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Evaluating the Impact of Tinted Eyewear on Spatial-Chromatic Contrast Sensitivity

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Abstract

This research explores the effect of various eyewear lenses, designed with varied transmittance properties, on human visual perception. These lenses are developed to enhance contrast for spatial-chromatic patterns like cyan-red (CR) and magenta-green (MG) compared to lenses with more uniform transmittance. The study evaluates participants' accuracy and response times in identifying contrast patterns, aiming to understand how different eyewear configurations affect these visual metrics. Two experiments were conducted: the first adjusted spatial frequencies to determine visibility thresholds with different eyewear, while the second utilized a 4-alternative forced-choice (4-AFC) method to measure participants' ability to identify contrast patterns. Results indicate that eyewear with varied transmittance enhances contrast sensitivity for these chromatic pairs more effectively than uniform transmittance lenses, offering valuable insights into optimizing color-enhancing eyewear for improving certain aspects of visual performance and providing broader applications in enhancing human visual perception across various visual tasks.

Introduction

Visual enhancement in protective eyewear is a useful tool for outdoor applications, such as detecting and discriminating among objects in the environment, which require high visual acuity and contrast sensitivity. These applications necessitate the development of specialized protective eyewear that optimizes visual performance under diverse environmental conditions.

Previous studies evaluating eyewear performance have largely relied on objective metrics, such as the Color Resolution Factor (CRF) and Color Volume Factor (CVF). CRF quantifies the number of distinguishable colors transmitted through the lenses, while CVF measures the range of perceivable colors compared to a clear lens. These metrics assess the ability of the lenses to maintain high color saturation and transmit wavelengths effectively. In contrast, this study takes a subjective, human-performance-centered approach, evaluating metrics like visibility thresholds, accuracy, and response times to provide a comprehensive assessment of visual performance.

The focus of this research is on spatio-chromatic contrast sensitivity, which examines the ability of the human visual system to detect spatial patterns defined by chromatic contrast, such as cyan-red and magenta-green gratings. Unlike achromatic contrast sensitivity, which involves luminance differences, chromatic contrast sensitivity depends on the differential stimulation of cone photoreceptors, short (S), medium (M), and long (L) wavelength cones, in the retina. These cones enable the perception of color by processing signals that are further interpreted in the visual cortex [5, 26, 27].

Chromatic adaptation is a critical factor in understanding the impact of color-tinted lenses on visual perception. This phenomenon involves the adjustment of the human visual system to changes in the spectral composition of light, allowing for consistent color perception under varying lighting conditions. Selective filtering of certain wavelengths by tinted lenses alters the spectral input, leading to neural recalibration and enhanced sensitivity to specific color contrasts [17, 23, 24]. By suppressing certain chromatic signals, these lenses effectively amplify the visibility of other wavelengths, improving contrast sensitivity and visual performance [30].

To measure the effect of these lenses on spatio-chromatic contrast sensitivity, this study employs a psychophysical approach using the 4-alternative forced-choice (4-AFC) paradigm. This method is statistically robust and minimizes response bias, making it ideal for assessing sensory thresholds in perceptual tasks [8, 28]. Participants are presented with spatial chromatic gratings at varying spatial frequencies, allowing for the determination of visibility thresholds. The human visual system exhibits peak sensitivity to spatial frequencies around 4 cycles per degree, with sensitivity declining at both lower and higher frequencies [10, 14, 29].

This research explores how spatial frequency, chromatic contrast, and lens transmittance properties interact to influence visual perception. By comparing performance across various eyewear configurations, including experimental lenses, reference lenses, and the comparative Other Eyewear lens, this study aims to provide insights into optimizing eyewear for applications requiring heightened visual performance, such as detecting and discriminating objects in dynamic outdoor environments [2, 6, 19]. The results of this research are expected to contribute to the development of high-performance eyewear, tailored to enhance visual capabilities in specific environments.

Methodology

The eyewear used in this research consists of two reference lenses, three experimental lenses, and one additional comparative lens referred to as Other Eyewear. Reference Lens 1 has high visible light transmission, while Reference Lens 2 has low visible light transmission. The experimental lenses include Eyewear A, which has high visible light transmission and a tint optimized for specific conditions, and Eyewear B and Eyewear C, which are dark-tinted lenses with comparatively lower visible light transmission, designed to enhance contrast under particular environmental conditions. The Other Eyewear lens also has low visible light transmission and is included as a comparative benchmark.

