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Color perception through tinted eyewear: An experimental evaluation using Visual Search with reflective samples

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Abstract

Tinted eyewear alters the spectral information reaching the human eye, potentially influencing visual performance in real-world tasks. Our previous work quantified changes in color discrimination ability under tinted eyewear using a psychophysical experiment. The present study extends this investigation by employing a visual search method to evaluate perceptual sensitivity. Two psychophysical experiments were conducted to evaluate visual performance under tinted eyewear: one focused on small color difference, assessed by reaction time and accuracy of target detection, and the other on large color differences, evaluating discrimination ability with increasing viewing distance. Overall, the results suggest that color appearance–based evaluations may help account for variations in task performance under tinted eyewear, particularly for small color difference stimuli. For large color difference stimuli, performance difference caused by tinted eyewear were observed, but the relationship between prediction and performance was not clear, which needs future investigation. By comparing the experimental data with model predictions, this study aims to provide a deeper understanding of the perceptual behavior changes caused by tinted eyewear.

Introduction

Tinted eyewear is widely used in outdoor environments to reduce glare and manage the amount of light reaching the human visual system. Beyond their protective and comfort-related functions, tinted eyewear can selectively filter incoming light across the visible spectrum, potentially influencing color perception [1, 2]. Previous research has examined the effects of tinted eyewear on various aspects of visual perception, including contrast sensitivity, visual acuity, and perceived color differences [3, 4]. Although our previous studies have examined how tinted eyewear influences color appearance, including color sensitivity and perceived color differences, the present work extends this line of research to visual performance outcomes, specifically speed and detection distance. By linking changes in color appearance to measurable performance effects, this study provides a more comprehensive understanding of how transmittance characteristics impact visual function.

In our previous work, we investigated how tinted eyewear influences color perception under controlled viewing conditions. In one study [5], we examined the perception of small color differences in reflective samples, where color differences were predicted based on the eyewear's spectral transmittance and the samples' spectral reflectance. These predictions were validated through psychophysical scaling experiments and showed strong agreement with observers' perceived color differences, demonstrating that the model effectively captured color discrimination through tinted eyewear for simple color appearance tasks. In a related study [6], we extended this line of inquiry to visual performance by examining how tinted eyewear affects spatial–chromatic contrast sensitivity, reaction time, and accuracy. The results showed that eyewear with varied transmittance enhanced contrast sensitivity for specific chromatic pairs more effectively than lenses with uniform transmittance, highlighting the role of transmittance characteristics in modulating performance-related outcomes. Building on our previous work, the present study moves from color appearance–based evaluations toward performance-oriented measures.

Visual search refers to the task of locating a target among distractors and has been widely used as a fundamental paradigm for studying visual performance and attention under controlled experimental conditions [7]. Visual search tasks require observers to locate or identify a target within a spatially organized environment, which helps assess how perceptual information supports task performance, typically measured using reaction time and response accuracy. Visual search has been used in previous research as a methodological approach to study color related aspects of visual perception. Experimental studies have demonstrated that changes in color properties and viewing conditions have been shown to influence observers' efficiency and accuracy in completing visual tasks, and these effects depend on both stimulus characteristics and tasks. These findings highlight the importance of evaluating color-related factors using functional visual tasks when assessing visual performance under realistic viewing conditions [8, 9, 10].

The aim of the present study is to evaluate how tinted eyewear influences functional visual performance in tasks that require the integration of color and spatial information. Building on our previous work, in which color difference predictions based on eyewear transmittance closely aligned with observers' perceived color differences, the current study extends this framework to functional visual tasks involving spatially structured stimuli and a broader range of color differences. Specifically, we investigate whether color difference measures that successfully predict color appearance can also serve as predictors of performance outcomes, such as detection across viewing distance, thereby linking changes in color perception induced by tinted eyewear to measurable visual performance.

Experiment One: Small Color Differences

Experiment one focused on observers' ability to discriminate small color differences using a visual search task. Performance was quantified using reaction time and response accuracy.

