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Color Perception through Tinted Eyewear: Theoretical and Computational Perspective

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Abstract

Tinted eyewear acts as a wavelength-dependent spectral filter in the visual chain and can alter both perceived color appearance and color discrimination, yet its perceptual impact is typically assessed only through physical transmittance or task-specific criteria. This paper proposes a theoretical and computational framework for evaluating tinted eyewear by integrating spectral transmittance with illumination spectra and luminance level. Color appearance changes are predicted using CIECAM16 attributes and bin-based gamut visualizations derived from the TM-30 Color Evaluation Samples, while discrimination performance is assessed for both small and large color differences and validated against behavioral data from two psychophysical experiments. Comparisons among CAM16-UCS color differences, CIEDE2000, HyAB, and cone-contrast metrics show that appearance-based measures effectively describe global color appearance changes, whereas cone-contrast–based metrics exhibit the strongest correspondence with behavioral discrimination performance. The framework provides a perceptually grounded basis for evaluating and comparing tinted eyewear across applications where both color appearance and visual performance are critical.

Introduction

Tinted eyewear is widely used across everyday, professional, and specialized visual environments, including sunglasses, protective eyewear, sports lenses, and wavelength-selective filters used in industrial and other contexts. In all such cases, the eyewear acts as a spectral filter inserted directly into the visual chain, modifying the spectral distribution of light reaching the human visual system. As a result, tinted eyewear has the potential to alter perceived color appearance[1], contrast[2], and color discrimination[3] across a wide range of visual tasks. However, despite its prevalence, the perceptual consequences of viewing scenes through spectrally selective eyewear remain inadequately characterized from a color-perception perspective.

Existing standards and guidelines for eyewear focus primarily on safety, optical density, luminous transmittance, and task-specific visibility requirements, such as signal recognition or glare reduction [4, 5]. Although these specifications are essential for ensuring adequate protection and visibility, they provide limited insight into how tinted eyewear alters global color appearance or the perceptual relationships among colors within a scene. Previous experimental studies have demonstrated that tinted lenses can influence contrast sensitivity, color naming performance, and task-specific visual behavior under certain conditions [6, 7, 8, 9]. However, these findings are typically reported for specific tasks, lighting environments, or color subsets, and do not produce a general, quantitative framework to evaluate the perceptual impact of eyewear on the appearance of colors in complex visual scenes.

Several prior studies have investigated the perceptual impact of tinted eyewear through computational simulation approaches, particularly in the context of laser eye protection and wavelength-selective filters. These works typically model the spectral transmittance of the eyewear and propagate its effects through display or scene spectra to predict changes in color appearance as viewed by a human observer [10, 11]. Such simulations have been valuable in illustrating qualitative shifts in color appearance and assessing potential visibility issues for specific applications. However, these studies generally focus on forward simulation of appearance rather than on the evaluation of perceptual metrics, and they do not systematically assess which computational representations best correspond to observed human perceptual or behavioral responses. As a result, the relationship between simulated color changes and measurable perceptual outcomes remains largely unexplored.

From a color science perspective, tinted eyewear presents a problem closely related to that of light source evaluation: a spectral modification is applied to a visual stimulus, and the resulting perceptual differences must be quantified in a way that is both perceptually meaningful and computationally tractable. In lighting research, this challenge has motivated the development of color rendition metrics, such as IES TM-30, which combine well-defined color sample sets with perceptually motivated metrics and visualization tools to assess color fidelity and gamut changes [12]. By contrast, no analogous framework currently exists for evaluating the perceptual performance of tinted eyewear, despite the fact that both problems involve spectral filtering followed by human color perception.

A central difficulty in developing such a framework lies in the choice of an appropriate perceptual metric. Multiple candidate representations of color difference and perceptual change are available, each grounded in different theoretical assumptions. Uniform color difference metrics such as CIEDE2000 and HyAB operate in perceptually uniform color spaces and are widely used to quantify color differences and discrimination between surface colors under controlled viewing conditions [13, 14]. Cone-contrast–based representations describe changes in an earlier stage of visual processing and are closely related to detection and discrimination thresholds [15]. Color appearance models such as CIECAM16 aim to predict perceived attributes of color appearance under varying viewing conditions, including changes in illumination and adaptation [16]. While each of these approaches has been used independently to study color perception, their relative ability to predict perceptual changes induced by tinted eyewear, and consequent performance on visual tasks, has not been systematically evaluated.