Eyewear A is compared with Reference Lens 1 to evaluate performance in high visible light transmission scenarios, while Eyewear B, Eyewear C, and Other Eyewear are compared with Reference Lens 2 to assess their performance in low visible light transmission conditions.These lenses are designed to enhance color contrast and visual performance, particularly in challenging environments, by optimizing color perception and discrimination through advanced tinting and filtering technologies. This study involved 27 participants, including 15 women, 11 men, and one non-binary individual. The research was conducted in two phases:

- **Experiment 1:** Aimed to determine the visual thresholds for detecting chromatic patterns while wearing different eyewear configurations. These thresholds served as input for Experiment 2 and were unique to each participant based on their performance in this phase.
- **Experiment 2:** Focused on a 4-alternative forced-choice (4-AFC) task to evaluate participants' performance in terms of two key metrics:
  1. *Correctness of response:* The probability of accurately selecting the correct color patch with a pattern when the threshold was adjusted by increasing or decreasing three levels in 2.5 cpd intervals, based on the participant-specific thresholds obtained from Experiment 1.
  2. *Response time:* The time taken to identify the correct color patch with a pattern during the 4-AFC task while wearing different eyewear.

These experiments provide insights into the variations in participants' responses to different colors and patterns across various eyewear types, offering a comprehensive understanding of how eyewear influences visual performance.

Experimental Stimuli

The stimuli for this study were derived from four opponent colors: cyan, red, magenta, and green. For the experiments, two specific color pairs were selected: cyan-red and magenta-green, based on their potential influence observed when the transmittance properties of the eyewear lenses were measured. These color pairs are selected at low contrast levels to evaluate their perceptibility with different eyewear configurations. These stimuli patches are shown in Figure 1

Each color pair consisted of distinct foreground and background colors, forming the basis for generating chromatic sine wave gratings using a Gabor filter. Gabor patterns, which combine a sinusoidal grating and a Gaussian envelope, are widely used in visual and attention experiments due to their effectiveness in simulating natural visual stimuli [2, 19]. In this study, the Gabor patterns were oriented diagonally, as diagonal orientation has been shown to produce more stable correctness responses compared to vertical orientation [14]. To generate the Gabor gratings for the color patches, key variables such as spatial frequency (measured in cycles per degree of visual angle, cpd) and the standard deviation of the Gaussian envelope were used. Spatial frequency determines the spacing between the grating bars, with higher spatial frequencies corresponding to narrower bars, while the standard deviation of the Gaussian envelope controls the width of the Gabor pattern [9].

Experiment 1: Stimuli were displayed at an initial fixed spatial frequency of 5 cpd. Participants used a slider to adjust the spatial frequency dynamically to identify their visibility threshold while wearing different eyewear configurations, as well as with no lenses.

Experiment 2: Stimuli were selected based on the thresholds identified in Experiment 1 without lenses. For each participant, stimuli were adjusted by three points above and below from their threshold in 2.5 cpd intervals. These stimuli served as input for a 4-AFC (4-Alternative Forced Choice) experiment.

In each trial of the 4-AFC experiment, participants were presented with four randomly arranged patches: one containing the Gabor pattern and the remaining three consisting of a uniform gray background. The task required participants to identify the patch containing the Gabor pattern. This design allowed for a robust assessment of correctness response and response time under varying eyewear conditions. To ensure accurate color reproduction, the stimuli patches were calibrated for display on an Epson projector. This calibration involved measuring approximately 460 colors projected onto the display using a CR250 spectrometer. The measured values were used to calculate color differences and confirm that the projector accurately reproduced the intended colors. A display model was then computed to ensure precise color rendering throughout the experiments. For each selected color pair, a Gabor sinewave pattern representing a contrast pattern was generated. This was achieved by multiplying a sinusoidal wave with a Gaussian function, creating a visually distinct pattern. The resulting Gabor patterns were then applied to the calibrated color pairs to produce the final stimuli patches used in the experiments. Participants were positioned approximately 6 feet away from the projector display during the experiments. This distance was carefully chosen to maintain a consistent visual angle, as both the viewing distance and the size of the stimulus significantly affect the perception of the contrast Gabor patterns.

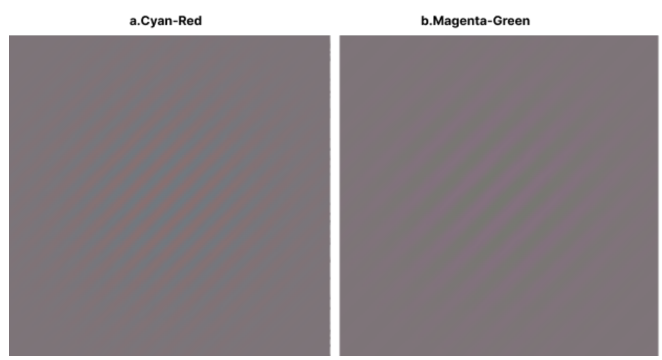

Figure 1. Stimuli used in the experiments representing the two color pairs: (Left) Cyan-Red and (Right) Magenta-Green. These spatial chromatic gratings were generated using Gabor patterns with calibrated colors to evaluate participants' contrast sensitivity across various eyewear configurations.

