M Dolores De Dez et al.[3] measured the contrast sensitivity function of ten observers for a set of tinted eyewear using sinusoidal grating by the adjustment method. The results suggest that yellow filters may offer advantages over gray filters in situations where enhancement of low achromatic contrast is desired. These studies demonstrate how different tinted eyewear can affect various aspects of visual performance.

Tinted eyewear can also influence color perception through its spectral transmittance properties, which may pose potential risks in critical situations, such as identifying traffic signals against bright backgrounds [5]. Several comprehensive studies have explored these effects on color discrimination ability using various testing methods. For instance, Verriest [6] examined the impact of yellow filters using multiple color discrimination tests, including AO H-R-R pseudoisochromatic plates and the Farnsworth-Munsell 100-hue test, The results shown that yellow filters can alter normal color vision to resemble congenital tritanope deficiency, and the illumination variance can significantly influence the color discrimination ability. These findings were further corroborated by Eero's research [6], which revealed that yellow filters cutting off radiation between 475nm and 500nm induced tritanope-type errors, while filters with cut-off wavelengths between 400nm-450nm showed no significant impact on hue discrimination accuracy. In examining the effects of different tint colors, R.H. Peckham [7] investigated five different tinted eyewear using a Rotation plate color-matching experiment and found no significant changes in chroma difference perception. The study observed shifts in the perception of hue and value, indicating that the tinted eyewear might have influenced these specific aspects of color perception. Additionally, De Fez et al. [3] used CRS's Color Vision Test to measure the discrimination threshold across different eyewear, concluding that none of the tested eyewear improved color discrimination ability in white, green, and blue areas. In contrast, Mahjoob et al. [8] evaluated the effect of different tinted eyewear colors on color vision using the D-15 test. Their study found that gray filters had the least impact on color vision, preserving normal color discrimination ability, while green filters caused the most significant deficiencies, particularly affecting the ability to differentiate between colors. Most previous studies [3, 5, 6, 9, 7] evaluated color discrimination through tinted eyewear using standardized tests like the 100-Hue test and the D-15 test, where observers rank printed samples differing only in hue. While these methods provide valuable insights, using samples printed with the same primary colorants cannot assess discrimination of paramers - samples that appear similar under a specific illuminant but have different spectral reflectance properties.

This study presents an alternative approach to evaluating color discrimination ability through tinted eyewear. With advancing eyewear technology, different tinted eyewear are designed for specific outdoor environments, such as driving, exploring woodlands, and working in snowy fields. Their spectral transmittance is optimized based on environmental lighting conditions and critical color discrimination needs [10] . From a spectral perspective, this study examines how eyewear's spectral transmittance influences both color discrimination across different hue ranges and the ability to distinguish paramers. While true metamers match exactly with identical colorimetric coordinates (resulting in a total color difference equal to zero), parameric pairs have small color differences (usually with the color difference between 0-3) but are not the same. Creating true metamers is technically challenging, so this study uses parameric pairs that have small but measurable color differences. This approach addresses two crucial questions: whether tinted eyewear might enhance discrimination ability in any specific hue range and whether they can aid in distinguishing colors with small visual differences but large spectral reflectance differences (parameric stimuli).

## Research Objectives

This study aims to investigate the impact of different types of eyewear on color perception, specifically focusing on the ability to distinguish small color differences in reflective samples. The aims of the study include:

· **Develop stimuli**

Two sets of stimuli were prepared for the study. The first set consists of several pairs of adjacent Munsell chips that differ only in hue. The second set includes parameric pairs, which are colors with similar CIELAB values ($L^\star$,$a^\star$, and $b^\star$) under a specific light source but with different spectral reflectance. These parameric pairs were generated by modeling 16 pigments using Kubelka-Munk theory. The parameric pairs are formulated based on the spectral reflectance of the Macbeth Color Checker's first five patches, which include the color of skin tones, sky, foliage, and blue flowers [11] .

· **Predict color differences under different eyewear.**

Compute the predicted color differences ($\Delta E_{2000}$) for the parameric pairs and Munsell sample pairs. The calculation utilized the spectral radiance of the light source measured through each eyewear, combined with the spectral reflectance ($R_\lambda$) of the samples and the CIE 1931 standard two-degree observer color-matching functions.

· **Collect perceived color differences assessment through a psychophysical experiment.**

Conduct experiments using the method of scaling to evaluate how observers perceive color differences in the sample pairs when wearing different eyewear.

· **Compare predictions with experimental results.**

Evaluate the accuracy of the predicted $\Delta E_{2000}$ values by comparing them to the perceived color differences measured in the psychophysical experiments.

This research aims to enhance understanding of how tinted eyewear affects color perception by examining their impact on the ability to distinguish small color differences in reflective samples. It is hypothesized that eyewear with varying spectral transmittance properties will influence color discrimination performance differently. The study predicts color differences based on the spectral transmittance of the eyewear and the spectral reflectance of the two samples and investigates whether the eyewear can enhance the ability to distinguish the patches in a sample pair. The predictions are validated through psychophysical experiments. This research offers insights into how eyewear design can improve color discrimination and support the development of eyewear to match specific outdoor environments.

