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Evaluation of Passive and Active Aids for Color Vision Deficiency: A Comparative Analysis of Perceptual Efficacy

ABSTRACT

Congenital red-green Color Vision Deficiency (CVD) affects approximately 8% of Caucasian males and 0.5% of females and can interfere with color-dependent daily and occupational tasks. This review synthesizes psychophysical and computational evidence on passive spectral filters (including EnChroma®, VINO®, and Colorlite®) and active digital recoloration methods. Passive filters alter color appearance but do not restore normal trichromatic vision and do not consistently improve diagnostic chromatic discrimination. Nevertheless, some filters may provide stimulus- and task-dependent enhancement of chromatic contrast or appearance in selected anomalous trichromats. Computational analyses also show that VINO® can reduce the number of discernible colors (NODC) under some simulated conditions. The CVD-MET metric, developed in previous papers, provides complementary measures of efficiency and naturalness for comparing visual aids. In the methods originally evaluated with CVD-MET, active recoloration achieved better efficiency than the tested passive filters, but naturalness did not uniformly favor active methods: EnChroma® showed the lowest total naturalness difference, whereas VINO® showed the highest. Thus, active recoloration offers greater potential for targeted compensation, but not restoration of normal color vision, and its benefit depends on the trade-off between discrimination and naturalness. Current development is moving toward degree-adaptable, real-time, and user-specific recoloration, supporting future evaluation frameworks that combine observer-specific discrimination, task performance, naturalness, and user preference.

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KEY WORDS
Color vision deficiency, visual perception, spectral filters, daltonization, CIECAM02

1. Introduction

Normal human color vision is based on a trichromatic system mediated by three types of retinal photoreceptors or cones, sensitive respectively to short-wavelength (S), medium-wavelength (M), and long-wavelength (L) spectral bands. However, approximately 8% of Caucasian males and 0.5% of females present some form of Color Vision Deficiency (CVD) (Birch, 2012; Simunovic, 2010). Congenital red-green deficiencies account for most cases and are classified physiologically according to the type of cone affected and the severity of the defect. When one of the photopigments undergoes a spectral shift in its sensitivity curve without being completely absent, anomalous trichromacy occurs (protanomaly in the case of L cones and deuteranomaly in M cones). In anomalous trichromacy, severity is related to the spectral separation of cone sensitivities. Conversely, the functional absence of one cone class results in dichromacy (protanopia or deuteranopia). Both severe anomalous trichromacy and dichromacy can substantially reduce chromatic discrimination. In daily life, observers with

severe CVD may experience difficulties in tasks such as interpreting maps, charts, signal lights, or food-related color cues, and color-vision standards can restrict eligibility for some safety-critical occupations (Barbur & Rodriguez-Carmona, 2012; Cole, 2004). For common congenital red-green CVD, there is currently no established restorative treatment; therefore, practical assistance has focused primarily on optical and digital compensation.

Faced with the lack of biological solutions, applied research and the optical industry have driven the emergence of various visual assistance systems (Popleteev, Louveton & McCall, 2015). These technologies fall into two main categories: passive aids and active aids (Muñoz-Postigo et al., 2022). Passive aids consist of tinted spectral filters mounted in spectacles or contact lenses (Karepov & Ellenbogen, 2020; Maxwell, 1857; Swarbrick et al., 2001). The idea of interposing optical filters to mitigate color confusion dates back to Seebeck's observations in 1837 and Maxwell's monocular spectacles developed in 1857 (Maxwell, 1857), continued in the 20th century by lenses such as X-Chrom or ChromaGen (ChromaGen, n.d.). In recent years, there has been a notable commercial resurgence led by binocular glasses with notch or multiband filters from brands like EnChroma®, VINO®, Colorlite®, or Pilestone® among others. The commercial claim of these devices is to block specific regions of the visible spectrum to attenuate the overlap between L and M cone responses, aiming to increase perceived chromatic contrast. On the other hand, active aids employ digital image processing techniques on displays or augmented reality devices (such as smart glasses or electronic viewfinders) (Popleteev, Louveton & McCall, 2015). Through recoloration or daltonization algorithms, these systems capture the real scene and dynamically remap confusing hues toward spectral components that are readily distinguishable by the observer's visual system (Milić et al., 2015; Ribeiro & Gomes, 2019).