Experimental Setup

Experiment 1: Visual Threshold Estimation

In this experiment, participants were presented with a color pair and instructed to use a slider to adjust the spatial frequency of a Gabor pattern until the pattern disappeared and was perceived as a single solid color. The experimental setup is shown in Figure 2.

The slider specifically controlled the spatial frequency, while the contrast remained constant. As the spatial frequency increased, the gaps between the gratings became smaller, eventually blending into what appeared as a uniform color to the participants.

Contrast sensitivity thresholds were measured across seven conditions: no lens, two neutral reference lenses (Reference Lens 1 and Reference Lens 2), three experimental lenses (Eyewear A, Eyewear B, and Eyewear C), and Other Eyewear. The thresholds obtained from the no-lens condition were further utilized to select stimuli for Experiment 2. Specifically, the no-lens threshold, along with three points forward and three points backward in increments of 2.5 cpd, were chosen as the input stimuli for the next phase.This approach aimed to evaluate whether different eyewear configurations improved visual performance by increasing contrast sensitivity thresholds compared to the neutral reference eyewear.

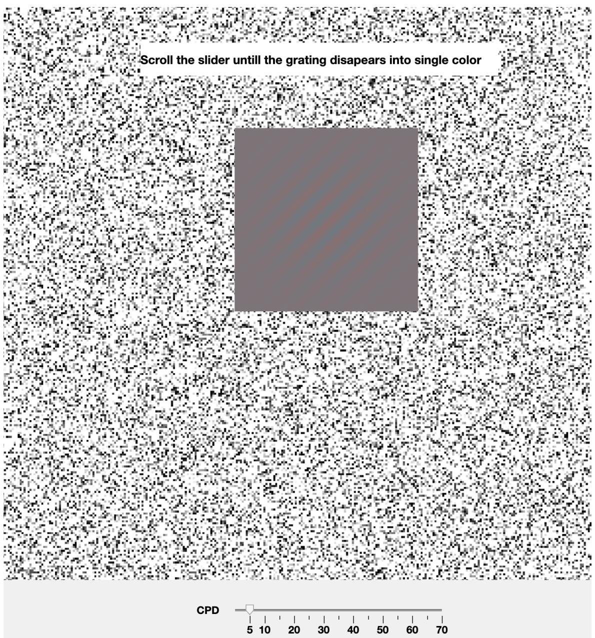

Figure 2. Visual threshold estimation interface used in Experiment 1. Participants adjusted the slider to increase spatial frequency until the grating pattern within the patch disappeared, blending into a single solid color. The spatial frequency is displayed in cycles per degree (CPD) on the slider.

Experiment 2: 4-Alternative Forced Choice

In this experiment, the thresholds derived from Experiment 1 were encoded as follows: the threshold value was labeled as 0, while additional values were assigned as ± 2.5, ± 5, and ± 7.5. A 4-AFC method was employed due to its suitability for contrast sensitivity experiments. This method reduces the probability of guessing correctly to 25%, offering greater reliability and precision compared to methods with fewer alternatives. The 4-AFC paradigm also minimizes decision criterion bias, resulting in consistent and unbiased data collection [21, 8].

Participants were tasked with identifying the color patch containing a Gabor grating in each trial while wearing various eyewear configurations, including experimental lenses, reference lenses, and Other Eyewear. The experimental setup is illustrated in Figure 3.The experiment consisted of six sections, each corresponding to a different eyewear configuration. Within each section, participants were presented with seven stimuli levels, each repeated four times, resulting in 56 trials per section. Across all six sections, participants completed a total of 336 trials. In each trial, the position of the Gabor grating was randomized for all color pairs, ensuring variability in the stimuli presented. Participants' responses were recorded as '1' for correct identifications and '0' for incorrect ones. The experiment provided data on participants' accuracy and response times (for both correct and incorrect responses) across various eyewear configurations. These metrics were used to evaluate the effectiveness of different lenses in enhancing visual performance for chromatic contrast patterns.