In this paper, we propose a theoretical and computational framework for evaluating the perceptual impact of tinted eyewear based on its spectral transmittance. The framework draws inspiration from color rendition evaluation methods and combines a representative set of color samples with perceptually motivated metrics. Specifically, we compare predictions derived from CAM16-UCS color differences, cone-contrast metric, HyAB, and CIEDE2000 against behavioral data obtained from two psychophysical experiments investigating the perceptual effects of tinted eyewear [17]. By directly relating computational predictions to empirical measures of perceptual change, this work assesses which classes of metrics best capture human perceptual responses to spectral filtering by eyewear.

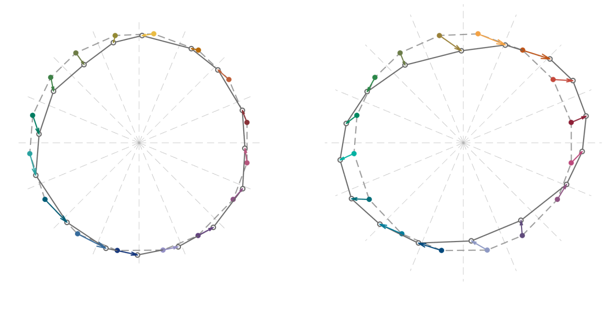
Theoretical Framework and Evaluation Methodology

There are three components of the computational framework that we used to evaluate the perceptual effects of tinted eyewear: (1) the selection of representative color sample sets, (2) the quantification and visualization of color appearance changes induced by spectral filtering, and (3) the assessment of contrast and color discrimination effects using alternative perceptual metrics. Together, these components provide a general methodology for analyzing eyewear-induced perceptual changes independent of any specific task or application.

Color Sample Sets

As a starting point, we adopt the IES TM-30 Color Evaluation Samples (CES), consisting of 99 spectrally defined surface reflectances. The TM-30 CES were specifically designed to provide uniform coverage of CIECAM02 while maintaining diversity in spectral structure. Importantly, the CES set spans a wide range of hues, lightness levels, and chroma values, while exhibiting balanced variation across the visible spectrum, making it an appropriate reference set for general color-perception analysis.

To assess the discrimination capability of tinted eyewear, it is necessary to consider *parameric pairs*: pairs of reflectances that produce similar perceived colors under a reference condition but differ substantially in spectral composition. Such pairs are particularly sensitive to changes in viewing conditions and provide a stringent test of perceptual metrics. For this purpose, we assembled a dataset comprising 8,207 spectrally measured reflectances collected from multiple published sources [18, 19, 20, 20]. These reflectances serve as candidates for constructing parameric counterparts to each TM-30 CES sample. Parameric pairing was performed in a two-stage selection process. First, for each of the 99 CES samples, color appearance was computed under D65 using CAM16-UCS assuming no eyewear condition. Candidate reflectances from the auxiliary dataset were then identified by requiring the CAM16-UCS color difference between the CES sample and the candidate reflectance to satisfy $\Delta E_{\mathrm{CAM16-UCS}} < 4$, ensuring close perceptual similarity under the reference condition. This threshold was chosen to restrict the selection to pairs that are parameric, while allowing sufficient flexibility for spectral diversity. Second, among the candidate reflectances satisfying the color-difference criterion, the reflectance with the maximum root-mean-square error (RMSE) in spectral reflectance relative to the corresponding CES sample was selected. This criterion intentionally maximizes spectral dissimilarity within each parameric pair, thereby increasing sensitivity to wavelength-selective filtering effects introduced by some tinted eyewear. The resulting set of 99 parameric pairs therefore consists of reflectance pairs that are perceptually similar under bare-eye viewing but spectrally distinct, making them well suited for evaluating small color changes induced by eyewear.