Despite widespread commercial claims, psychophysical studies do not support the interpretation that passive notch filters restore normal color vision (Almutairi et al., 2017; Badawy et al., 2018; Gómez-Robledo et al., 2018; Martínez-Domingo et al., 2019; Martínez-Domingo et al., 2020; Mastey et al., 2016; Patterson, 2017). EnChroma® testing found changes in perceived color without improvement in standard diagnostic tests or normalization of color vision, while VINO® could improve recognition of some pseudoisochromatic plates while worsening arrangement and color-naming performance (Gómez-Robledo et al., 2018; Martínez-Domingo et al., 2019; Martínez-Domingo et al., 2020). Such gains on screening plates can arise because spectral filtering introduces luminance or brightness cues that were not intended to carry the target information. Computational analyses likewise show that passive filters do not consistently increase the number of discernible colors (NODC), and selected filters may reduce it (Martínez-Domingo et al., 2020). However, the evidence should not be stated as an absolute absence of perceptual benefit: long-term notch-filter use has been associated with increased chromatic contrast response in anomalous trichromats, and recent experiments found task- and stimulus-dependent changes in color appearance with limited effects on threshold discrimination (Somers, Franklin & Bosten, 2024; Werner, Marsh-Armstrong & Knoblauch, 2020). These findings support a distinction between restoration of normal trichromacy, for which evidence is lacking, and selective enhancement of particular chromatic signals or perceptual tasks.

To complement psychophysical testing, computational approaches have used color-appearance modeling and dedicated image metrics. CVD-MET was developed to evaluate two complementary properties of CVD aids using simulated observer vision: efficiency, reflecting how well the transformed image reduces CVD-specific perceptual differences, and naturalness, reflecting preservation of the original scene appearance (Muñoz-Postigo et al., 2022). In the original comparison, the evaluated active recoloration methods (Fidaner, Lin & Ozguven, 2005; Hassan & Paramesran, 2017) achieved lower, and therefore better, CVD-MET efficiency differences than the tested passive filters. Naturalness, however, did not show the same ordering: EnChroma® had the lowest total naturalness difference among the four compared methods, VINO® the highest, and the active methods occupied intermediate positions. The evidence therefore supports an efficiency–naturalness trade-off rather than the broader claim that active recoloration is uniformly both more efficient and more natural.

This review paper presents a comparative synthesis of evidence on the perceptual efficacy of passive and active aids for color vision deficiency. Integrating psychophysical results, hyperspectral simulations, and quantitative image metrics, the objectives are: to analyze the performance of widely used passive optical filters (including EnChroma®, VINO®, and Colorlite®) in standardized color-vision tasks and under adaptation; to compare the efficiency and naturalness dimensions captured by CVD-MET; to distinguish restoration of normal color vision from task-specific perceptual enhancement; and to place the previously evaluated active algorithms in the context of more recent degree-adaptable, real-time, and personalized recoloration approaches.

2. Methods

2.1. Experimental subjects and psychophysical testing protocols

In different studies (Gómez-Robledo et al., 2018; Martínez-Domingo et al., 2019; Gómez-Robledo et al.,

2020; Huertas et al., 2024) the psychophysical evaluation engaged cohorts of human observers diagnosed with congenital red-green CVD (protanomalous, deuteranomalous, protanopes, and deuteranopes) alongside a control panel of color-normal trichromats. Subjects underwent standard diagnostic screening using the Ishihara Pseudoisochromatic Plates (Ishihara, 1977), the FM-100 (X-Rite) and/or an anomaloscope (anomaloscope OCULUS® HMC-Anomaloskop USA) and/or the CAD test (Rodriguez-Carmona et al., 2005).

Chromatic discrimination capacity and error patterns were quantitatively measured using the Farnsworth-Munsell 100 Hue Test. To evaluate color naming accuracy, a dedicated color-naming experiment was conducted utilizing 21 color patches from an X-Rite® GretagMacbeth ColorChecker Chart. Patches were presented in isolated 55 x 55 mm color squares on a dark background on an HP® 2510i 25'' display calibrated with an X-Rite® Eye-One spectrophotometric device. Observers were instructed to categorize each color using the 11 basic color terms established by Berlin and Kay (1991) (white, black, red, green, yellow, blue, brown, purple, pink, orange, grey). Tests were administered under two distinct experimental conditions: without glasses (Glasses OFF) and while wearing commercial passive filters (Glasses ON), including EnChroma® Cx-65, VINO® O2 Amp Oxy-Iso, and Colorlite® spectral lenses.