Methodology

Stimuli and Light Source

Five parameric pairs were designed as small color difference stimuli in experiment one. The first five patches on the Macbeth

Color Checker [11], representing foliage, skin tones, blue sky, and purple 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, selected to provide accurate chromaticity matches with these patches.

Each parameric pair was then used to construct a 10 cm × 10 cm sample plate. Each plate consisted of an 8*8 array of dots with a diameter of 8 mm, resulting in a total of 64 dots. One dot located at a randomly selected position, corresponded to one color of the parameric pair, which was regarded as the target. All remaining dots were identical to the background color, as shown in Figure 4. For each parameric pair, two sample plates were prepared, each with a different background color. All the samples used in this experiment are measured by the Macbeth ColorEye 7000A spectrophotometer with UV excluded and specular component included setting. Each sample was measured three times with repositioning, and the average spectral reflectance was computed.

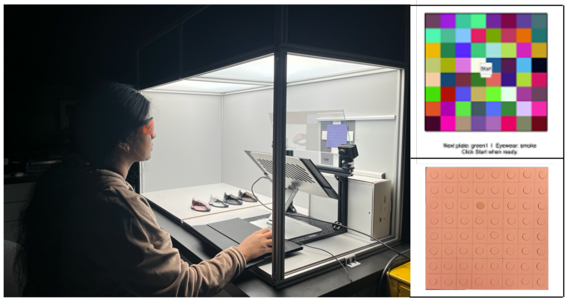

Figure 1. *Experimental setup (left), display on the beam splitter before trial onset (top right), and an example stimulus plate (bottom right).*

The experiment setup used a beam splitter to combine stimuli presented on a display (i.e., noise pattern, mouse pointer, and start button) with physical sample plate positioned inside a controlled light booth, allowing observers to indicate the target using a mouse and enabling a more precise measurement of reaction time and response accuracy. As shown in Figure 1, the sample was mounted on the back wall of the light booth, while the display was positioned on the front of the beam splitter. This arrangement allowed the visual stimuli presented on the display to align with the physical sample plate.

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]. Spectral radiance of the light source was obtained from the measurement of a Halon sample through the beam-splitter using a CR-250 spectroradiometer under a fixed measurement geometry. The measured spectral radiance for the experiment is shown in Figure 2 (black line), with a luminance of approximately 428 $\mathrm{cd/m^2}$ in the sample plane.

Eyewear Selection and Optical Characterization

Five types of eyewear were selected for this experiment, consisting of two neutral eyewear and three tinted eyewear. Spectral radiance through each eyewear were obtained from the measurement of a Halon sample using a CR-250 spectroradiometer. For each eyewear, luminance was computed by weighting the measured spectral radiance with the CIE standard photopic luminous efficiency function $V(\lambda)$. Luminous transmittance [1] was then obtained as the ratio of luminance measured with the tinted eyewear to that measured without any eyewear.

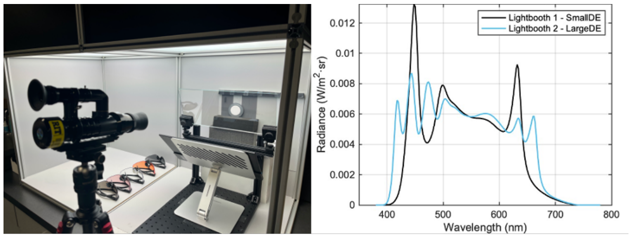

Figure 2. *Measurement Geometry of the light booth (left), measured spectral radiance of the light booth (right) used in Experiment One (black line) and Experiment Two (blue line)*

Two neutral eyewear were chosen for their relatively uniform filtering across all visible spectrum, with different luminous transmittance levels for comparison. The eyewear with higher transmittance, referred to as 'Neutral 1', has a luminous transmittance of 89% across 380nm - 780nm. The eyewear with lower transmittance, Neutral 2, shows a luminous transmittance of 16% within the same spectral range. Additionally, three tinted eyewear, labeled 'Tinted 1' through 'Tinted 3' have variable luminous transmittance. Tint 1 and Tint 3 selectively filtered across wavelengths, they were designed to reduce the transmittance at specific wavelengths, and exhibited luminous transmittance values of 52% and 17%, respectively. In contrast, Tinted 2 represented a normally colored tint with a smoother spectral transmittance and a luminous transmittance of 54%.