(a) EW1 condition (b) EW2 condition

Figure 1: Gamut boundaries constructed from the 99 TM-30 CES samples in CAM16-UCS a'–b' space. Samples are grouped into 16 hue bins and averaged within each bin.

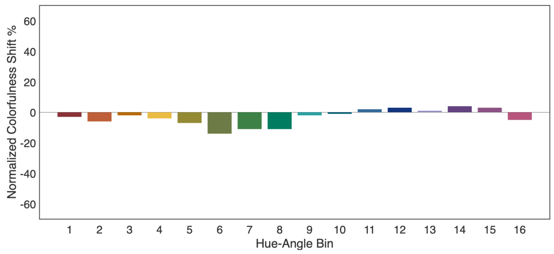
Color Appearance Change

Tinted eyewear alters both the spectral composition and the retinal illuminance of the stimulus reaching the eye. Consequently, modeling eyewear-induced appearance changes requires a representation that depends on viewing conditions and adaptation, rather than treating the effect as a purely chromatic transformation. In this work, appearance changes are modeled using CIECAM16, which predicts perceptual correlates under specified illumination and adaptation conditions and provides absolute appearance attributes that facilitate comparisons between eyewear and bare-eye viewing.

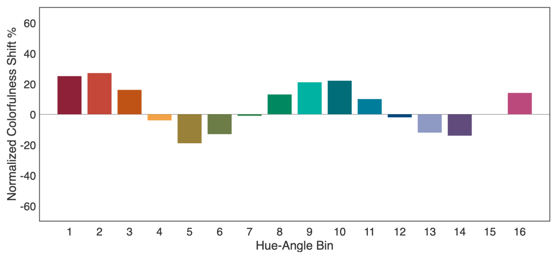
To visualize these appearance changes, we adopt a bin-based gamut representation analogous to those commonly used in color rendition evaluation. The 99 CES samples were grouped into 16 hue bins by partitioning the a'–b' plane of CAM16-UCS into equal angular sectors following a radial pattern, with each sector spanning 22.5°. Within each bin, perceptual attributes are averaged to obtain representative values for the reference (no-eyewear) and eyewear viewing conditions. The resulting bin centroids are then connected to form a closed boundary, providing a compact visualization of the effective color gamut under each condition. Figure 1 illustrates the resulting gamut boundaries for two specific eyewear (EW 1 and EW 2), highlighting global expansions or contractions as well as hue-dependent distortions in color appearance.

Beyond overall gamut shape, attribute-specific shifts provide further insight into the perceptual consequences of eyewear. In particular, changes in colorfulness reflect the combined influence of spectral filtering and luminance-dependent adaptation on perceived chromatic strength. Figure 2 shows the distribution of colorfulness shifts across the 16 hue bins for EW 1 and EW 2 examined in this study. The positive values indicate increased colorfulness and negative values indicate reduced colorfulness relative to the reference.

In addition to changes in gamut extent and chromatic strength, tinted eyewear can induce systematic hue rotations. To

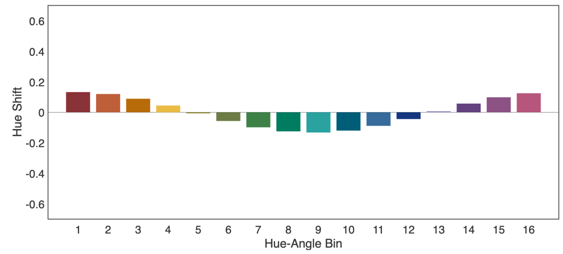


(a) EW1

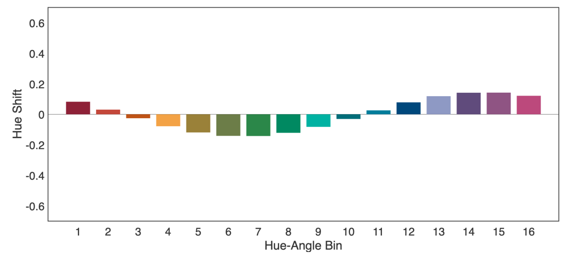


(b) EW2

Figure 2: Normalized CIECAM16 colorfulness shifts (%) across the 16 hue-angle bins for the eyewear conditions. Positive values indicate increased colorfulness relative to bare-eye viewing, while negative values indicate reduced colorfulness.