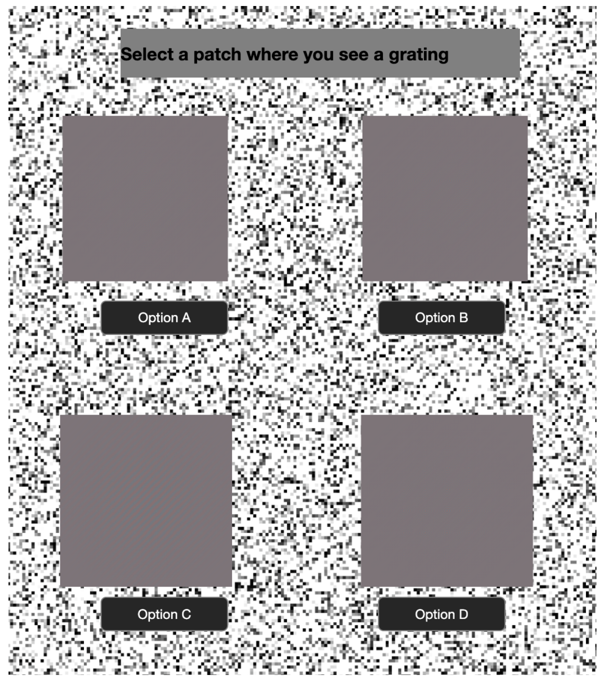

Figure 3. 4-Alternative Forced Choice (4-AFC) task interface used in Experiment 2. Participants were instructed to identify and select the patch containing the Gabor pattern among the four presented options (A, B, C, or D) against a noisy background.

Results

Experiment 1 Results: Visual Threshold Across Different Eyewear Configurations

In Experiment 1, participants determined their spatial frequency thresholds (measured in cycles per degree, cpd) while wearing various eyewear configurations. Pairwise comparisons of mean cutoff frequencies across different types of eyewear were analyzed for two pairs of opponent colors: Cyan-Red (CR) and Magenta-Green (MG). The paired t-tests evaluated the statistical significance of differences in thresholds, as shown in Figure 4.

The mean cut-off frequencies for all eyewear configurations across both color pairs are presented in Figure 5. This figure highlights the comparative performance of eyewear in enhancing spatial frequency thresholds for low-contrast stimuli.

Key Findings

The comparison between No Lens and Reference Lens 1 revealed that for the Cyan-Red pair, the mean cut-off frequency de-

Pair_ID	Group1	Group2	Mean_Group1	Mean_Group2	T_Statistic	P_Value	Sig	DF
CR	Cutoff_No_lens	Cutoff_Ref_1	30.86607143	29.17464286	3.80441	<0.05	1	27
CR	Cutoff_No_lens	Cutoff_Eyewear_A	30.86607143	31.09107143	-0.28046	0.781	0	27
CR	Cutoff_Ref_1	Cutoff_Eyewear_A	29.17464286	31.09107143	-2.35559	<0.05	1	27
CR	Cutoff_Ref_2	Cutoff_Eyewear_B	23.20392857	25.31285714	-4.13567	<0.05	1	27
CR	Cutoff_Ref_2	Cutoff_Eyewear_C	23.20392857	26.25392857	-6.14077	<0.05	1	27
CR	Cutoff_Other_Eyewear	Cutoff_Eyewear_B	24.17857143	25.31285714	-2.5885	<0.05	1	27
CR	Cutoff_Other_Eyewear	Cutoff_Eyewear_C	24.17857143	26.25392857	-5.54002	<0.05	1	27
MG	Cutoff_No_lens	Cutoff_Ref_1	26.69	25.53	2.980998	<0.05	1	27
MG	Cutoff_No_lens	Cutoff_Eyewear_A	26.69	27.58607143	-1.13058	0.268	0	27
MG	Cutoff_Ref_1	Cutoff_Eyewear_A	25.53	27.58607143	-2.41963	<0.05	1	27
MG	Cutoff_Ref_2	Cutoff_Eyewear_B	20.27642857	22.15571429	-3.98825	<0.05	1	27
MG	Cutoff_Ref_2	Cutoff_Eyewear_C	20.27642857	22.87428571	-5.24172	<0.05	1	27
MG	Cutoff_Other_Eyewear	Cutoff_Eyewear_B	21.04535714	22.15571429	-2.26657	<0.05	1	27
MG	Cutoff_Other_Eyewear	Cutoff_Eyewear_C	21.04535714	22.87428571	-4.20098	<0.05	1	27

Figure 4. *Paired t-test results comparing the mean cut-off frequencies (cycles per degree, cpd) for various eyewear configurations across two chromatic color pairs (Cyan-Red and Magenta-Green). The table includes statistical comparisons between No Lens, Reference Lenses 1 and 2, Eyewear A, Eyewear B, Eyewear C, and Other Eyewear. Mean values for each group, t-statistics, p-values, and significance levels are provided. Significant differences ($p < 0.05$) are highlighted, showcasing the relative performance of each eyewear type in enhancing spatial frequency thresholds.*