## Methodology

### *Selection and Measurement of Stimulus*

All the samples used in this experiment are measured by the ColorEye 7000A spectrophotometer with UV excluded and specular component included. Each sample is measured three times with replacement, and the average spectral reflectance is calculated based on these three measurements. Six pairs of samples were selected from the Munsell Matte Sample set, including the five intermediate hues (Chroma 6 and Values 6) and one pair of neutral stimuli (Figure 1a). The size of the sample pair is 2cm * 4cm. These printed samples were chosen to examine the effect of hue variation.

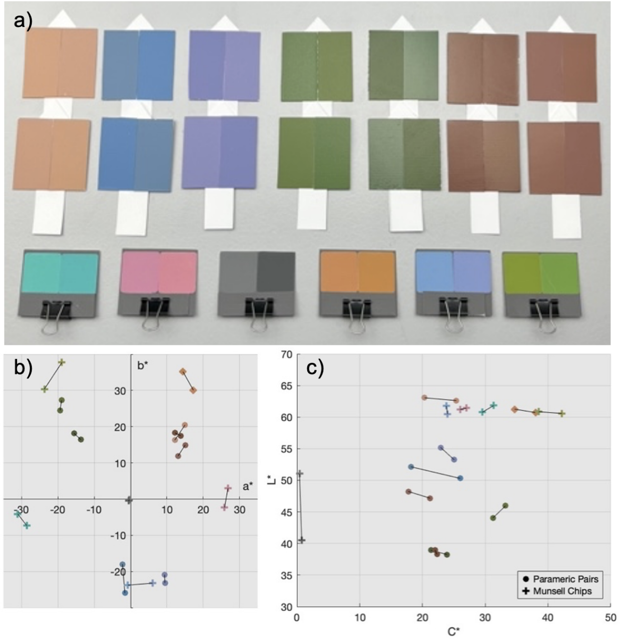

***Figure 1.*** *a) Photo of all samples used in the experiment. b) the $a^\star$ $b^\star$ plot of the stimuli. c) the $L^\star$ $C^\star$ plot of the stimuli.*

There were also seven parameric pairs included in the experiment. The first five patches on the Macbeth Color Checker [7], representing foliage, skin tones, blue sky, and blue flowers, were selected. The Macbeth Color Checker was chosen due to its design and widespread use in imaging referencing applications, ensuring consistency and reliability in color matching. The Kubelka-Munk theory was applied to predict the recipes needed using 16 Golden Artist Colors matte acrylic dispersion paints that could produce chromaticity matches with these patches. More details can be found in Appendix 1. From these mixtures, seven pairs of samples were chosen: three for skin tones, two for foliage, and one each for sky blue and blue flowers. The sample size is 4cm * 4cm. To conclude, 13 pairs of stimuli were selected in this experiment, and the color difference for the stimuli is between 1 and 5 $\Delta E_{2000}$ units. Plots of the L$^\star$ C$^\star$ and a$^\star$ b$^\star$ are shown in Figure 1.

## Normalization of the illuminance

Six types of eyewear were selected for this experiment: two pairs were chosen for their relatively uniform filtering across all wavelengths, with different total transmission levels for comparison. The one with higher spectral transmittance, referred to as 'Neutral1', has a transmittance ranging from 85% to 95% across 450nm - 700nm. The one with lower transmittance, referred to as 'Neutral2', has a spectral transmittance of ranging from 10% to 20% within the same range. Additionally, four tinted eyewear, labeled 'Tinted1' through 'Tinted4' have variable total transmittance. These tinted eyewear unevenly filtering across wavelengths, and they were designed to reduce the transmittance at specific wavelengths.

The experiment was conducted under a seven-channel LED light source, with the Correlated Color Temperature (CCT) at about 6500K (Figure 2). The intensity of each LED channel was optimized in MATLAB, minimizing spectral differences while ensuring a colorimetric match to the CIE Standard D65 [12, 13].

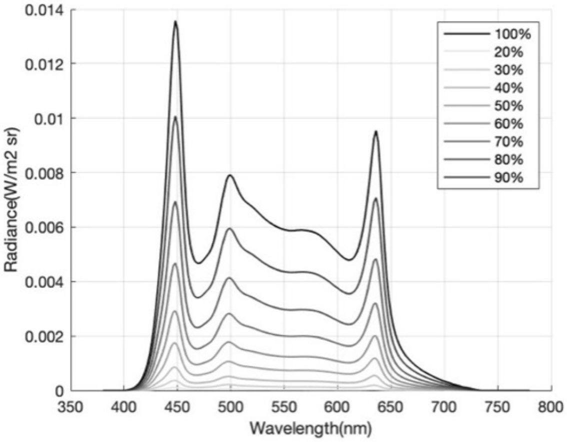

**Figure 2.** *The spectral power distribution of the light source.*

To ensure consistent total illumination across different eyewear, the total luminance is normalized for each eyewear by computationally adjusting the luminance level of the light booth. Firstly, the CR250 spectroradiometer was used to measure the spectral radiance of the Halon sample under different luminance levels in the light booth (Figure 2), which was controlled by adjusting the input percentage of the light source. The normalized spectral radiance indicated that when the input is higher than 50%, the spectral radiance for the light source is linear. Then, measurements were taken through different eyewear at a distance of 1.5 cm from the spectroradiometer and 60 cm from the Halon sample The setup of the measurement is shown in Figure 3. Using this linear relationship, the total luminance through different eyewear was measured and calculated to determine the corresponding input percentages required to normalize the luminance across eyewear. Finally, the light booth was adjusted to the calculated luminance levels, and the total luminance through each eyewear was re-measured to verify the calculations, The total luminance is between 52 cd/$m^2$ and 54 cd/$m^2$ across all eyewear.