2.2. Computational simulation and hyperspectral image processing

To model perceptual changes objectively under controlled viewing conditions, the computational work summarized here used hyperspectral scenes drawn from the image sets employed in the original aid-evaluation studies, including hyperspectral measurements of test stimuli and natural-scene data from established spectral-image databases. In the CVD-MET study, the six evaluated scenes were assembled from hyperspectral acquisitions and public spectral-image collections, including the Nascimento/Ferreira/Foster natural-scene database and the Columbia CAVE database (Color Imaging Lab, University of Granada, n.d.; Columbia University CAVE Laboratory, 2008; Foster, Nascimento & Amano, n.d.; Nascimento, Ferreira & Foster, 2002). Scene spectral radiances were transformed into retinal cone responses using standard cone fundamentals, and CVD simulation was then applied at defined severity levels.

Perceptual color coordinates were calculated using the CIECAM02 Color Appearance Model to account for chromatic adaptation effects (Fairchild, 2013). The model parameters reported in the underlying work used a D65 reference white with Xw=97.10, Yw=100.00, and Zw=111.062, an adapting-field luminance La=23 cd/m², background luminance Yb=28, surround factor c=0.59, chromatic induction factor Nc=0.9, and degree of adaptation D=0.84. For every scene element, lightness (J), chroma (C), hue angle (h), and rectangular chromaticity coordinates (ac, bc) were derived.

2.3. Active aid algorithms and the CVD-MET metric

Active digital recoloration algorithms, commonly referred to as daltonization methods, including the Fidaner, Lin and Ozguven (2005) and Hassan and Paramesran (2017) approaches, were evaluated against passive filters. Because conventional image-quality metrics are not designed around CVD-specific confusions, CVD-MET was developed to assess aid performance through separate efficiency and naturalness analyses (Muñoz-Postigo et al., 2022). CVD-MET evaluates two complementary components, efficiency and naturalness. A Fuzzy C-means clustering step in CIELAB color space is used as a preprocessing color-quantization procedure before identifying confused and non-confused color clusters. The two CVD-MET analyses can be summarized as follows:

4. Efficiency (E): Quantifies the degree to which the processed image reduces color confusion, bringing the CVD observer's perception closer to that of a normal trichromat.
5. Naturalness (N): Measures the extent to which the original visual appearance and spatial realism of non-confusing scene elements are preserved.

CVD-MET scores were benchmarked alongside conventional full-reference and no-reference image quality metrics modified for CVD perception, including MS-iCID, cVIF, cVSI, and NIQE difference.

3. Results

3.1. Psychophysical performance with commercial passive filters

Systematic psychophysical testing revealed a major divergence between screening plate recognition and diagnostic chromatic discrimination when observers wore commercial passive filters (Gómez-Robledo et al., 2018; Martínez-Domingo et al., 2019; Martínez-Domingo et al., 2020). Table 1 summarizes the results obtained.

As demonstrated in quantitative psychophysical trials, VINO® glasses produced a notable reduction in error rates on Ishihara pseudoisochromatic plates. However, this improvement in screening plates was accompanied by a severe degradation in chromatic ordering and naming performance.

Table 1

Performance of passive filters (Gómez-Robledo et al., 2018; Martínez-Domingo et al., 2019; Martínez-Domingo et al., 2020)

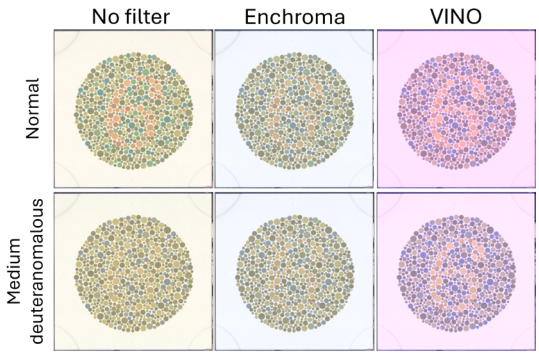
Performance Indicator	Glasses OFF	EnChroma® Cx-65	VINO® O2 Amp	Colorlite®
Ishihara Recognition	High Error Rate	Slight Improvement	Marked Error Reduction	Variable Pass
FM-100 Total Error (SQR)	Baseline (~96.37)	Unchanged (~91.32)	Severe Elevation (~181.32)	Elevated Errors
Color-Naming Fails	Baseline	Unchanged	Increased (+3.05 terms)	Mild Increase
Discernible Colors (NODC)	Baseline Gamut	Slight Drop / Equal	Net Reduction (-22% to-45%)	Net Reduction

In the case of FM-100 Error Scores, while baseline error scores without glasses averaged 96.37 ± 112.43, wearing VINO® glasses elevated mean total error scores to 181.32 ± 106.59, for one of the databases used (Dataset D1). EnChroma® Cx-65 glasses yielded no statistically significant change in FM-100 scores (91.32 ± 100.00) (Martínez-Domingo et al., 2019).