(a) EW1



(b) EW2

Figure 3: Local hue shifts across the 16 hue-angle bins for EW 1 and EW 2 relative to bare-eye viewing. Negative values indicate clockwise hue rotation and positive values indicate counterclockwise rotation.

quantify hue distortions in a way that is robust to the circular nature of hue, we compute a *local hue shift* for each of the 16 hue-angle bins. This measure captures the *purely tangential* component of the change in CAM16-UCS chromaticity, i.e., the component orthogonal to the radial direction in the a'–b' plane, and therefore isolates hue rotation from changes in chroma magnitude. For each bin, the chromaticity displacement vector between the eyewear and reference conditions is projected onto the local tangent direction associated with that bin. This yields a signed local hue shift value for each hue-angle bin. A negative value indicates a clockwise hue rotation (e.g., orange toward red, blue toward green, and green toward yellow), whereas a positive value indicates a counterclockwise rotation. Figure 3 summarizes the resulting local hue shifts across the 16 hue bins for EW 1 and EW 2 relative to bare-eye viewing.

Contrast and Color Discrimination

The perceptual utility of tinted eyewear is often determined by its effect on contrast and color discrimination. To evaluate these effects, we leverage behavioral data collected in a separate psychophysical study, which examined how tinted eyewear influences observer performance in tasks involving both small and large color differences. The experimental procedures and statistical analyses are described in detail in that work [17]; here, we use the resulting behavioral measures as an empirical reference for assessing the predictive power of different color difference metrics.

Two complementary behavioral tasks were considered. In the first task, observers performed a visual search task in which they were required to identify a stimulus differing subtly in color from its surroundings while wearing one of five tinted eyewear conditions. Reaction time served as the behavioral measure, with longer reaction times suggesting reduced discriminability for small color differences. In the second task, observers judged the presence of a spatial gap between stimuli exhibiting large color differences, and the threshold viewing distance at which the gap could be reliably detected was measured. More distant thresholds correspond to improved discriminability for large color differences. Together, these tasks probe discrimination performance across distinct regions of the perceptual difference scale.

To relate behavioral performance to computational predictions, we evaluated several candidate metrics: cone contrast, CIEDE2000, the HyAB (designed for large color differences), and CAM16-UCS color differences under three adaptation conditions. Cone contrast represents a physiologically motivated measure operating at the level of photoreceptor responses and is closely associated with early-stage visual sensitivity. CIEDE2000, HyAB, and CAM16-UCS are color difference metrics designed to predict suprathreshold color differences. CAM16-UCS differences were computed using three configurations to examine the role of adaptation assumptions: (i) a condition assuming complete chromatic adaptation without specifying luminance, (ii) a condition incorporating absolute luminance with the degree of adaptation D set to a fixed value ($D = 0.7$) based on the observer adaptation time in the experiment, and (iii) a condition in which D was computed using the standard CIECAM16 adaptation model, yielding $D \approx 0.9$.

For each metric, predicted color differences were computed for all stimulus conditions and eyewear types and compared with the corresponding behavioral measures. Figures 4 and 5 summarize the resulting correlations for the reaction time task (small color differences) and the distance threshold task (large color differences), respectively. Across both tasks, cone contrast exhibited the strongest monotonic association with behavioral performance, showing the highest magnitude of correlation among the evaluated metrics. CAM16-UCS metrics demonstrated moderate correlations that were relatively stable across adaptation assump-

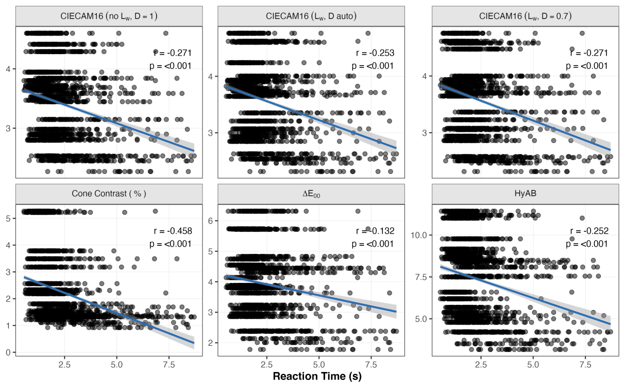


Figure 4: Correlation between predicted color difference metrics (y-axes) and reaction time for the visual search task involving small color differences.

