Ambient-Adaptive Tunable Ophthalmic Filters for Colour Vision Deficiency and Photophobia

A Collaboration Whitepaper

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This document is formatted as a collaboration whitepaper, not a journal manuscript.

Not a Funding Request

1. Device Overview and Intended Use

Colour vision deficiency (CVD) affects an estimated 300 million people worldwide (Birch, 2012). Migraine affects approximately one billion people globally (Stovner et al., 2022), with photophobia reported as a symptom in a substantial majority of cases—estimates of 80% or higher appear in the clinical literature (Digre & Brennan, 2012), though exact prevalence depends on the migraine subtype studied.

Existing corrective lens products—including EnChroma, Pilestone, ChromaGen, Avulux, and FL-41 tinted lenses—share a common limitation: their spectral filtering profiles are fixed. Evidence for the clinical efficacy of fixed-notch CVD correction filters remains inconclusive. Gómez-Robledo et al. (2018) found no statistically significant improvement in standard colour vision tests with EnChroma lenses, and broader systematic reviews have not established clinically significant benefit for passive notch filters as a class. A comprehensive meta-analysis covering all passive CVD notch filter products has not, to the author's knowledge, been published as of February 2026.

This whitepaper proposes a dynamically tunable spectral filter in an ophthalmic form factor as a concept for investigation. The device would require an optimisation algorithm to adjust notch parameters for individual CVD profiles under varying illumination—an algorithm that does not currently exist and represents one of several critical research challenges. A simpler baseline approach (manual user adjustment of notch parameters) could provide value while algorithmic solutions are explored, though the clinical benefit of manual adjustment over existing fixed filters has not been established.

Intended use: An active, electronically tunable ophthalmic spectral filter worn as spectacles, designed to improve colour discrimination for individuals with CVD and to attenuate wavelengths associated with photophobia in migraine patients. The device would adapt its filtering profile in response to ambient illumination conditions and the wearer's individual visual profile.

Classification: Active tunable spectacles with embedded software would likely classify as medical devices under EU MDR 2017/745 (Class IIa or above for software-driven therapeutic function) and would require MHRA registration in the United Kingdom.

2. Clinical Rationale

Clinical evidence for fixed CVD correction products is mixed. One plausible explanation is that optimal filter parameters vary by CVD subtype, individual severity, and illumination condition, such that a fixed filter cannot address this variability across users and environments. Other explanations exist: spectral notch filtering may be inherently limited as a CVD intervention; individual neuroadaptation may vary unpredictably; or current filter designs may be suboptimal in ways that could be corrected without dynamic tuning. The case for tunable filters rests on the first explanation, and this assumption should be tested rather than taken as given.

Tunable filters are not the only alternative to fixed one-size-fits-all products. Intermediate approaches deserve acknowledgement: patient-customised fixed filters manufactured to individual prescription (analogous to personalised spectacle lenses), multi-filter clip-on or snap-in systems allowing the user to switch between pre-set profiles, and software-assisted filter selection tools that recommend a fixed filter based on diagnostic testing. The proposed tunable approach offers potential advantages over these alternatives in continuous adaptability, but carries substantially greater technical complexity and cost.

2.1 Wearable Liquid Crystal Optics: State of the Art

Liquid crystal (LC) optics have been demonstrated in wearable form factors. IXI (Finland) demonstrated auto-focus LC glasses at 22 g total weight with all-day battery life in late 2025. FlexEnable produces LC lenses on substrates thinner than 100 m. These references validate that LC elements can be integrated into spectacle frames, but they address simpler optical problems (binary focus switching, uniform tint modulation) than the proposed system. The proposed device adds substantially more componentry—miniature spectrometer, computational platform, multi-layer photonic crystal stack, ITO electrodes, and controller firmware—and the feasibility of integrating all of these into a wearable form factor has not been demonstrated. The IXI reference should be understood as evidence that LC-in-spectacles is viable, not that the proposed complete system is viable at comparable weight or battery life.