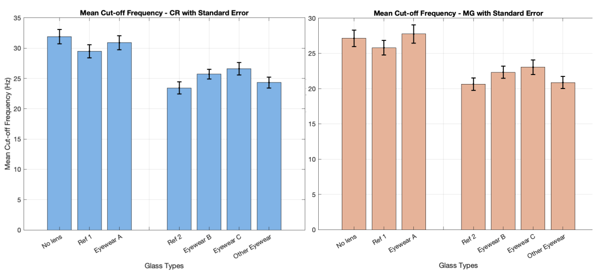

Figure 5. *Mean cut-off frequency (cycles per degree, cpd) for various eyewear types, including No Lens, Reference Lenses 1 and 2, Eyewear A, Eyewear B, Eyewear C, and Other Eyewear, across two chromatic color pairs (Cyan-Red and Magenta-Green). The error bars represent the standard error of the mean for each condition.*

creased significantly from 30.87 cpd (No Lens) to 29.17 cpd (Reference Lens 1, $p < 0.05$). Similarly, for the Magenta-Green pair, the cut-off frequency dropped from 26.69 cpd (No Lens) to 25.53 cpd (Reference Lens 1, $p < 0.05$). This indicates that wearing Reference Lens 1 slightly reduced spatial frequency thresholds.

When comparing No Lens and Eyewear A, no significant difference was observed for the Cyan-Red pair, with cut-off frequencies of 30.87 cpd (No Lens) and 31.09 cpd (Eyewear A, $p = 0.781$). For the Magenta-Green pair, Eyewear A (27.59 cpd) showed a marginally higher threshold compared to No Lens (26.69 cpd), but this difference was not statistically significant ($p = 0.268$).

The comparison of Reference Lens 1 and Eyewear A showed significant differences for both color pairs ($p < 0.05$), with Eyewear A yielding higher thresholds. For the Cyan-Red pair, the mean threshold increased from 29.17 cpd (Reference Lens 1) to 31.09 cpd (Eyewear A). Similarly, for the Magenta-Green pair, the thresholds rose from 25.53 cpd (Reference Lens 1) to 27.59 cpd (Eyewear A), demonstrating the superior performance of Eyewear A.

For Reference Lens 2 versus Eyewear B and C, both experimental lenses consistently outperformed Reference Lens 2. For the Cyan-Red pair, thresholds increased from 23.20 cpd (Reference Lens 2) to 25.31 cpd (Eyewear B) and 26.25 cpd (Eyewear C), both statistically significant ($p < 0.05$). For the Magenta-Green pair, Eyewear C (22.87 cpd) also significantly outperformed Reference Lens 2 (20.28 cpd, $p < 0.05$).

Lastly, the comparison of Reference Lens 2 and Other Eyewear showed intermediate performance for the latter. For the Cyan-Red pair, the mean cut-off frequency was 24.18 cpd (Other Eyewear), which was significantly lower than Eyewear C (26.25 cpd, $p < 0.05$). Similarly, for the Magenta-Green pair, thresholds were 21.05 cpd (Other Eyewear) versus 22.87 cpd (Eyewear C, $p < 0.05$). This highlights the comparatively better performance of Eyewear C.

Experiment 2 Results: Threshold Analysis of (4-AFC)

In the 4-Alternative Forced Choice (4-AFC) paradigm, a threshold of 0.625 (62.5%) was adopted as the performance criterion to evaluate participants' sensitivity to visual stimuli. This threshold is widely used in psychophysical experiments due to its theoretical and practical significance:

- In a 4-AFC task, the chance level for a correct response is 25% (1 out of 4). A 62.5% threshold ensures that performance is well above chance while avoiding ceiling effects that can occur with near-perfect detection rates.
- The threshold provides a robust and unbiased measure of sensory sensitivity, minimizing random guessing effects and enhancing statistical reliability.

In this study, the threshold label "0" represents the no-lens threshold determined from Experiment 1. Additional threshold labels correspond to three steps above and below from the no-lens threshold, each in intervals of 2.5 cpd (e.g., -2.5, -5.0, -7.5, and 2.5, 5.0, 7.5). The effectiveness of eyewear is evaluated based on changes in thresholds relative to the no-lens reference. An increase in thresholds compared to the no-lens reference indicates that the eyewear enhances contrast sensitivity and improves participants' ability to detect visual patterns.

Probit Fit and Confidence Intervals

The analysis employs probit regression, a widely used statistical method in psychophysics for fitting binary response data (e.g., correct vs. incorrect responses). Probit regression models the relationship between stimulus intensity (label) and response probability, enabling the estimation of the sensory threshold (62.5%) and its associated confidence intervals:

- **Probit fit curve:** The red curve in the plots represents the probit fit, which smooths the measured data and predicts the proportion of correct responses at varying stimulus labels.
- **Confidence intervals (CI):** The blue dashed lines represent the 95% confidence intervals of the probit fit. These intervals provide a measure of uncertainty in the estimated relationship, reflecting variability across participants.
- **Threshold marker:** The threshold is the stimulus intensity at which the predicted probability of a correct response reaches 62.5%. This value is marked on the plot with vertical and horizontal dashed lines. The lower and upper confidence interval bounds are also marked to show the range of uncertainty in the threshold estimate.