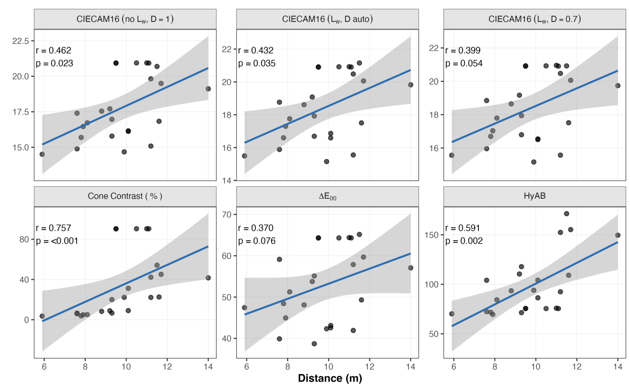


Figure 5: Correlation between predicted color difference metrics (y-axes) and threshold viewing distance for the discrimination task involving large color differences.

tions, while CIEDE2000 showed weaker associations, particularly for the small-difference reaction time task. These results indicate that metrics grounded in early visual processing better capture the perceptual factors governing discrimination performance through tinted eyewear.

Importantly, the purpose of this analysis is not to identify a universally optimal metric, but rather to assess which computational representations best align with observed perceptual behavior in the specific context of eyewear-induced spectral filtering. The observed advantage of cone contrast suggests that discrimination through tinted eyewear is strongly influenced by changes at the photoreceptor response level, whereas appearance-based color difference metrics are more informative for describing global shifts in perceived color appearance.

Results and Discussion

The proposed framework integrates the spectral transmittance of tinted eyewear with the spectral power distribution and luminance level of the illumination to jointly characterize color appearance and color discrimination effects. Given these inputs, the framework provides a set of complementary visualizations and perceptual measures that together describe how eyewear reshapes perceived color appearance and alters discrimination performance. These include changes in the effective color gamut relative to bare-eye viewing, shifts in colorfulness and Hue, and discrimination sensitivity for both small and large color differences.

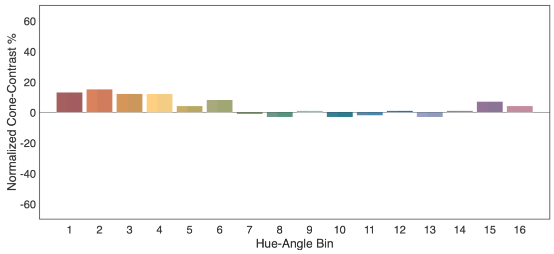
The resulting gamut visualizations reveal that tinted eyewear induces structured, hue-dependent distortions rather than uniform scaling of the color gamut. These distortions depend jointly on the spectral selectivity and total luminous transmittance of the eyewear, demonstrating that color appearance changes cannot be inferred from total transmittance alone. As an illustrative example, shown in Fig. 1, EW 1 has 58% total luminous transmittance. Specifically, EW 1 transmits short wavelengths weakly and reaches a high-transmittance plateau at longer wavelengths. Its overall color gamut structure is largely preserved, with only subtle changes resulting from its relatively uniform spectral transmittance. A slight desaturation in the green region is observed, but overall colorfulness remains relatively stable across hues. On the other hand, EW 2, with 65% total luminous transmittance, selectively attenuates mid wavelengths while transmitting more of the short and long wavelengths. Due to this wavelength selectivity, it produces a more structured effect on the color gamut. The gamut expands in the red and blue regions, indicating an increase in colorfulness for those hues. This comparison highlights the importance of spatially resolved visualization for interpreting color fidelity effects.

To further examine attribute-level changes, colorfulness and hue shifts relative to bare-eye viewing were evaluated for EW 1 and EW 2 using the CIECAM16, as shown in Figs. 2 and 3. This spectral selectivity of EW 2 leads to pronounced, hue-dependent colorfulness shifts, with increases observed in red and blue hue bins, while the EW 1 shows only minor changes.