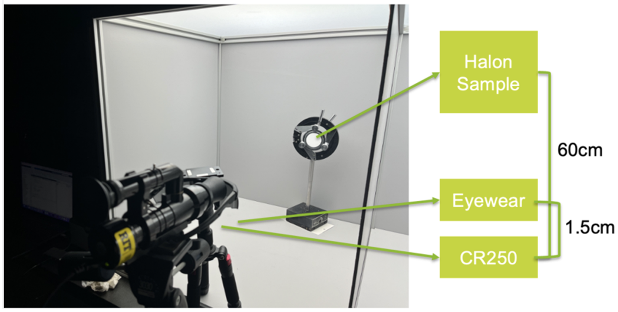

**Figure 3.** *Setup for the spectral radiance measurement for eyewear.*

Each stimulus's corresponding CIELAB values ($L^\star$, $a^\star$, and $b^\star$) were computed using the spectral radiance of the light source measured through each eyewear, the sample spectral reflectances ($R_\lambda$), and the CIE 1931 standard two-degree observer color-matching functions. The measurement of spectral radiance through each eyewear is considered as the light source, the normalization factor (k) was calculated for each eyewear based on the measured spectral radiance. Since each eyewear has a different spectral transmittance, the reference white point ($XYZ_n$) is calculated specifically for each eyewear. The CIEDE2000 color differences ($\Delta E_{2000}$) for all sample pairs under different eyewear were calculated. The calculated $L^\star$, $a^\star$, and $b^\star$ values without eyewear and the predicted color differences through each eyewear are presented in Appendix 2.

## Experimental Setup and Procedure

An achromatic anchor (Figure 4) is chosen as a reference based on the assumption that the tinted lens does not alter the lightness difference of the anchor. The reference patches used in this experiment are printed by Canon Pro-4100 inkjet paper on Epson DoubleWeight Matte Paper. The achromatic anchor pairs used in this experiment ranged from 0 to 12, with adjacent intervals corresponding to approximately two $\Delta E_{2000}$ color difference units. The standard patch has a lightness value of $L^\star = 50$. Lightness differences ($\Delta L^\star$) primarily contributed to the color differences, with $\Delta L^\star/\Delta E \approx 1.0$. The light booth is painted in gray at about 45% reflectance (similar to Munsell N7) on four sides as a neutral background [13]. A gray board, with the same color as the background, was placed at a 45-degree angle relative to the horizontal surface inside the light booth and the achromatic anchor pairs were firmly adhered to the board. Thus, the stimuli are presented in 45/0 geometry, and the viewing field of each stimulus is approximately 2 degrees, as shown in Figure 4.

During the experiment, the observers were asked to wear Neutral1 first and adapt to the lighting condition for approximately 20 seconds. Then, the observer was asked to hold each pair of samples at the same angle as the achromatic anchor, scale the perceived color difference of the color pair, and assign a number that they think matches the given reference achromatic pair. After finishing all the pairs, the other five eyewear were given in a random order, and the samples were randomized as well when switching eyewear. The observer was asked to evaluate the per-

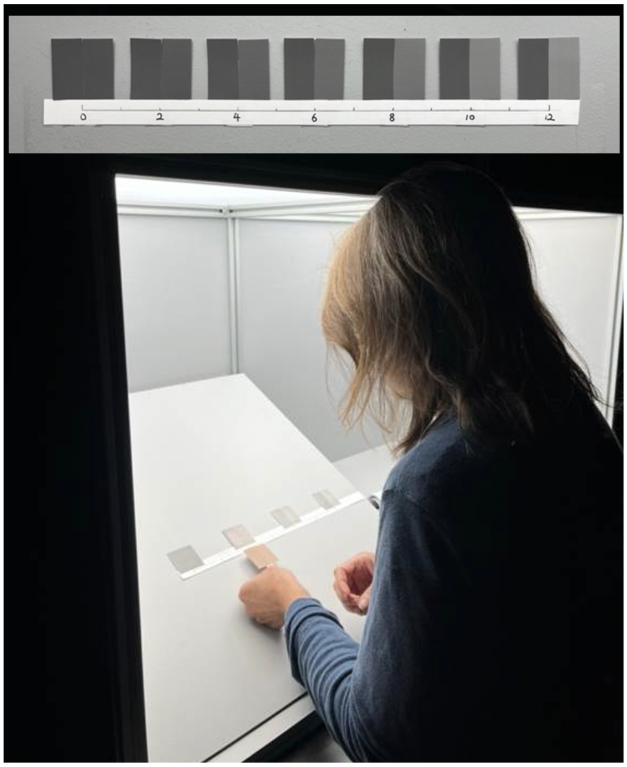

*Figure 4. Diagram of visual assessment experiment and a picture of the achromatic anchor*

ceived color difference twice for each eyewear. For the paramer stimuli, two sample pairs were prepared that alternate the left-right placement of the samples. This was done to avoid observers only matching the lightness difference of the stimulus. Thirteen pairs of stimuli were provided, and six eyewear were used in the experiment. As a result, a total of 156 assessments were collected from each observer. The experiment takes about 45 minutes for each observer.