Wearing VINO® filters increased color-naming errors by an average of 3.05 ± 5.39 terms changed relative to the baseline. Observers frequently misidentified neutral and chromatic patches due to the heavy pinkish/reddish tint introduced by the filter.

3.2. Color appearance shifts and chromatic diversity

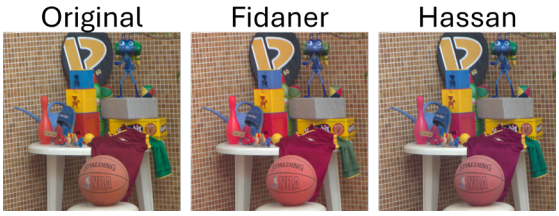
Color vision deficiencies can be modeled by different algorithms, as can the effects of passive filters (Muñoz-Postigo et al., 2022). Chromatic adaptation can also be considered, for example by CIECAM02. Figure 1 shows the simulation result for an Ishihara plate as viewed by a medium-severity deuteranomalous observer.



» **Figure 1:** *Simulation result for a medium deuteranomalous observer viewing an Ishihara plate*

The application of active aids is illustrated in Figure 2 for the Fidaner, Lin and Ozguven (2005) and Hassan and Paramesran (2017) algorithms.

In Muñoz-Postigo et al. (2022), CIECAM02 color appearance simulations illustrated the color shifts caused by passive notch filters. In the CIECAM02 chromaticity plane (ac, bc), unprocessed natural scenes exhibit a continuous distribution of hue angles (h). Interposing VINO® filters forces chromaticity coordinates into a bimodal distribution along a single diagonal line, altering mean angular directions. The angular direction shift depends on the images included in the dataset. This clustering along a single axis reduces overall chromatic diversity, suppressing greens and blues while artificially boosting red-luminance contrast.



» **Figure 2:** *Recoloration results for a mild-deuteranomalous observer*

Calculations of the Number of Discernible Colors (NODC) confirmed that passive filters do not increase the chromatic gamut of CVD observers, and in severe deutan or protan conditions, decrease the total NODC.

3.3. Metric evaluation: passive filters vs. active recoloration

Quantitative assessment using image-difference metrics and CVD-MET demonstrated clear performance differences between passive optical filters and active recoloration algorithms (Muñoz-Postigo et al., 2022). For filtered and recolored images, Tables 2 and 3 show the results of the metrics for naturalness and efficiency, respectively (mean data and standard deviation).

For CVD-MET naturalness (total score), values indicate the perceptual differences, so lower values indicate better naturalness performance. For the CVD-MET efficiency (total score) lower values indicate better efficiency (Muñoz-Postigo et al., 2022).

Table 2

Metrics of naturalness for filtered (EnChroma® and VINO®) and recolored (Fidaner and Hassan recoloration algorithms) images (Muñoz-Postigo et al., 2022)

Metric Category	EnChroma® (Passive)	VINO® (Passive)	Fidaner (Active)	Hassan (Active)
Ms-iCID (Structural)	0.0142±0.0145	0.0700±0.0743	0.0450±0.0462	0.0368±0.0390
cVIF (Information Ratio)	0.2145±0.0613	0.4841±0.1705	0.4285±0.1550	0.2798±0.0842
cVSI (Visual Saliency)	0.0006±0.0007	0.0077±0.0039	0.0103±0.0103	0.0092±0.0090
NIQE Difference (Naturalness)	-0.0346±0.0677	0.0883±0.1281	-0.0040±0.1117	0.0617±0.0859
CVD-MET (Confused Colors)	6.4457±2.2903	22.7177±11.82	10.1310±7.874	8.6198±6.1769
CVD-MET (Non-Confused Colors)	6.8848±0.9950	23.7909±10.34	12.9592±5.867	11.2563±5.239
CVD-MET Total Score	6.8464±1.2035	23.5842±10.67	12.2714±4.908	10.6402±4.147