By visualizing the probit fit and confidence intervals, the plots effectively capture both the central tendency and variability of participants' responses, offering a detailed and intuitive understanding of how different eyewear configurations influence contrast sensitivity.

Results and Observations

Cyan-Red pair: For cyan-red pair, the comparison of thresholds revealed that Eyewear A (6.29) consistently enabled participants to detect gratings at significantly higher thresholds than Reference Lens 1 (3.25). This highlights the superior contrast sensitivity of Eyewear A, making it more effective for tasks requiring precise visual discrimination.

When comparing Reference Lens 2 (-6.16) with Eyewear B (-3.00), Eyewear C (-0.16), and Other Eyewear (-3.33), Reference Lens 2 exhibited the lowest threshold, indicating reduced contrast sensitivity relative to the other eyewear. Among this group, Eyewear C achieved the highest threshold, suggesting the best performance, followed by Eyewear B and Other Eyewear, which showed similar thresholds.

Figure 6 presents the tabulated threshold values along with their confidence intervals for cyan-red pair. Figure 7 (left panel) visually illustrates these thresholds and confidence intervals, highlighting the superior performance of Eyewear A and Eyewear C.

Magenta-Green pair: For magenta-green pair, the thresholds for Eyewear A (6.13) were again higher compared to Reference Lens 1 (2.62), confirming the superior contrast enhancement capabilities of Eyewear A.

Comparing Reference Lens 2 (-7.44) with Eyewear B (-2.42), Eyewear C (-0.24), and Other Eyewear (-3.51), Reference Lens 2 exhibited the most impaired performance, similar to its results in cyan-red pair. Eyewear C outperformed Eyewear B and Other Eyewear, achieving the best threshold among these configurations.

Figure 6 presents the numerical results for magenta-green pair, while Figure 7 (right panel) provides a visual comparison of the thresholds and confidence intervals. It clearly depicts the consistent advantage of Eyewear A over the reference lenses and the improved performance of Eyewear C over other configurations.

Experiment 2: Response Time Analysis

The response time analysis from the second experiment evaluates how quickly participants identified the correct color patch containing a Gabor pattern under different eyewear configurations during a 4-AFC task. The results provide insights into the efficiency of various eyewear configurations based on mean response times (in seconds) and statistical comparisons shown in Figure 8 and Figure 9.

Key Findings

For mean response time, results varied across the eyewear configurations. For cyan-red pair, Reference Lens 2 and Eyewear B demonstrated shorter response times compared to other configurations, indicating faster and more efficient visual processing. Eyewear A showed slightly longer response times than Reference Lens 2 and Eyewear B but outperformed configurations like Reference Lens 1 and Other Eyewear. For magenta-green pair, Eyewear C and Other Eyewear showed slightly improved response times over Reference Lens 2, suggesting better support for faster decision-making. Eyewear A exhibited moderate performance, with response times falling between Reference Lens 1 and Reference Lens 2, indicating its potential in specific scenarios.

Pair_ID	Glass	Threshold	Lower_CI	Upper_CI
CR	Ref_1	3.25	2.41	4.28
CR	Eyewear_A	6.29	5.16	7.95
CR	Ref_2	-6.16	-8.57	-4.44
CR	Eyewear_B	-3	-4.12	-2.04
CR	Eyewear_C	-0.16	-1.06	0.68
CR	Other_Eyewear	-3.33	-4.56	-2.29
MG	Ref_1	2.62	1.77	3.51
MG	Eyewear_A	6.13	5.04	7.69
MG	Ref_2	-7.44	-10.39	-5.44
MG	Eyewear_B	-2.42	-3.62	-1.43
MG	Eyewear_C	-0.24	-1.24	0.71
MG	Other_Eyewear	-3.51	-5.2	-2.19

Figure 6. *Threshold values with their corresponding 95% Confidence Intervals (CI) for different eyewear configurations across cyan-red pair and magenta-green pair. These thresholds quantify the contrast sensitivity for each eyewear type, with higher values representing better performance.*

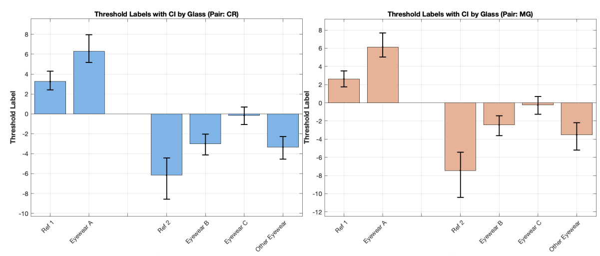

Figure 7. *Bar plots of threshold labels with 95% confidence intervals for different eyewear configurations. The left panel corresponds to cyan-red pair, and the right panel corresponds to magenta-green pair. Eyewear A consistently shows higher thresholds, while Eyewear C demonstrates better performance compared to other options in both pairs.*