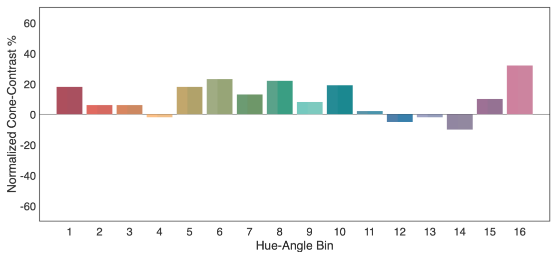
The local hue shifts exhibit systematic variations across the 16 hue bins, reflecting the tangential component of the chromaticity displacement in the CAM16-UCS a'–b' plane. Because this metric isolate rotational changes in hue, it captures hue distortions independently of changes in chroma magnitude or overall luminance scaling. For EW 1, the resulting hue rotations remain modest and structured, with green hues shifting slightly toward blue and red and purple hues shifting toward yellow. In comparison, EW 2 produces stronger and more pronounced hue rotations. These effects are particularly evident in the yellow and blue regions, which shift toward red and green directions, respectively.

Discrimination performance for small color differences was evaluated using parameric pairs constructed for each CES sample and analyzed within the same hue-bin framework. For each parameric pair, cone contrast was first computed based on normalized differences in cone excitations relative to a reference white, and the resulting values were then averaged within each of the 16 hue bins. This aggregation allows discrimination sensitivity to be examined as a function of hue while reducing sample-level variability.

Figure 6 shows the normalized cone-contrast shifts for EW 1 and EW 2 across the hue bins. For EW 1, a clear hue-dependent pattern is observed, with positive cone-contrast shifts concentrated in the long-wavelength (reddish) hue regions and near-zero or slightly negative shifts in the mid- and short-wavelength regions. This indicates an enhancement of discriminability for small color differences in red-dominated hues when viewing through EW 1, consistent with its higher transmission of longer wavelengths. The EW 2 enhances discrimination primarily in reddish and greenish-blue regions, reflecting its wavelength-selective fil-

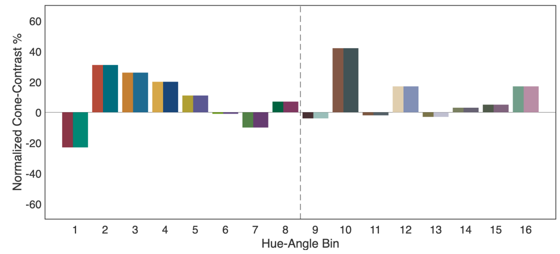


(a) EW1

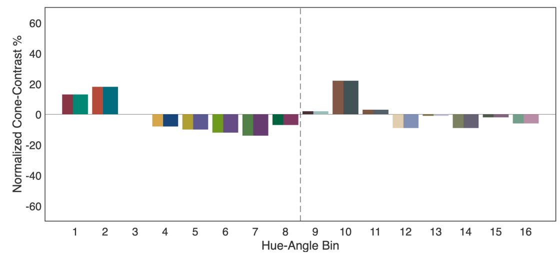


(b) EW2

Figure 6: Normalized cone-contrast shifts for small color differences across the 16 hue-angle bins for (a)EW 1 and (b)EW 2.



(a) EW1



(b) EW2

Figure 7: Normalized cone-contrast shifts for large color differences across the 16 hue-angle bins for (a)EW 1 and (b)EW 2. Hue bins 1–8 correspond to high-chroma samples, and bins 9–16 correspond to low-chroma samples.

tering.