Table 3

Metrics of efficiency for filtered (EnChroma® and VINO®) and recolored (Fidaner and Hassan recoloration algorithms) images (Muñoz-Postigo et al., 2022)

Metric Category	EnChroma® (Passive)	VINO® (Passive)	Fidaner (Active)	Hassan (Active)
Ms-iCID (Structural)	0.0313±0.0339	0.0706±0.0722	0.0160±0.0169	0.0092±0.0102
cVIF (Information Ratio)	0.3182±0.0497	0.4662±0.1651	0.2785±0.1294	0.0409±0.0548
cVSI (Visual Saliency)	0.0032±0.0022	0.0060±0.0019	0.0031±0.0026	0.0027±0.0023
NIQE Difference (Efficiency)	-0.0783±0.1074	0.0446±0.1239	-0.0476±0.1101	0.0181±0.0342
CVD-MET (Confused Colors)	10.0904±3.9226	23.8317±10.6487	5.2143±3.1246	3.9575±3.0580
CVD-MET (Non-Confused Colors)	11.7277±2.9577	25.1695±8.4239	6.5723±2.3132	5.4546±2.7152
CVD-MET Total Score	11.3425±2.0822	24.7721±8.9941	6.2206±1.7993	5.1430±2.3945

Comparing the values for passive and active aids as shown in Table 3, from the efficiency point of view, the active aids are superior according to all metrics. Regarding the information content (assessed by the cVIF metric), there is also a higher similarity between the original and recolored images, as perceived by the CVD observer, than between the original and filtered images.

From the perspective of naturalness, the EnChroma® filter performs best across all metrics, except for the NIQE difference, as shown in Table 2. However, it provides minimal chromatic differentiation in confusing regions. The VINO® filters exhibited high distortion values, reflecting substantial distortion of scene naturalness without a proportional gain in true chromatic efficiency.

In contrast, active recoloration algorithms (Fidaner and Hassan) achieved a more effective balance: they selectively remapped confusing color clusters to high-efficiency discrimination channels while keeping overall scene distortion within moderate boundaries.

The results suggest that filters that introduce slight changes do so at the expense of effectiveness, while active aids that are more effective produce a less natural appearance in the scenes. The principal result is therefore a method-dependent efficiency–naturalness trade-off, not a general finding that active aids necessarily produce more natural images.

4. Discussion

The primary finding of this literature review is the distinction between restoration of normal chromatic coding and selective enhancement of cues that can improve a particular task. Passive spectral filters alter cone excitations by attenuating selected wavelength bands. In pseudoisochromatic plates, this can introduce luminance or brightness differences that make a hidden target easier to recognize without restoring normal red-green sensitivity. VINO® illustrates this dissociation: improved recognition of some Ishihara plates can coexist with worse FM-100 arrangement and

color-naming performance. At the same time, more recent work indicates that selected anomalous trichromats can experience enhanced chromatic contrast or appearance under some notch-filter conditions (Werner, Marsh-Armstrong & Knoblauch, 2020; Somers, Franklin & Bosten, 2024). Consequently, "does not restore normal trichromacy" is a stronger and better-supported conclusion than "cannot provide any perceptual benefit."

The dimensionality argument should distinguish dichromacy from anomalous trichromacy. In dichromacy, the absence of one cone class creates a missing receptor dimension that a passive spectral filter cannot recreate. In anomalous trichromacy, however, three cone classes remain functional, but their spectral sensitivities are less separated; a notch filter could redistribute relative cone excitations and may enhance selected chromatic contrasts without restoring normal cone fundamentals. This distinction is consistent with evidence of increased chromatic contrast response after two weeks of notch-filter use in anomalous trichromats (Werner, Marsh-Armstrong & Knoblauch, 2020) and with more recent task-dependent effects on color appearance (Somers, Franklin & Bosten, 2024).Such adaptive or contrast-enhancement effects should not be interpreted as reconstruction of the missing or altered photopigment signal, but they do require qualifying the claim that long-term adaptation is entirely unable to modify functional color response.