### Observers

Twenty-seven observers (aged between 22 and 60) participated in the color difference evaluation experiment. All observers who participated in this study were students and faculty members from the Rochester Institute of Technology (RIT) with fundamental knowledge of color science. All observers had normal color vision, as verified by the Ishihara color vision test [14]. Each observer provided informed consent after being briefed on the study procedures. RIT's Human Subjects Research Office approved this experiment (approval FWA #01110424).

## Result and Discussion

This study first examined how tinted eyewear's spectral transmittance theoretically influences perceived color differences through colorimetric predictions. Then the perceived color differences through these tinted eyewear were collected through psychophysical experiments with observers. Finally, the relationship between these predictions and observations was assessed to understand the accuracy of current calculations.

### Predicted Color Differences

Analysis of predicted CIELAB values indicated distinct patterns in how different eyewear types should affect the color perception of the selected Munsell chips. While predicted lightness ($L^\star$) values remained notably stable across all eyewear ($L^\star$ range between 63 and 65), substantial variations emerged in the chromatic coordinates ($a^\star$ and $b^\star$). Most stimuli exhibited shifts toward higher chroma compared to Neutral1 and Neutral2. As illustrated in Figure 5, tinted eyewear produced systematic shifts in color appearance relative to Neutral1. Tinted1-3 show predicted values shifting toward positive $b^\star$ (yellowish) and negative $a^\star$ (greenish). In contrast, Tinted4 shifts toward positive $a^\star$ (reddish) and negative $b^\star$ (blueish). Among these, Tinted2 has the largest impact on achromatic pairs, with the chromaticity shifting toward positive $b^\star$ values, making the neutral colors appear more yellowish.

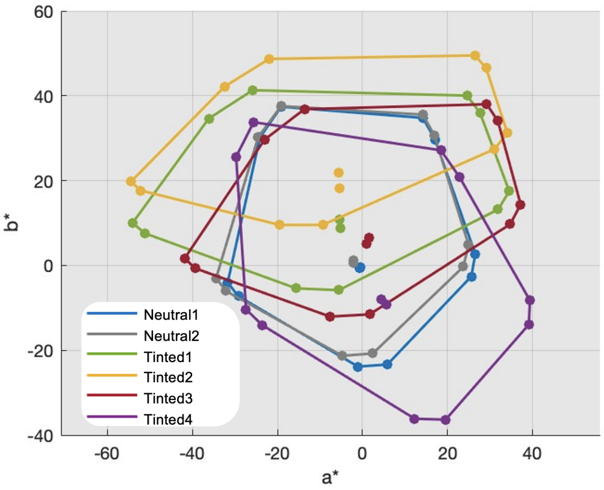

*Figure 5. Predicted chromaticity in the CIELAB $a^\star b^\star$ plane for Munsell chips used in this study under different eyewear. Tinted1-3 show systematic shifts toward yellowish-green (positive $b^\star$, negative $a^\star$), while Tinted4 shifts toward reddish-blue (positive $a^\star$, negative $b^\star$), relative to Neutral1.*

For parameric pairs designed to have similar chromaticity under Neutral1 conditions, their chromatic differences are altered by the varying transmittance properties of tinted eyewear. This highlights how the interaction between the eyewear's selective spectral transmission and the samples' spectral reflectance can change color discrimination ability, even when the initial colorimetric values appear similar. For example, one of the foliage pairs shows similar CIELAB values under Neutral1 conditions ($\Delta E_{2000}$ = 1.38), while under Tinted2, the predicted color difference increases substantially to $\Delta E_{2000}$ = 5.97. This enhancement may be attributed to Tinted2's distinct spectral transmission properties with minimal transmittance in the 550–600 nm range and the samples' spectral curves showing their greatest variation around 550 nm (Figure 6a). In contrast, Neutral2, with its relatively uniform spectral transmission, produces only a slight increase in color difference ($\Delta E_{2000}$ = 1.64), indicating a color appearance more consistent with that under Neutral1. This consistency aligns with Neutral2's design purpose of providing neutral density attenuation without substantially altering spectral composition, resulting in minimal impact on relative color differences.