A similar but more structured pattern is observed for discrimination of large color differences. In this case, complementary color pairs were constructed from the CES samples by separating high- and low-chroma subsets within each hue bin and computing cone contrast between opposing directions in the a'–b' plane. Figure 7 shows the normalized cone-contrast shifts for EW 1 and EW 2, with hue bins 1–8 corresponding to high-chroma samples and bins 9–16 corresponding to low-chroma samples. For large color differences, the two lenses produce distinct patterns of cone-contrast shifts. EW 1 produces pronounced and predominantly positive cone-contrast shifts in several hue regions, indicating enhanced discriminability for large color differences. This effect is particularly evident for hue pairs spanning yellow–blue and orange–blue regions, consistent with the spectral transmittance of EW 1 favoring longer wavelengths. In contrast, EW 2 shows improved discrimination primarily in the hue regions where colorfulness increased, reflecting the wavelength-selective nature of its spectral filtering. Mid-spectrum high-chroma hues exhibit smaller or slightly negative shifts, highlighting the wavelength-dependent character of the spectral transmittance.

Conclusion and Future Work

The results provide insight into the strengths and limitations of commonly used color metrics when applied to tinted eyewear and contribute to the development of a general methodology to assess changes in color perception induced by eyewear. This work presents a unified theoretical and computational framework for evaluating the perceptual impact of tinted eyewear on color appearance and color discrimination. By combining eyewear spectral transmittance with illumination spectra and luminance level, the framework enables a joint analysis of color appearance changes and task-relevant discrimination performance. Through perceptually grounded visualizations and metric comparisons, the framework links spectral filtering properties to both appearance-oriented descriptors and behaviorally relevant discrimination measures.

The results demonstrate that tinted eyewear induces structured, hue-dependent changes in perceived color appearance that cannot be captured by transmittance-based specifications alone. At the same time, discrimination performance for both small and large color differences is shown to be more strongly associated with physiologically motivated cone-contrast measures than with appearance-based color difference metrics. Importantly, the framework also accommodates cases in which minimal or no color appearance change may be desirable. In certain applications, eyewear performance may be considered optimal when color appearance is preserved while luminance is reduced to protect the visual system, highlighting that the absence of color alteration can represent a favorable outcome rather than a limitation.

The proposed framework should be viewed as a starting point toward a more general methodology for evaluating tinted eyewear across a range of applications. Its modular structure allows it to be adapted for use in different industries, including vision protection, imaging, display viewing, transportation, and sports eyewear, where performance requirements may differ substantially.

Several directions for future work remain. Additional perceptual metrics that explicitly account for perceptual phenomena such as the Helmholtz–Kohlrausch [21, 22] effect could be incorporated and evaluated within the same framework. Further psychophysical data are needed to strengthen generalization and validation across tasks, observers, and viewing conditions. In particular, direct measurements of contrast sensitivity through tinted eyewear may provide deeper insight into the mechanisms underlying discrimination performance and suggest refinements to the current model. Finally, expanding the evaluation to a broader range of eyewear and spectral filters with diverse transmittance characteristics will improve coverage of the design space and support more comprehensive performance assessment.

Acknowledgments

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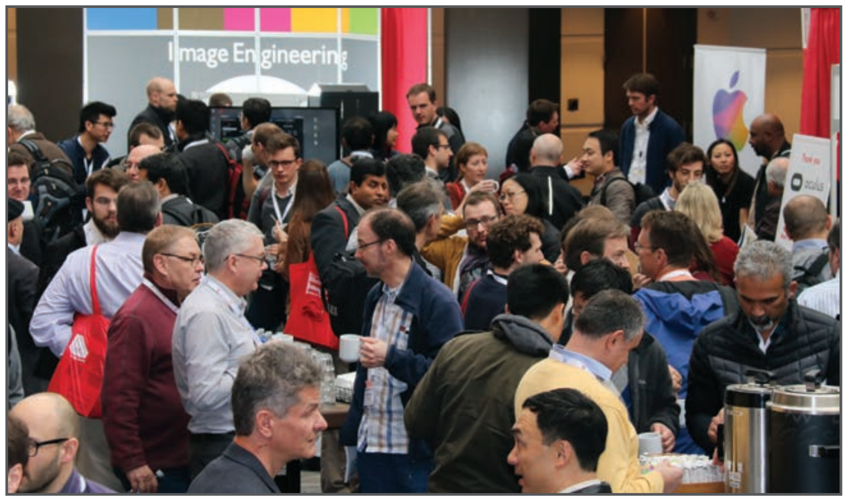

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