Active recoloration on digital displays, cameras, and augmented-reality systems offers greater flexibility because the transformation can be content-, task-, and observer-dependent. The Fidaner and Hassan methods evaluated in the original CVD-MET comparison demonstrate the principle, but they no longer represent the full state of the art. Degree-adaptable recoloration has been evaluated with CVD observers while explicitly optimizing contrast enhancement and naturalness (Zhu et al., 2022); real-time daltonization can preserve luminance and temporal stability at interactive frame rates (Ebelin et al., 2023); and recent models such as ColorAdaptNet learn individualized transformations from each user's subjective evaluations rather than relying only on a fixed simulated severity (Chen et al., 2026). These developments strengthen the case for active aids while also shifting the research question from a universal recoloring transform toward personalized and context-dependent compensation.

4.1. Contemporary implementation and personalized active aids

At the implementation level, active color transformations are no longer confined to laboratory prototypes. Windows, Android, iOS, and macOS provide system-level color-filter or color-correction options for common CVD categories (Microsoft, n.d.; Apple, n.d.; Google, n.d.), while Chrome DevTools provides CVD simulation models for developers testing interface accessibility (Google Chrome Developers, n.d.). These functions should not be conflated: developer simulation emulates how content may appear under a CVD condition, whereas end-user compensation intentionally transforms displayed content to improve access. Their widespread availability nevertheless increases the translational relevance of active color-processing research and underscores the importance of evaluating algorithms under realistic screen and interface conditions.

A parallel trend is personalization. Earlier daltonization methods typically assumed a predefined CVD type or severity, whereas newer approaches optimize the transformation for an individual observer or learn directly from user judgments. Personalized evaluation should therefore include not only model-based efficiency, but also discrimination performance on relevant tasks, naturalness, visual comfort, stability over time, and user preference. This is especially important because a transformation that improves one confusing color pair may introduce distortions elsewhere in the image.

These findings have practical implications for clinical diagnostics, occupational standards, and industrial lighting design:

1. Screening Vulnerability: Relying solely on Ishihara plates for occupational screening is insufficient if candidates wear tint-altering filters. Standardized evaluation protocols should incorporate secondary diagnostic tests (such as the FM-100, anomaloscope or CAD) that are resistant to luminance contrast artifacts.
2. Inclusive Lighting Standards: Industrial and architectural lighting metrics must be updated to account for CVD vision. Consequently, a specific colorimetry (including chromatic adaptation models, color difference formulae, etc.) must be developed for CVD observers.

4.2. Limitations and scope

This synthesis combines evidence from heterogeneous studies with different observer samples, tests, filters, illuminants, image sets, CVD models, and severity assumptions. In particular, CVD-MET is simulation-based and therefore inherits the assumptions of the selected CVD simulation, scene set and confused/non-confused color classification; it should complement rather than replace psychophysical testing with CVD observers. The active-aid comparison in the original dataset also includes only two older recoloration algorithms, so conclusions about "active aids" as a class should be restricted to the methods evaluated. Finally, evidence for passive filters differs between dichromacy and anomalous trichromacy, making phenotype-specific interpretation essential.

5. Conclusions

This comparative synthesis leads to the following conclusions regarding passive and active aids for Color Vision Deficiency:

1. Passive spectral filters such as EnChroma®, VINO®, and Colorlite® do not restore normal trichromatic vision. Improvements on pseudoisochromatic plates may be driven by added luminance/brightness cues rather than recovery of normal red-green sensitivity. However, selected anomalous trichromats may show task- and stimulus-dependent enhancement of chromatic contrast or appearance, so restoration and perceptual enhancement should be treated as distinct outcomes.
2. In the studies reviewed in this paper, VINO® produced a clear dissociation between improved recognition of some Ishihara plates and poorer FM-100 and color-naming performance. More broadly, the benefit of passive notch filters depends on CVD phenotype, spectral sensitivities, illuminant, stimulus, and task; therefore, their effects should not be generalized from a single screening test.
3. Within the simulation framework and aid systems evaluated by CVD-MET, active digital recoloration methods achieved better efficiency than the tested passive filters. This advantage does not imply restoration of normal color vision and is accompanied by a naturalness trade-off: EnChroma® was more natural than the two active methods on the total naturalness score, whereas VINO® was substantially worse. Future systems should therefore optimize discrimination and naturalness jointly rather than treating either dimension in isolation.
4. The emerging direction for active CVD assistance is individualized and context-dependent compensation. Recent approaches range from severity-adaptable optimization and real-time temporally stable daltonization to learned models trained from individual perceptual judgments. Future evaluation frameworks should consequently combine observer-specific color-discrimination data, task performance, naturalness, and user preference, and should favor redundant visual cues (e.g., labels, patterns, icons, and luminance structure) whenever color alone is not sufficient.

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