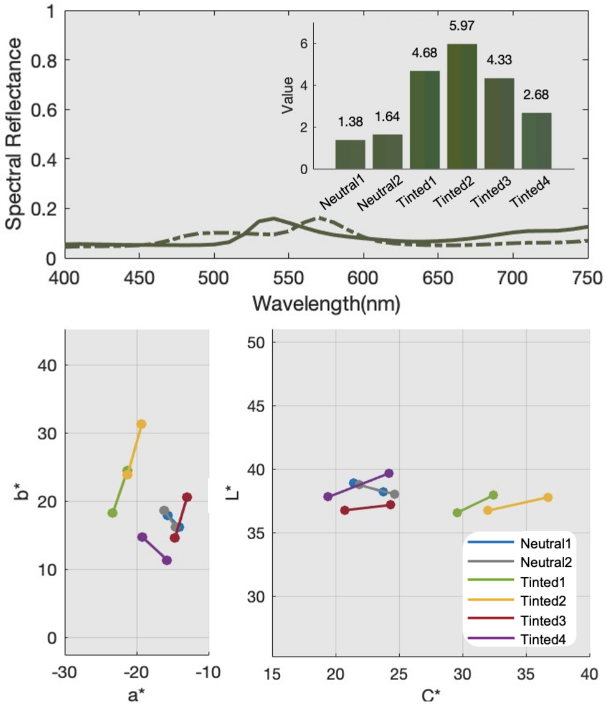

***Figure 6.*** *a) The spectral reflectance of the parameric pair for Foliage and the predicted color difference through the tinted eyewear. b) the $a^\star b^\star$ plane and c) $L^\star C^\star$ plane of the sample pair's predicted chromaticity*

Appendix 2 presents the calculated corresponding CIELAB values ($L^\star$, $a^\star$, and $b^\star$) for all stimuli and the predicted color differences ($\Delta E_{2000}$) under different tinted eyewear. Overall, Neutral1 and Neutral2 show similar values for each pair of stimuli, with an average predicted color difference of 3.73 and 3.78, respectively. In contrast, Tinted1 and 2 show notably larger average predicted color differences (average $\Delta E_{2000}$ values of 4.96 and 4.93), indicating that these two eyewear might overall enhance the ability to distinguish between the sample pairs used in this study. Additionally, for the achromatic pair, the predicted color difference is between 10 and 10.1 for all of the eyewear, which implies that the color difference perception for the achromatic pair is more consistent. This also supports the use of achromatic anchors as experimental references, as the perceived color difference under different eyewear remains approximately consistent.

## Perceived Color Differences

To validate the colorimetric predictions and understand how different eyewear affects color discrimination ability, a psychophysical experiment was conducted to assess how observers perceived color differences ($\Delta V$) while wearing different eyewear. Twenty-seven observers (aged between 22 and 60) participated in the color difference evaluation experiment. Each observer completed 156 assessments, comprising 13 sample pairs viewed through six eyewear with two replicates, for a total of 4,212 observations across all 27 observers. The consistency of individual observers' assessments was evaluated by analyzing the differences between their replications for each sample pair and eyewear combination. The average difference of the first and second assessment ($\Delta V_1$ - $\Delta V_2$) was calculated for each observer to assess consistency. The average difference across all observers was 0.955, with individual values ranging from 0.391 to 2.269, indicating that observers provided relatively consistent and stable color difference evaluations for the same stimuli.

To minimize scaling variations between observers, the color difference assessments were normalized by subtracting each observer's evaluation of Neutral1 ($\Delta V$- $\Delta V_{Neutral1}$). This approach was chosen because, the achromatic anchor primarily involves lightness differences, whereas most sample pairs in this experiment involve chroma and hue differences. Consequently, each observer may have a different scaling standard for evaluating color differences, particularly when comparing more complex chromatic changes. Normalizing relative to Neutral1 helps reduce these individual scaling differences, enabling a more consistent comparison across observers and eyewear types.

## Comparison of Predicted vs. Perceived Color Differences

The relationship between predicted and observed color differences was analyzed by comparing normalized values - both predicted values ($\Delta E$ - $\Delta E_{Neutral1}$) and visual assessments ($\Delta V$- $\Delta V_{Neutral1}$) relative to Neutral1. Positive values indicate enhanced color discrimination ability compared to Neutral1, while negative values suggest reduced discrimination. As shown in Figure 7, along the x-axis, the analysis included 13 sample pairs: three skin tone pairs (pairs 1, 3, 7), two foliage pairs (pairs 5-6), blue sky (pair 2), blue flowers (pair 4), five selected Munsell chips (pairs 8-12), and an achromatic pair (pair 13).

Analysis of the Pearson correlation coefficient (r) between predicted and observed differences revealed varying degrees of agreement across eyewear types. Neutral2 demonstrated the strongest alignment with the prediction, as shown in Figure 7. However, as the adjuested values are close to zero, the correlation (r = 0.097) is poor. The other tinted eyewear showed moderately strong correlations, with Tinted1 (r = 0.854), Tinted2 (r = 0.834), Tinted3 (r = 0.837), and a Tinted4 (r = 0.816) all performing similarly. While other tinted eyewear generally showed good agreement between predicted and observed differences, there were systematic deviations for certain color pairs, with predictions sometimes overestimating the observed differences. These patterns of agreement and deviation varied by both eyewear type and stimuli. The overall correlation of 0.839 across all eyewear types supports the general validity of the prediction while acknowledging room for improvement.

