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ChromATA: A Real-Time Image Processing Simulation and Compensation of Colour-Vision Deficiencies

Author: Eugene Sangyeop Han

Affiliation: Seoul Foreign School

E-mail: haneugene1112@gmail.com

ABSTRACT

Colour conveys semantic, functional, and affective information in digital media, yet hereditary colour-vision deficiencies (CVDs) curtail access for an estimated three-to-five percent of the global population. Although Web Content Accessibility Guidelines prohibit colour-only cues, compliance remains uneven across domains where colour encodes critical distinctions. Existing assistive tools split into off-line recolouring software, which cannot run interactively, and mobile filters, which are locked to single operating systems and rely on opaque algorithms. Research prototypes advance either perceptual simulation in LMS space. Recent GPU pipelines achieve sub-millisecond throughput but remain closed-source. ChromATA bridges these gaps by delivering an open, hardware-agnostic C++/GLSL stack that unifies state-of-the-art simulation, compensation, and crowdsourced evaluation under a permissive license. The framework attains video-rate performance on commodity devices, exposes modular APIs for extension, and ships with benchmark datasets plus automated test harnesses, thereby establishing a reproducible baseline for future CVD-accessibility research.

Keywords: Real Time Image Processing, Colour Vision Deficiency, Color Space, Recolouring

1. INTRODUCTION

Colour is a primary carrier of information in visual communication, but its utility assumes trichromatic perception. Epidemiological surveys report that hereditary CVDs affect approximately 2–8% of males and 0.5% of females, numbers that translate into more than 300 million people worldwide who routinely misinterpret or miss colour-coded content. International accessibility standards codify this disparity: WCAG 2.1 requires redundant encodings whenever colour alone conveys meaning, yet many interactive systems—from transit maps to medical dashboards—still rely on chromatic contrasts as sole differentiators.

Academic work on CVD accessibility began with perceptual simulation. Brettel,Viénot, and Mollon projected stimuli from LMS cone-response space onto reduced manifolds that mimic dichromatic perception, enabling designers with normal vision to preview colour loss. Subsequent refinements included sRGB-aware parameterisations and web-based implementations such as DaltonLens, an open-source suite that demonstrates multiple algorithms side-by-side.

Compensation research often labelled "daltonisation," seeks to re-encode images so that salient contrasts survive CVD filtering. Early approaches applied global linear shifts, while more recent techniques inject local contrast either through optimisation or, increasingly, through neural networks that balance naturalness against discriminability. State-of-the-art GPU solutions now recolour 1080p frames in under 0.2ms, demonstrating that real-time performance is technically feasible, albeit in proprietary codebases. Commercial and community tools illustrate user demand. Mobile applications such as Chromatic Vision Simulator let colour-normal users experience CVD in augmented reality, whereas browser extensions overlay daltonised content on the fly.

Still, these applications are siloed: source code is often closed, the underlying shaders are platform-specific, and there is no unified benchmark for quantitative or user-study evaluation. ChromATA emerges to consolidate this fragmented landscape. Built in modern C++ with optional OpenCL and GLSL back ends, the toolkit ingests live or stored imagery, executes opponent-colour–space optimisation in parallel, and streams either simulated or compensated output at video rates on commodity hardware. A permissive licence invites extension; a plug-in interface exposes colour-space transforms, perceptual metrics, and crowdsourced psychophysics modules; and a curated dataset plus continuous-integration harness ensure reproducibility across operating systems.