Color Difference Computation

Color difference predictions were computed following the methodology adopted in our previous work, with modifications to the present study. For each stimulus, the corresponding CIELAB values (L^*, a^*, b^*) were calculated using the measured spectral radiance of the light source transmitted through each eyewear, the measured spectral reflectance of the physical samples (R_λ), and the CIE 1931 standard two-degree observer color-matching functions. For each eyewear, the measured spectral radiance through the eyewear was treated as the light source. Because each eyewear exhibited a different spectral transmittance, the reference white point (X_n, Y_n, Z_n) was calculated to account for chromatic adaptation across each eyewear. Based on the computed CIELAB values, CIEDE2000 color differences (ΔE_{00}) were calculated for all stimulus pairs under each eyewear. The predicted CIEDE2000 color differences for each parameric stimulus pair under each eyewear are shown in Figure 4.

Procedure

During the experiment, observers were asked to wear the eyewear and adapt to the lighting condition for approximately 20 seconds. At the beginning of each trial, a plate with a random color cube was presented on the display (Figure 1), and observers initiated the trial by clicking a "Start" button located at the center of the scene. After clicking "Start", the noise pattern mask was removed, and observers were asked to locate the target dot that differed in color from the surrounding dots by clicking it using a mouse, as shown in Figure 1. Response accuracy was determined based on where the observers clicked the target location, and the reaction time was recorded from the disappearance of the mask until the observer's mouse click.

Observers completed the task under five eyewear presented in a random order, with two repetitions per stimulus plate, resulting in 100 trials per observer. The experiment lasted approximately 45 minutes. Twenty-four observers (aged between 19 and 39) participated in the experiment. All observers were students and faculty members from the Rochester Institute of Technology (RIT) with fundamental knowledge of color science. Normal color vision was required, and all observers passed the Ishihara color vision test [14]. Written informed consent was obtained from all observers, and the experiment protocol was approved by RIT's Human Subjects Research Office (approval FWA #01091525).

Result and Discussion

Response Accuracy

Response accuracy was evaluated to examine how tinted eyewear influenced observers' ability to correctly identify the target stimuli. For the sky blue, purple flower, and light skintone pairs, error rates remained low across all eyewear, generally below 10%. In contrast, higher error rates were observed for the dark skintone and foliage pairs, as shown in Figure 3. For the dark skintone pair, error rates increased under Tint 1 and Neutral 2, while remaining relatively low for the other eyewear. The foliage stimulus exhibited the largest performance differences in accuracy, with error rates exceeding 45% under the two neutral eyewear and Tint 2, indicating that observers had difficulty in accurately identifying the target location under these conditions.

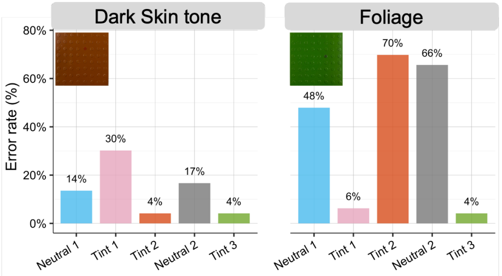

Figure 3. *Error rate as a function of eyewear in Experiment One for dark skintone and foliage pairs.*

These results suggest that response accuracy decreased when the predicted color differences between the target and background approach or fall below perceptual threshold. For example, the CIEDE2000 predictions for the foliage stimulus indicate relatively small color differences under several eyewear ($\Delta E_{00} \approx 2.1$ for Neutral 1, 0.94 for Neutral 2, and 1.44 for Tint 2). These low predicted color differences are consistent with the error rates collected from observers.