For the Munsell pairs, the pattern of enhancement or reduction in color discrimination ability largely aligned with predictions across different eyewear, as shown in Table 1. Figure 7 shows that Tinted1-3 enhanced discrimination in the Purple-Blue and Yellow-Green hue regions. In contrast, the Tinted4 enhanced discrimination in the Blue-Green and Red-Yellow hue regions. However, some predicted color differences were consistently larger than the observed differences, particularly for the Purple-Blue and Yellow-Green pairs, with the largest overprediction occurring in Tinted1 and Tinted2. For the parameric pairs, the effect of eyewear on color discrimination varied based on the spectral properties of the samples. For the three skin tone pairs (pairs 1, 3, 7) used in this study, the perceived color difference

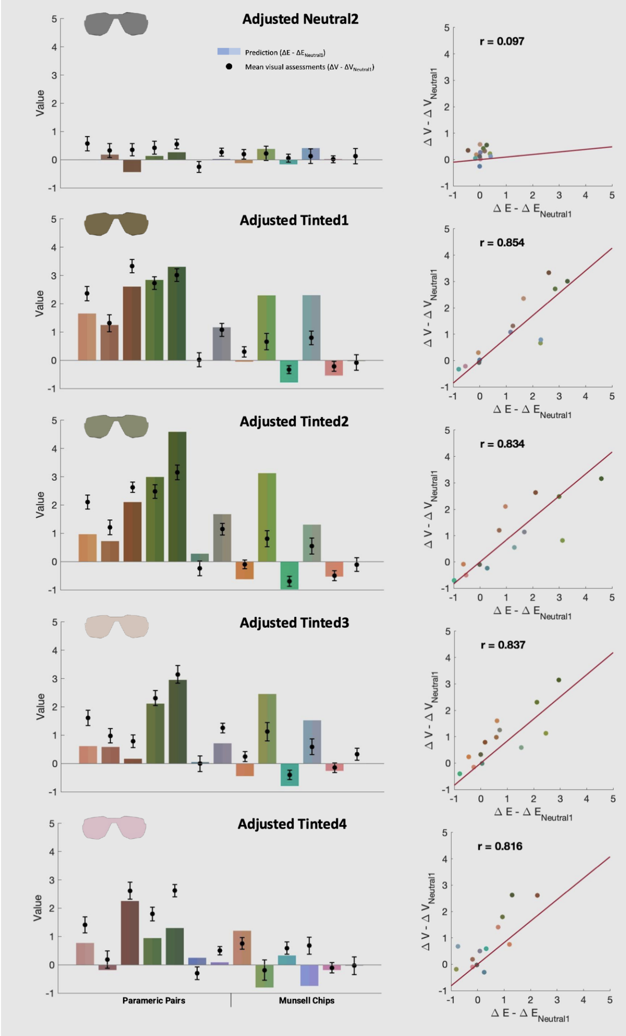

*Figure 7.* *The comparison between predicted colorimetric differences and observed visual assessments for different eyewear types relative to Neutral1. The bars represent the predicted color difference values ($\Delta E$ - $\Delta E_{Neutral1}$), while the black dots with error bars show the mean visual assessments ($\Delta V$ - $\Delta V_{Neutral1}$) and standard error across all observers. For each panel, the x-axis shows the 13 sample pairs (pairs 1, 3, 7: skin tones, pairs 5-6: foliage, pairs 2: blue sky, pairs 4: blue flowers, pairs 8-12: selected Munsell Chips, pair 13: achromatic pair).*

is larger than the prediction across all the tinted eyewear. However, for foliage pairs (pairs 5, 6), despite predictions of substantial enhancement under tinted eyewear, observers reported smaller differences than predicted - Tinted2 showed the largest discrepancy with observations 1.2 units below predictions, followed by Tinted1 (1.0 units) and Tinted3 (0.8 units).

**Table 1 Correlation coefficients (r) between normalized predicted ($\Delta E$ - $\Delta E_{Neutral1}$) and observed ($\Delta V$ - $\Delta V_{Neutral1}$) color differences.**

| No. | Description | r value | No. | Munsell Chips | r value |
|---|---|---|---|---|---|
| 01 | Skin Tone 1 | 0.930 | 08 | 7.5 & 5 YR | 0.875 |
| 03 | Skin Tone 2 | 0.936 | 09 | 7.5 & 5 GY | 0.937 |
| 07 | Skin Tone 3 | 0.979 | 10 | 7.5 & 5 BG | 0.960 |
| 02 | Blue Sky | -0.683 | 11 | 7.5 & 5 PB | 0.453 |
| 04 | Blue Flower | 0.836 | 12 | 7.5 & 5 RP | 0.867 |
| 05 | Foliage 1 | 0.943 | 13 | N4 & N5 | 0.545 |
| 06 | Foliage 2 | 0.878 | | | |

This deviation between predictions and observations might be attributed to several factors. First, individual variations in spectral sensitivity among observers can contribute to these differences. While predictions are based on the CIE 1931 standard observer, actual color perception for different observers exhibits variations in photoreceptor sensitivities and cortical processing. This variation is particularly relevant when evaluating small color differences through tinted eyewear, as the eyewear's spectral transmission may interact differently with each observer's unique spectral sensitivity. Additionally, the mismatch could be explained by chromatic adaptation mechanisms not accounted for in the current prediction. However, this hypothesis requires further investigation to understand the role of chromatic adaptation in color discrimination through tinted eyewear.