Pair_ID	Group1	Group2	Mean_Group1	Mean_Group2	T_Statistic	P_Value	Sig	df
CR	RT_Ref_1	RT_Eyewear_A	3.644074074	3.153703704	3.27752	<0.05	1	26
CR	RT_Ref_2	RT_Eyewear_B	3.885555556	3.872592593	0.056384	0.955	0	26
CR	RT_Ref_2	RT_Eyewear_C	3.885555556	3.695185185	1.169873	0.253	0	26
CR	RT_Other_Eyewear	RT_Eyewear_B	3.781111111	3.872592593	-0.52482	0.604	0	26
CR	RT_Other_Eyewear	RT_Eyewear_C	3.781111111	3.695185185	0.751047	0.459	0	26
MG	RT_Ref_1	RT_Eyewear_A	3.689259259	3.354444444	1.544815	0.134	0	26
MG	RT_Ref_2	RT_Eyewear_B	3.97962963	3.898888889	0.458678	0.65	0	26
MG	RT_Ref_2	RT_Eyewear_C	3.97962963	3.608148148	2.155392	<0.05	1	26
MG	RT_Other_Eyewear	RT_Eyewear_B	3.973703704	3.898888889	0.568552	0.575	0	26
MG	RT_Other_Eyewear	RT_Eyewear_C	3.973703704	3.608148148	2.29546	<0.05	1	26

Figure 8. *Statistical results of paired t-tests comparing response times (RT) between different eyewear configurations for cyan-red pair and magenta-green pair. The table includes mean response times, t-statistics, p-values, and significance levels. Significant differences ($p < 0.05$) indicate that certain eyewear configurations, such as Reference Lens 1 vs. Eyewear A and Reference Lens 2 vs. Eyewear C, significantly affect response efficiency.*

The statistical analysis revealed significant differences between certain configurations. For cyan-red pair, Reference Lens 1 vs. Eyewear A showed a significant difference ($p < 0.05$), suggesting Reference Lens 1 allowed faster responses compared to Eyewear A. Similarly, Reference Lens 2 vs. Eyewear B also

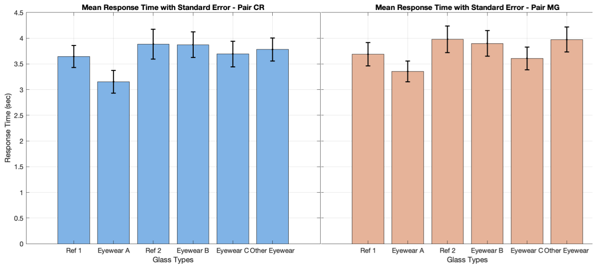

Figure 9. *Mean response time with standard error for each eyewear configuration across cyan-red pair and magenta-green pair. Response times were recorded during the 4-alternative forced-choice (4-AFC) task, revealing variations in visual processing efficiency. Eyewear A, Eyewear B, and Eyewear C demonstrated shorter response times, suggesting enhanced visual performance compared to other configurations.*

showed a significant improvement ($p < 0.05$), indicating Eyewear B provided better response efficiency than Reference Lens 2. Eyewear A performed comparably to Reference Lens 1 and better than Other Eyewear, though without significant improvement over Reference Lens 2 or Eyewear B. For magenta-green pair, Reference Lens 2 vs. Eyewear B ($p < 0.05$) and Reference Lens 2 vs. Eyewear C ($p < 0.05$) demonstrated that these eyewear configurations improved response time over neutral configurations like Reference Lens 2. Eyewear A did not show statistically significant differences compared to Reference Lens 1 but still performed better than Reference Lens 2.

In terms of performance trends, Eyewear A consistently delivered reliable response times across both color pairs, suggesting its suitability for balanced visual conditions, though it may not be ideal for tasks demanding higher contrast sensitivity or rapid responses. Reference Lens 1 showed consistent response times, reflecting minimal distortion and high visual clarity. Eyewear B and Eyewear C, both color-enhanced, exhibited significantly shorter response times, highlighting their efficiency in enhancing contrast and facilitating rapid decision-making. On the other hand, Reference Lens 2, as a neutral reference, generally resulted in slower response times compared to the color-enhanced eyewear, demonstrating its limitations in contrast-enhancing scenarios.