Reaction Time

In addition to response accuracy, reaction time (RT) was analyzed to further investigate the relationship between visual performance and predicted color differences. To ensure that the reaction time reflected the visual performance, only trials in which observers correctly identified the target location were included in the reaction time analysis.

To reduce the influence of extreme values while preserving the overall distribution of response times, RT data were processed in several steps. First, RTs were grouped separately for each eyewear and stimulus combination. For each group, the mean RT and the standard deviation (SD) were computed. RT values exceeding 3 SDs above the group mean were treated as outliers and were clipped by replacing them with the corresponding cutoff value (mean RT $+3\times$ SD). The eyewear was then grouped on the basis of total transmittance into high- and low- transmittance groups based on their measured luminous transmittance. Within each transmittance group, reaction time differences were computed between tinted eyewear and their corresponding neutral references, Tint 1 and Tint 2 were compared relative to Neutral 1, and Tint 3 was compared relative to Neutral 2. Finally, differences in reaction time between tinted and neutral eyewear were compared with the corresponding differences in predicted color differences (ΔE_{00}).

Figure 4 shows the mean reaction time (RT) for correctly identified targets as a function of eyewear and stimulus pair, with pairwise comparisons revealing that reaction time for certain tinted eyewear differed significantly from their corresponding neutral references for selected stimulus pairs. Across eyewear, the dark skintone and foliage stimulus pairs had generally longer reaction times and larger standard errors than the sky blue, purple flower, and light skintone pairs. This pattern is consistent with the response accuracy results reported in the previous section, indicating that these two stimulus pairs were generally more difficult to discriminate. Additionally, systematic differences in reaction time were observed between tinted eyewear and their corresponding neutral references. For the high transmittance group, pairwise comparisons revealed significantly shorter reaction times for Tint 2 relative to the Neutral 1 for the dark skintone stimulus pair ($p = 0.02$), accompanied by an increase in predicted color difference (ΔE_{00} increase of 0.96). A similar decrease in reaction time was observed for the foliage stimulus under Tint 1 compared with Neutral 1 ($p = 0.02$), corresponding to a predicted color difference increase of 2.11. For the low transmittance group, Tint 3 produced significantly shorter reaction times than Neutral 2 for three stimulus pairs ($p = 0.008$ for purple flower, $p = 0.002$ for light skintone, and $p = 0.002$ for foliage). This pattern demonstrates a clear performance advantage of Tint 3 over Neutral 2 for discriminating these stimulus pairs, even though the two eyewear have similar total transmittance.

Reaction time was examined in relation to predicted color differences for each pair. As shown in the bottom row of Figure 4. For the sky blue, purple flower, and light skintone pairs, no systematic relationship was observed between reaction time and predicted color difference (sky blue: $r = -0.01$, $p = 0.87$; purple flower: $r = 0.08$, $p = 0.11$; light skintone: $r = 0.00$, $p = 0.97$). In contrast, significant negative correlations were observed for the dark skintone and foliage stimulus pairs, indicating that larger predicted color differences were associated with shorter reaction times (dark skintone: $r = -0.41$, $p < 0.001$; foliage: $r = -0.55$, $p < 0.001$). Changes in reaction time were further examined in relation to changes in predicted color differences. Across eyewear