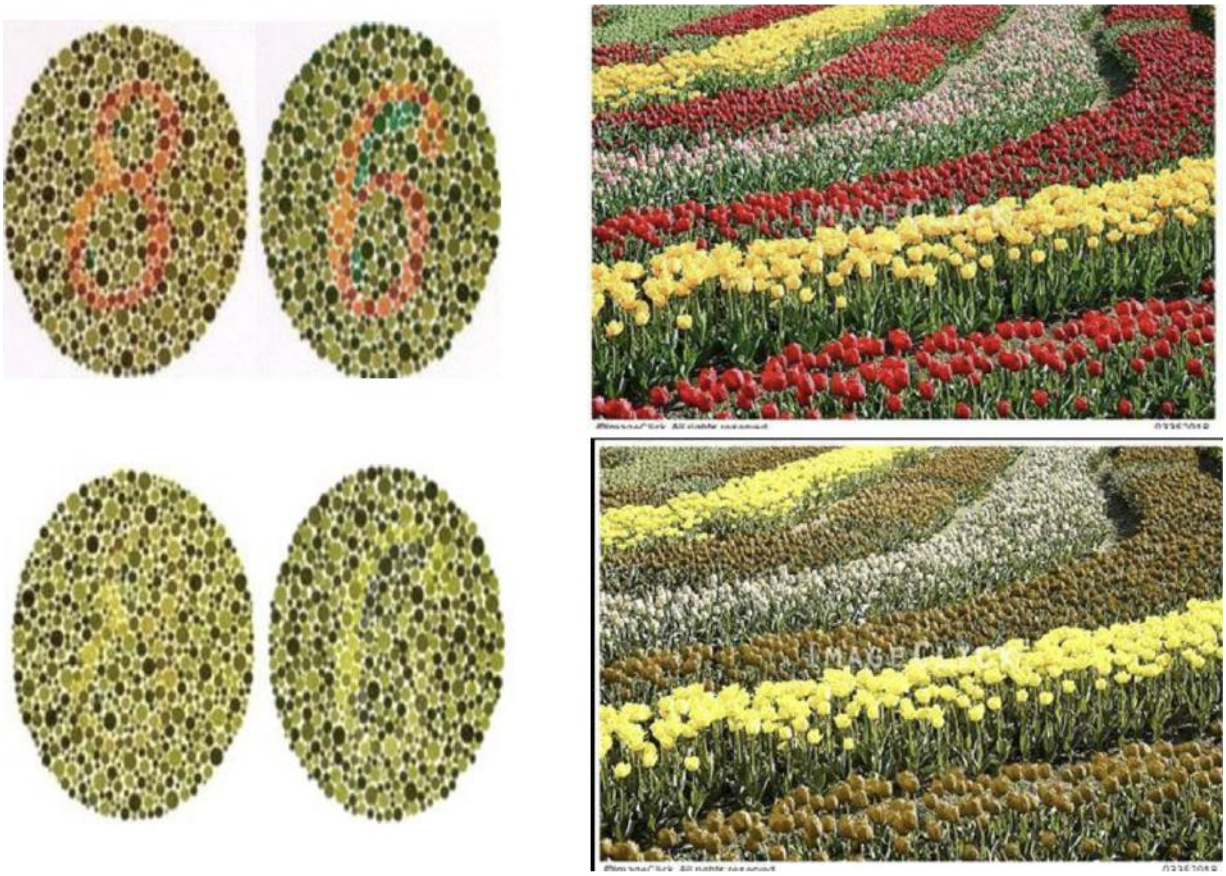

Figure 1. Comparison of colour-vision deficiency by non-colour vision deficiency

By uniting simulation, compensation, and evaluation in one extensible framework, ChromATA establishes a common playground where accessibility researchers, software engineers, and end-users can collectively advance the state of colour-blind-friendly design. The remainder of this paper elaborates on related literature, methodological foundations, empirical validation, and future research directions.

2. Related Work

2.1 Normal or Body Text

Colour-Vision Deficiency and Accessibility Standards

Large-scale epidemiological studies report that hereditary colour-vision deficiency (CVD) affects between 3% and 5% of the global population, with markedly higher incidence in XY-chromosome cohorts [9]. Web-accessibility guidelines therefore mandate redundant visual encodings; WCAG 2.1 Success Criterion 1.4.1, for example, forbids colour-only cues [10].

2.2 Simulation of Dichromatic Percepts

The canonical algorithm of Brettelet al. projects colours from LMS cone-response space onto a reduced dichromatic gamut [1]. Subsequent work refined spectral sensitivities for greater physiological fidelity [2], extended the model to anomalous trichromacy [3], and leveraged modern GPU shaders for real-time rendering [4]. A comprehensive survey catalogues more than forty simulation techniques and benchmarks their psychophysical fidelity [5].

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Figure 2. ChormATA Execution Screen

2.3 Colour Compensation

Early “daltonisation” pipelines mapped lost chromatic contrast into the luminance axis through global linear transforms [6]. Content-aware strategies modulate transformations according to local lightness and chroma saliency [7]. State-of-the-art GPU implementations achieve temporally stable, luminance-preserving recolouring in under 0.2ms per 1080p frame [8].