## Conclusion

This study investigated how different tinted eyewear affects color discrimination ability through a psychophysical experiment. The research utilized two sets of stimuli with small color differences - Munsell chips varying in hue and parameric pairs with similar CIELAB values but different spectral reflectance - to evaluate color discrimination performance across six eyewear that vary in spectral transmittance properties. Key findings include:

· Tinted eyewear can substantially alter color discrimination ability compared to neutral (Neutral1, Neutral2) eyewear, with effects varying based on the interaction between eyewear spectral transmittance and stimuli spectral reflectance properties.

· Tinted eyewear 1-3 enhanced discrimination in specific hue regions (Purple-Blue, Yellow-Green) while potentially reducing discrimination ability in others, suggesting their utility may be optimized for specific visual tasks or environments.

· The relationship between predicted and observed color differences showed good general agreement but with systematic deviations (overall r = 0.839), particularly for parameric pairs. Skin tone pairs consistently showed larger perceived differences than predicted, while foliage pairs showed smaller observed differences than predicted.

· Intra-observer consistency was generally good. The average difference of the first and second assessment ($\Delta V_1$ - $\Delta V_2$)

across all observers was 0.955, with individual values ranging from 0.391 to 2.269.

## Future work

A more detailed spectral analysis could be conducted to understand the mechanisms behind enhanced color discrimination. This analysis could examine the Root Mean Square Error (RMSE) between sample pairs across different wavelength ranges, focusing on identifying specific spectral regions where color difference enhancement occurs. By analyzing the relationship between the spectral transmittance of the eyewear and the spectral reflectance properties of the sample, it could help better understand why certain types of eyewear are more effective in enhancing color differences for specific pairs of samples.

The current results show systematic differences between the predicted and observed color differences. Understanding these deviations is crucial for improving our ability to predict color discrimination performance with tinted eyewear. Future work should examine how to improve the accuracy of the prediction. The goal is to be able to calculate the predicted color difference, given two spectral reflectances of interest are provided, for the spectral transmittance of the eyewear.

## Acknowledgements

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## Author Biography

*Shuyi Zhao received her B.S. in Printing Engineering from the Beijing Institute of Graphic Communication, during which she spent one year as an exchange student at the University of Leeds, studying Graphic and Communication. She later earned an M.S. in Additive Manufacturing and 3D Printing from the University of Nottingham. She is currently pursuing a Ph.D. in Color Science at the Rochester Institute of Technology, focusing on human color vision, color 3D printing, and color reproduction.*

## Appendix 1

This section provides details of the process of creating a database of color patches used in this study. Sixteen Golden Artist Colors were used to create the dataset. For each color, a tint ladder was prepared at three different concentrations (20%, 50%, and 80%) of titanium white (titanium dioxide) along with a mass tone, as shown in Figure 8. A drawdown bar was used to apply the colorant uniformly on Lenetta opacity charts. The ColorEye 7000A spectral photometer with a specular component included setting was used to measure three times on both black and white sections of these charts with replacement to test the opacity. Measurements were collected from 400nm to 750nm in 10nm intervals, as shown in Figure 9.

**Table 2 Name of Colorants**

| No. | Paint Name | |
|---|---|---|
| 1 | Titanium White | TW01 |
| 2 | Bone Black | BB02 |
| 3 | Ultramarine Blue | UB03 |
| 4 | Cerulean Blue | CeB04 |
| 5 | Phathlo Green Yellow shade | PGYS5 |
| 6 | Diarylide Yellow | DY06 |
| 7 | C.P.Cadmium Yellow | CY07 |
| 8 | Arylide (Hansa) Yellow | HY08 |
| 9 | Cadmium Orange | CO09 |
| 10 | Pyrrole Orange | PO10 |
| 11 | Cadmium Red | CR11 |
| 12 | Quinacridone Red | QR12 |
| 13 | Quinacridone Crimson | QC13 |
| 14 | Quinacridone Magenta | QM14 |
| 15 | Pyrrole Red | PR15 |
| 16 | Cobalt Blue | CoB16 |
| 17 | Biz Vanadate Yellow | VY17 |