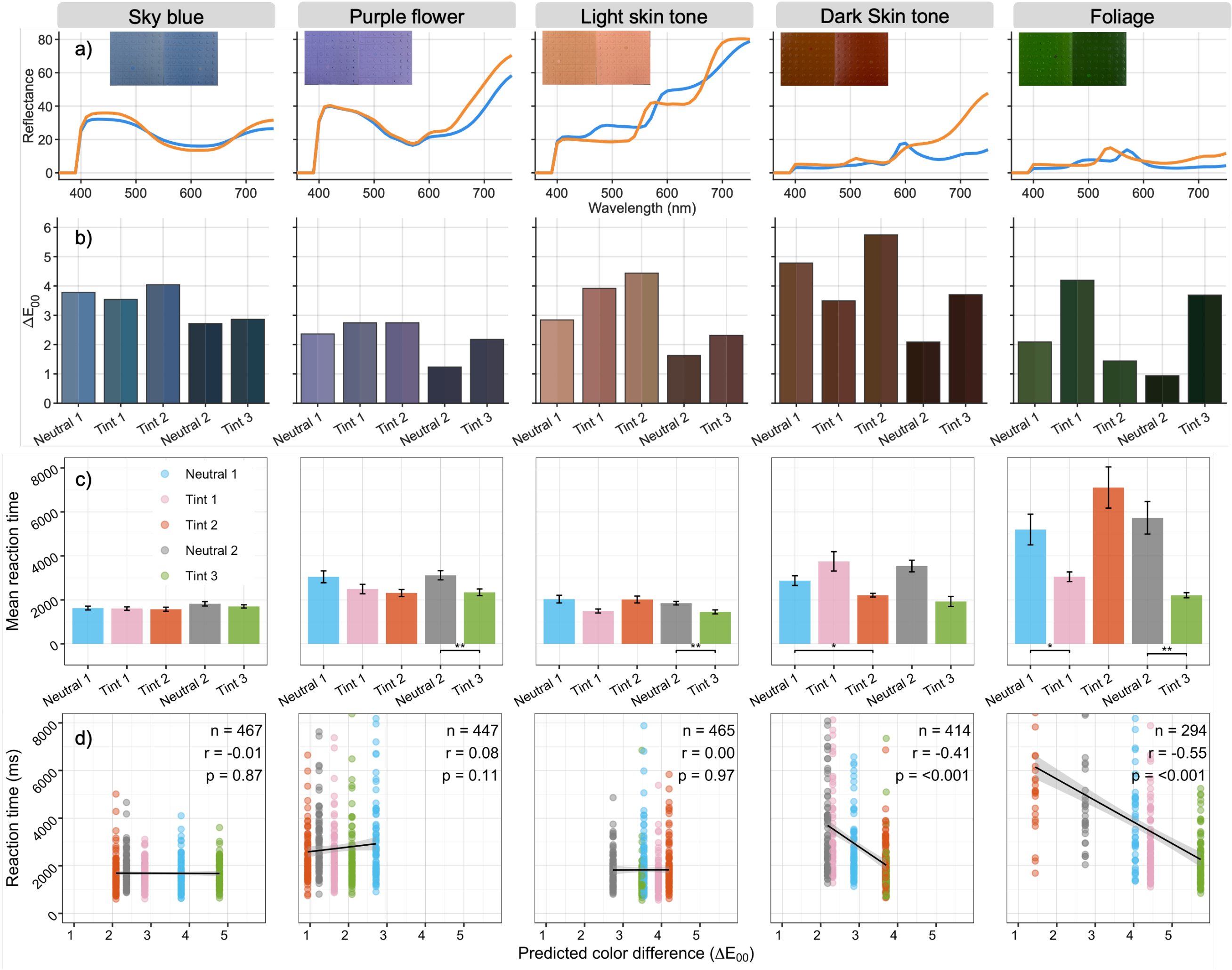

Figure 4. *Photo and reflectance of stimulus pairs, predicted color differences, reaction times (RT), and the relationship between RT and predicted color difference (ΔE_{00}) in Experiment One. a) Photos of the physical stimulus plates and their measured reflectance. b) The ΔE_{00} between target and background samples for each pair. c) The mean RT under each eyewear condition, with error bars indicating the standard error across observers and significance markers summarizing pairwise comparisons. d) The relationship between RT and ΔE_{00} for each stimulus pair. Each point represents an individual trial, colors indicate eyewear conditions, the solid line shows the linear regression fit, and the reported r value denotes the Pearson correlation between RT and ΔE_{00}.*

conditions, differences in reaction time between tinted and neutral eyewear showed a significant negative correlation with the corresponding differences in predicted color differences. As the predicted color difference increased, reaction time decreased. Pearson correlation analysis, performed on reaction time differences averaged across all observers, revealed a strong negative correlation ($r = -0.63$), as shown in Figure 5. This result indicates that eyewear conditions associated with smaller predicted color differences tended to produce longer reaction times for correctly identified targets.