Discussion and Future Work

This study demonstrates the significant impact of eyewear configurations on human visual performance, particularly in the context of chromatic contrast sensitivity and response times. The findings confirm that specialized eyewear can enhance visual sensitivity and reduce response times under challenging visual conditions. Among the tested eyewear, Eyewear A consistently delivered higher thresholds for detecting chromatic patterns, outperforming reference lenses such as Reference Lens 1 and Reference Lens 2. Meanwhile, color-enhanced eyewear such as Eyewear C and Eyewear B exhibited shorter response times, emphasizing their efficiency in facilitating rapid visual detection.

In terms of spatial frequency thresholds derived from Experiment 1, Eyewear A maintained higher thresholds than Reference Lens 1 across both chromatic pairs, highlighting its ability to enhance contrast sensitivity. Eyewear C consistently achieved the best performance among color-enhanced eyewear, surpassing both Eyewear B and Other Eyewear. Reference Lens 2, used as a neutral reference, consistently exhibited the lowest thresholds, indicating its limited capacity to enhance contrast sensitivity compared to the advanced eyewear.

The response time analysis from Experiment 2 further emphasized the advantages of advanced eyewear configurations. Eyewear C and Eyewear B enabled participants to respond more quickly during the 4-alternative forced-choice (4-AFC) task, indicating their efficacy in improving visual detection. Eyewear A, while not demonstrating the fastest response times, provided reliable performance, suggesting its suitability for scenarios requiring a balance between sensitivity and enhancement. Reference Lens 1, while consistent in its performance, was generally outperformed by advanced eyewear options such as Eyewear A and Eyewear C in both thresholds and response times.

The study also revealed that not all differences were significant across configurations. For example, the comparison of No Lens with Eyewear A showed no statistically significant improvement in certain conditions, indicating that not all eyewear configurations resulted in substantial enhancements. These results highlight the need to consider the specific attributes of eyewear when evaluating their effectiveness for different visual tasks.

The use of probit regression for analyzing sensory thresholds provided a robust statistical framework for estimating thresholds and their associated confidence intervals. This approach facilitated a detailed understanding of variability in participants' responses and effectively highlighted differences among eyewear configurations.

Overall, the findings underscore the importance of tailoring eyewear design to enhance visual performance for diverse applications. Eyewear A and Eyewear C demonstrated significant advantages in improving contrast sensitivity and response times, making them well-suited for tasks requiring precise visual detection. Future studies should expand on these results by exploring additional chromatic pairs, incorporating real-world scenarios, and refining lens designs to further optimize visual performance across varied environments.

Future research should address several key areas to build on the findings of this study:

1. **Luminance Normalization:** Future work should normalize luminance across different eyewear to eliminate brightness variations as a confounding factor, ensuring that observed differences are solely due to chromatic and spatial enhancements.
2. **Temporal Stimulus Evaluation:** Temporal stimuli, such as flickering patterns or dynamic scenes, should be introduced to evaluate the impact of eyewear on temporal visual processing and its interaction with chromatic contrast sensitivity.
3. **Real-World Scenarios:** Studies should incorporate naturalistic visual tasks, such as target detection and object recognition in outdoor simulated environments, to assess the applicability of eyewear in practical settings.
4. **Visual Representations:** The inclusion of visual stimuli and example tasks in future work should provide a more intuitive understanding of the challenges and benefits associated with different eyewear configurations.
5. **Expanded Eyewear Testing:** Additional eyewear configurations, including emerging lens technologies and competi-

tor products, should be included to provide a broader comparison of performance metrics.

One important limitation of this study is that the observed performance differences were specific to the opponent chromatic pairs tested (Cyan-Red and Magenta-Green). These pairs were selected based on the specialized transmission properties of the tested lenses. The results may differ with other opponent chromatic pairs or for eyewear configurations optimized for alternative spectral bandwidths. Addressing these factors in future work will enhance the generalizability of the findings and provide a more comprehensive understanding of eyewear performance.

Conclusion

This research underscores the critical role of eyewear design in enhancing human visual perception, particularly for applications requiring heightened contrast sensitivity and rapid response times. Eyewear A emerged as the most effective in enhancing spatial frequency thresholds, demonstrating its capability to amplify visual sensitivity to chromatic patterns. Color-enhanced eyewear such as Eyewear C and Eyewear B, on the other hand, excelled in reducing response times, making them suitable for tasks requiring swift and accurate visual processing.

The findings have significant implications for the design of high-performance eyewear tailored for specific applications and tasks. While Eyewear A is ideal for applications demanding precise detection of chromatic patterns, color-enhanced eyewear such as Eyewear C and Eyewear B are better suited for environments where rapid decision-making is critical. Reference Lens 2, with its limited enhancement capabilities, was the least effective in improving visual performance, emphasizing the need for advanced tinting and filtering technologies in eyewear design.

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