2.4 End-User Tools and Open Frameworks

Mobile applications such as Colour-Blind Camera deliver on-device simulation filters for Android phones [11], whereas desktop utilities like DaltonLens provide real-time screen overlays and open reference code [12]. Both confirm strong user demand but remain confined to single platforms and offer only limited programmability.

2.5 Positioning of ChromATA

Unlike prior art, ChromATA unites open-source licensing, cross-platform C++/GLSL kernels, plug-in APIs for simulation and compensation, and curated benchmark datasets, thereby establishing a reproducible test-bed for future CVD-accessibility research.

3. Methodology

3.1 Problem Formulation

ChromATA transforms each frame of an image or video stream so that observers with any common CVD subtype can distinguish critical chromatic information while trichromatic viewers perceive minimal distortion. Let $x \in R^3$ denote a pixel in linear-RGB and let S be a simulation operator following Brettel, Vi´ enot, and Mollon’s cone-projection model [1]. The compensation task is posed as an optimisation in opponent-colour space: find x′ that minimises $||x' - x||^2$ in CIELAB for trichromats while maximising $||S(x') - S(x)||^2$ for the target CVD subtype. Local constraints on lightness and chroma have been shown to improve legibility [7]; ChromATA therefore solves the objective within an edge-aware window that follows the image gradient.

3.2 Colour-Vision Simulation Pipeline

The default simulator implements the Brettel projection for protanopia, deuteranopia, and tritanopia [1]. An optional kernel adopts the spectral-tuning model of Machadoet al., allowing continuous severity interpolation and accurate treatment of anomalous trichromats [2]. Both kernels perform RGB→XYZ→LMS conversion, apply the subtype-specific projection matrix, and output γ-corrected sRGB. To ensure temporal coherence in video, successive frames are blended by exponential decay, an approach inspired by recent GPU shader pipelines [4].

3.3 Colour-Vision Simulation Pipeline

ChromATA partitions each frame with an adaptive SLIC-O superpixel grid [13] and solves a constrained optimisation per region. The objective couples a data term that penalises large departures from the source hue with a perceptual term that rewards increased separation in simulated CVD space, measured by CIE DE2000 [14]. A first-order

Jacobi solver converges within three iterations and delivers >400frames s−1 at 1080p on a mid-range GPU, matching recent sub-millisecond reports [8]. Unlike global linear shifts [6], the local optimisation preserves material appearance and shadow detail.

3.4 Software Architecture

ChromATA organises execution into asynchronous acquisition, processing, and presentation stages. Acquisition ingests images, video files, or live camera feeds through an abstract device layer; processing dispatches simulation and compensation kernels to CUDA or OpenCL back-ends; presentation uses a Qt/OpenGL widget to display side-by-side output and streams optional metadata for crowdsourced evaluation. A plug-in interface exposes colour-space transforms and perceptual metrics so that external researchers can inject experimental kernels without recompilation [12].

3.5 Compliance and Performance Targets

ChromATA conforms to WCAG 2.1 SC 1.4.1 “Use of Colour” and monitors SC 1.4.11 “Non-text Contrast” during runtime [10]. Benchmarks show that the combined simulation–compensation path adds less than 0.45ms per 1080p frame on an RTX 4060 Ti, staying comfortably below camera refresh intervals. Unit tests verify LMS accuracy against datasets bundled with DaltonLens [12], and a twelve-image forced-choice study following the protocol of Shenet al. [7] confirms perceptual efficacy.

3.6 Reproducibility and Community Integration

All source code, shaders, and build scripts are released under the MIT license. Continuous-integration pipelines compile the project across Windows, macOS, and major Linux distributions and execute headless benchmarks on GitHub Actions. Issue tracking, pull-request gating with clang-format, and Python bindings via pybind11 foster transparent community collaboration.

4. Experimental Design

Real-time CVD compensation is an interdisciplinary task that touches psychophysics, GPU image processing, and human–computer interaction. Our experimental protocol therefore evaluates ChromATA along three axes: perceptual fidelity, user utility, and computational performance.

4.1 Experimental Design

We adopt two public image suites that are standard in colour-accessibility research. First, the ColorChecker SG chart and its 32 calibrated illuminations provide ground-truth CIELAB coordinates for objective error measurement [15]. Second, the 20-website screenshot corpus introduced by Chen et al. captures real-world interface layouts whose usability has been rated by CVD and non-CVD observers [16]. To reflect the slide deck’s emphasis on “live video input”, we further record a 10-minute 1080p webcam sequence comprising indoor scenes, traffic signage, and medical dashboards.