Overall, these results demonstrate that reaction time differences between tinted and neutral eyewear are closely aligned with predicted changes in color difference. Stimuli associated with larger predicted ΔE_{00} values tended to support faster target localization, whereas reduced predicted color differences were associated with decreased visual search efficiency. Consistent with this pattern, when predicted color differences approached or fell below the perceptual threshold, observers required more time to locate the target, even when the target was correctly identified.

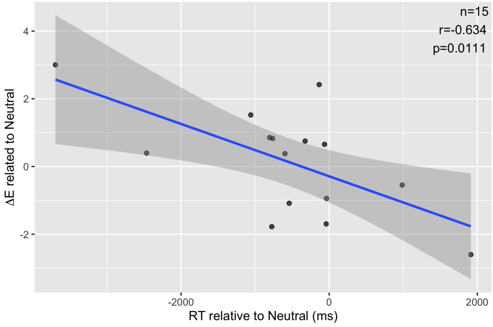

Figure 5. *Relationship between predicted color difference and reaction time. Each data point represents the mean reaction time difference for one stimulus pair plotted against the corresponding normalized predicted color difference. The solid line indicates the linear regression fit, with the 95% confidence interval.*

These findings indicate that reaction time in visual search tasks involving small color differences can be systematically predicted by color difference calculations.

Experiment Two: Large Color Differences

Experiment two was designed to assess the effects of tinted eyewear on observers' performance in discriminating large color difference stimuli as a function of viewing distance, using an orientation identification task.

Methodology

Stimuli and Light Source

Four pairs of color combinations were designed in this experiment, inspired by real-world applications such as a stop sign, a life jacket, and a safety vest in outdoor environments. Each stimulus consisted of a background (10cm*10cm) selected to match the color of foliage or open water, and the target stimuli cut in the shape of a letter "C" with a 1mm gap. In addition to the chromatic stimuli, one achromatic pair consisting of a white target on a black background was included as a reference. All physical samples were produced by mixing Golden Artist Colors matte acrylic paints according to color recipes predicted using the Kubelka-Munk theory. The measured spectral reflectance of sample pairs is shown in Figure 6.

Experiment two was conducted under an eight-channel LED light source provided by Telelumen. The spectral output was adjusted to achieve a correlated color temperature (CCT) of approximately 6500K. The luminance level was adjusted to match the light source used in experiment one. The measured spectral radiance for experiment two is shown in Figure 2 (blue line).

Procedure

During the experiment, all five stimuli were placed at the back of light booth For each stimulus, the orientation of the gap in the target was randomized across trials. Observers wore each of the five eyewear described in experiment one and were adapted to the lighting condition for approximately 20 seconds.

For each trial, observers viewed all five stimuli at a fixed viewing distance and report the gap orientation for each stimulus. Five viewing distances were tested, approximately equally spaced across a range from 5.7 m to 9.7 m. Observers began at the farthest distance and completed the task for all stimuli before moving forward to the next closer distance. A repetition was conducted in which observers began at the closest distance and move backward to the farthest distance. All stimuli are randomized for each trial, and the eyewear are provided in a random order. In total, the experiment consisted of 250 trials, and the experiment took about 45 minutes for each observer. A total of 23 observers (aged between 19 and 39) participated in the second experiment.

Results and Discussion

The primary objective of experiment two was to evaluate observers' color discrimination ability as a function of viewing distance under different eyewear. Performance was quantified using response accuracy at each tested distance, reflecting the ability to correctly identify the gap orientation of the target stimulus as viewing distance increased. For each observer, accuracy across viewing distances was examined to evaluate the sensitivity of performance to distance. For seven observers, mean accuracy at the farthest viewing distance exceeded 0.75 across all trials, indicating relatively good visual acuity and minimal performance degradation with distance. As these data did not provide meaningful constraints for comparing discrimination performance across different eyewear, they were excluded from further analysis.