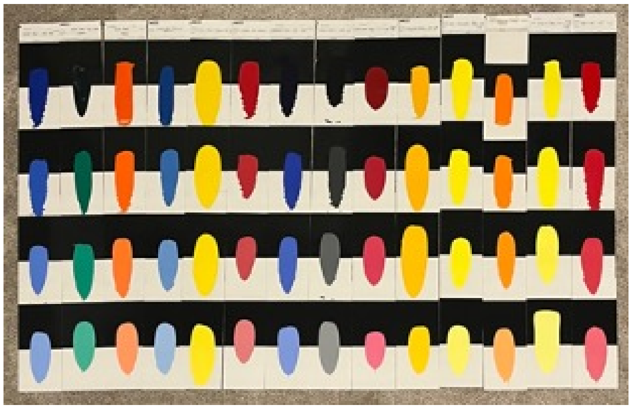

*Figure 8. Measured spectral reflectance of all tint ladders*

In this study, the two-constant Kubelka-Munk (K-M) theory was chosen for its higher accuracy relative to the single-constant model. It separately calculates the absorption and scattering coefficients and accounts for refractive index discontinuities, providing a more precise model [15]. The mass tone and a tint with 80 wt% colorants were used to calculate the absorption coefficient ($k_\lambda$) and scattering coefficient ($s_\lambda$) separated. For the Saunderson equations, $K_1$=0.03 and $K_2$=0.65 were selected. Each $k_\lambda$ and $s_\lambda$ It was calculated and optimized using the fmincon function, minimizing the root mean square error (RMSE) between the predicted spectral reflectance and the measurements.

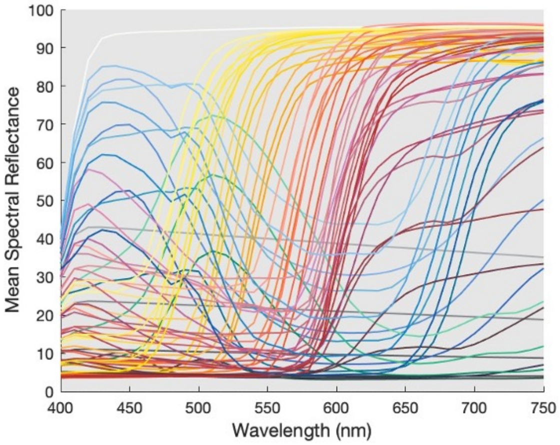

*Figure 9. A photo of mass tones and tint ladders made in this study*

Further investigation will also focus on evaluating the accuracy of the Kubelka-Munk (K-M) theory predictions for the paramers pairs. By examining the sources of prediction errors and refining the K-M model paramers, we aim to enhance the accuracy of spectral reflectance predictions for complex color formulations.

## Appendix 2

**Table 3 The calculated L*, a*, and b* values and the predicted color differences.**

| Pair No. | Colorimetry | | | $\Delta E_{2000}$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | L* | a* | b* | Netural1 | Netural2 | Tinted1 | Tinted2 | Tinted3 | Tinted4 |
| 1 | 62.79 | 15.62 | 20.76 | 2.60 | 2.61 | 4.26 | 3.57 | 3.22 | 3.37 |
| | 63.10 | 11.99 | 16.11 | | | | | | |
| 2 | 50.25 | -1.25 | -25.85 | 4.00 | 4.00 | 3.99 | 4.28 | 4.05 | 4.25 |
| | 52.11 | -2.00 | -17.93 | | | | | | |
| 3 | 48.14 | 13.29 | 11.66 | 2.35 | 2.53 | 3.60 | 3.07 | 2.93 | 2.16 |
| | 47.23 | 14.99 | 15.01 | | | | | | |
| 4 | 53.23 | 9.74 | -23.21 | 2.35 | 2.37 | 3.51 | 4.02 | 3.06 | 2.43 |
| | 55.22 | 10.27 | -20.85 | | | | | | |
| 5 | 45.93 | -18.23 | 27.07 | 2.37 | 2.50 | 5.21 | 5.36 | 4.48 | 3.31 |
| | 44.15 | -19.09 | 24.14 | | | | | | |
| 6 | 38.45 | -15.50 | 18.39 | 1.38 | 1.64 | 4.68 | 5.97 | 4.33 | 2.68 |
| | 38.95 | -13.14 | 15.87 | | | | | | |
| 7 | 38.23 | 14.42 | 17.41 | 1.59 | 1.15 | 4.19 | 3.69 | 1.75 | 3.84 |
| | 38.99 | 12.48 | 18.02 | | | | | | |
| 8 | 61.28 | 17.23 | 29.72 | 3.91 | 3.79 | 3.87 | 3.29 | 3.47 | 5.12 |
| | 60.77 | 14.35 | 34.79 | | | | | | |
| 9 | 60.80 | -18.90 | 37.56 | 4.97 | 5.35 | 7.26 | 8.10 | 7.42 | 4.17 |
| | 60.97 | -23.57 | 30.77 | | | | | | |
| 10 | 61.79 | -30.48 | -4.41 | 2.77 | 2.60 | 1.98 | 1.78 | 1.97 | 3.10 |
| | 60.71 | -28.08 | -7.61 | | | | | | |
| 11 | 61.70 | -0.84 | -23.45 | 6.80 | 7.21 | 9.10 | 8.10 | 8.32 | 6.05 |
| | 60.49 | 6.06 | -22.86 | | | | | | |
| 12 | 61.14 | 25.73 | -2.16 | 3.36 | 3.38 | 2.81 | 2.83 | 3.10 | 3.17 |
| | 61.34 | 26.74 | 2.71 | | | | | | |
| 13 | 40.55 | -0.67 | -0.32 | 10.06 | 10.06 | 10.03 | 10.04 | 10.05 | 10.03 |
| | 51.03 | -0.46 | -0.02 | | | | | | |