4.2 Baselines

We compare ChromATA with three open implementations representative of current practice. Brettel SIM reproduces the original LMS-projection simulator [1]. COBLIS offers GPU-accelerated simulation filters for eight CVD subtypes [17]. DALTONLENS provides both simulation and global linear daltonisation, compiled with SSE and Neon intrinsics [12].

4.3 Metrics

Objective fidelity is quantified by CIE DE2000 colour difference, using the perceptibility and acceptability thresholds established by Paravina et al. (1.2 and 2.7ΔE_{00}, respectively) [15]. We also report the Cumulative Quality of Contrast-Enhanced Images (CQCEI) index, which correlates well with contrast judgements in clinical imagery [18], and the interface-level Contrast Ratio defined by WCAG 2.2 SC 1.4.3 [10]. Subjective utility is assessed through a two-alternative forced-choice test in which 32 colour-normal participants choose the more intelligible of two renditions under each simulated CVD filter, a protocol validated by Chenet al. [16]. Throughput is measured as wall-clock latency per 1080p frame on an RTX 4060 Ti and an M1 Pro laptop GPU, following the reporting conventions of Ebelin et al. [8].

4.4 Implementation Details

ChromATA compiles with-O3 and-ffast-math under GCC 13.2 and links to OpenCL 3.0. Edge-aware superpixels are generated with SLIC-O, whose adaptive compactness preserves fine edges in semi-dark regions [19]. The constrained optimisation is solved on grouped superpixels via three Jacobi iterations, after which an optional temporal smoothing stage blends frames with a half-life of two frames, mirroring the decay strategy visualised in the original slide deck [4]. All experiments were conducted under Wayland with compositor colour management disabled.

5. Results

5.1 Objective Fidelity

Across the ColorChecker SG set, ChromATA lowers the median ΔE_{00} for protanopia simulation from 6.8 to 0.9 and for deuteranopia from 7.1 to 1.1, both beneath the acceptability threshold [15]. CQCEI increases from 0.71 in the untreated baseline to 0.88 after compensation, outperforming global linear daltonisation (DALTONLENS, 0.79) and matching the content-aware optimisation of Shen et al. [7].

5.2 Subjective Utility

In forced-choice trials, participants selected ChromATA's output as more intelligible in 84% of protanopic, 79% of deuteranopic, and 75% of tritanopic comparisons, each well above the 50% chance line (two-tailed binomial, $p < .001$). Reported task-completion times on colour-critical UI widgets fell by a median of 23% relative to the unmodified interface, replicating usability improvements noted in recent UI-accessibility studies [16].

5.3 Computational Performance

On a Google Colab Pro, ChromATA processes 1080p frames in 0.41ms (simulation 0.19ms, compensation 0.22ms), matching the sub-millisecond benchmark of Ebelin et al. [8]. The same pipeline sustains 92fps on an M1 Pro without a discrete GPU. Peak power draw measured with nvidia-smi averages 46W, comparable to DALTONLENS despite finer per-superpixel optimisation.

6. Discussion

ChromATA closes a gap identified in earlier accessibility toolchains: open, cross-platform, and real-time CVD support with extensible APIs. Objective gains stem primarily from local hue re-allocation, which aligns with neuro-plastic compensation observed in early visual cortex [20]. Nevertheless, two limitations remain. First, our solver assumes uniform lighting; extreme HDR scenes can violate the lightness-chroma balance and overshoot CIEDE2000 targets. Second, the forced-choice study enlisted colour-normal observers viewing simulated CVD, a common but imperfect surrogate for genuine dichromats [5].

7. Conclusion

This paper introduced ChromATA, an open, GPU-accelerated toolkit that unifies state-of-the-art simulation, compensation, and evaluation for colour-vision deficiencies. Experiments on calibrated charts, real-world UIs, and live video confirm perceptual, usability, and throughput advantages over widely used baselines. By releasing source code, datasets, and CI scripts under MIT terms, ChromATA establishes a reproducible foundation on which both researchers and practitioners can iterate. Future work will extend the optimisation to HDR imagery, integrate adaptive tone mapping, and conduct longitudinal trials with diagnosed CVD users to validate sustained usability gains.

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