Mean accuracy was computed for every stimulus and eyewear combination across the remaining 15 observers at each viewing distance. To characterize discrimination performance, psychometric functions were fitted to the accuracy data as a function of viewing distance. A probit model was used to estimate the relationship between distance and response probability for each stimulus and eyewear combination. The five eyewear were separated into low and high transmittance groups, and the fitted curve is shown in Figure 6. The dashed line represent the discrimination threshold for the four alternative force choice experiment. When the fitted psychometric curve lies above this threshold, observers are able to reliably discriminate the target orientation; when it falls below the threshold, discrimination performance is unreliable.

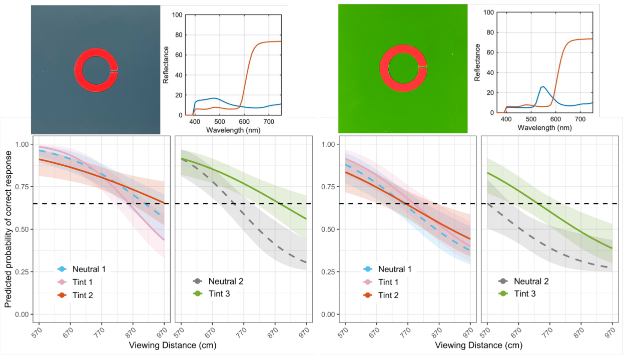

Figure 6. *Blue–red (left) and green–red (right) stimuli pairs and psychometric functions for large color-difference discrimination as a function of viewing distance, plotted with 95% confidence interval*

Across all stimulus conditions, discrimination performance decreased with increasing viewing distance. This pattern is expected because increasing viewing distance increased the spatial frequency of the stimuli, constraining discrimination performance. However, the accuracy decline varied across eyewear conditions and stimulus pairs. In particular, eyewear belonging to the high transmittance group generally supported higher accuracy over a broader range of viewing distances, whereas low transmittance eyewear exhibited earlier crossings of the discrimination threshold, indicating reduced detection abilities.

Within the high-transmittance group, only the red–green stimulus pair approached or crossed the discrimination threshold. However, no clear performance differences were observed among the three high transmittance eyewear for these stimuli, suggesting that these color pairs posed a similar level of difficulty across all high transmittance conditions. For the remaining stimulus pairs, the stimuli size and viewing distance limitations prevented further investigation for these eyewear. In contrast, more variations were observed in the low transmittance group. For the red–green and red–blue stimulus pairs, Tint 3 consistently supported higher accuracy than Neutral 2 as viewing distance increased, indicating improved discrimination performance when observers wore Tint 3. This might related to the spectral transmittance characteristics of Tint 3, which could enhance the chromatic contrast sensitivity for these specific stimulus pairs. As the color differences formula in this experiment were designed to evaluate small color difference perception, no systematic relationship was observed between discrimination accuracy and color difference predictions.

A limitation of the present experimental design is that discrimination performance for many stimulus pairs remained similar, largely limited by stimulus size and viewing distances. As a result, performance differences across eyewear were similar for several stimulus pairs. Improved experimental designs are needed to more precisely quantify performance differences across eyewear conditions, which will be essential for systematically evaluating the functional impact of tinted eyewear. In addition, further development and evaluation of perceptual models are needed to better account for discrimination performance in tasks involving large color differences.

Conclusions

This study examined how tinted eyewear influences functional visual performance using psychophysical visual search tasks. Overall, the results suggest that model-based color difference predictions may help account for variations in task performance under tinted eyewear, particularly for small color-difference stimuli. For large color-difference stimuli, performance effects of tinted eyewear were observed, but the relationship between model-based predictions and task performance was not clear and did not show a consistent pattern across conditions, indicating the need for further investigation. By comparing experimental data with model predictions, this study contributes to a better understanding of task-based visual performance changes associated with tinted eyewear.

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