Kent Optronics has demonstrated polariser-free nematic tunable notch filters with 5 ms switching speed and over 40% transmittance outside the notch. That 40% broadband transmittance represents 60% light loss—equivalent to moderately dark sunglasses (approximately Category 2–3 tint). This transmittance level may be acceptable for outdoor daytime use but would likely be functionally unacceptable for indoor use, low-light conditions, or night driving. If the photonic crystal stack cannot achieve substantially higher broadband transmittance (indicatively above 70%), the device may be restricted to outdoor daytime applications, significantly narrowing the addressable use cases. This is a hard physics constraint of the current material system, not an engineering optimisation problem with a clear path to resolution.

2.2 Electrochromic Materials

Next-generation electrochromic materials—MXene nanosheets with 75% transmittance modulation, polymer-MXene-viologen suprahybrids with approximately one-second switching and 85% optical contrast at very low maintenance power—represent an alternative material pathway. For real-time adaptive correction responding to ambient illumination changes (walking from indoors to outdoors, for example), a one-second switching time is perceptually noticeable and may induce transient colour distortion during the transition. The perceptual latency threshold for acceptable chromatic adaptation in a worn corrective device has not been established in the literature, and this threshold would need to be determined empirically.

LC remains the preferred pathway for ophthalmic use owing to superior switching speed (5–230 ms) and cycle lifetime (exceeding 100 million cycles), but LC carries its own limitations as discussed in the risk analysis.

2.3 Project History

An earlier iteration of this project proposed exploiting the passive angle-dependence of the Bøggild stack for CVD correction. A critical external review identified that this creates binocular disparity hazards and violates chromatic constancy, leading to visual fatigue and motion sickness. The pivot to active electronic tuning eliminates these specific physiological risks, though active systems introduce different risks—electronic failure, software faults, latency artefacts—that must be separately addressed.

3. Technical Specifications

A prior-art search was conducted across patent databases and academic literature during January–February 2026. Three aspects were identified as potentially novel, with the caveat that absence of prior art does not, by itself, indicate that an idea is promising. Absence may also indicate that others have considered and rejected the approach, or that the underlying constraints make it impractical.

3.1 Proposed System Architecture

First, the integration of a liquid crystal or electrochromic defect layer within a polymer one-dimensional photonic crystal for ophthalmic spectral notch filtering.

Second, ambient-illumination-adaptive CVD correction—dynamically adjusting the notch position based on ambient spectral content and individual CVD profile. This requires a spectral optimisation algorithm that is currently an unsolved problem and constitutes one of several critical research challenges.

Third, combined CVD correction and photophobia management in a single tunable device. An important limitation applies: for tritanomaly (blue-cone CVD), blocking 480 nm for photophobia directly conflicts with the CVD correction requirement. This subtype conflict must be resolved on a per-patient basis and may preclude the combined mode for tritanomaly patients.

3.2 Spectral Optimisation Algorithm

The proposed adaptive correction system is best described as a spectral notch filter optimisation problem: given the ambient illuminant spectrum, a model of the individual patient's cone sensitivity functions (including the specific CVD deficit), and the set of object reflectance spectra likely present in the visual scene, compute the notch filter parameters (centre wavelength, full width at half maximum, depth) that maximise colour discrimination for the patient. This is distinct from metameric matching, which in colorimetry refers specifically to finding different spectral power distributions that produce identical tristimulus values for a given observer.

The core computational challenge involves ambient spectral capture via a miniature spectrometer; modelling of the individual patient's cone sensitivity deficit (requiring per-patient calibration data and a cone response model, where obtaining sufficiently accurate individual cone models in a clinical or point-of-care setting remains unsolved); estimation or assumption of object reflectance distributions in the visual scene (a fundamental limitation, since the algorithm would need to optimise for colours the patient is likely to encounter, which cannot be known in advance); real-time computation of optimal notch parameters from these inputs; and LC actuation with latency below the perceptual threshold, likely under 50 ms based on flicker fusion and chromatic adaptation literature.

Several of these steps remain unsolved problems. A simpler manual-adjustment baseline could be investigated as a near-term alternative, though its clinical benefit relative to existing fixed filters is unproven.

3.3 Component Requirements

The proposed system requires the following components integrated within a spectacle frame: a miniature spectrometer for ambient light measurement, a computational platform for running the optimisation algorithm, a multi-layer photonic crystal stack with LC or electrochromic defect layers, ITO electrodes for applying control voltages, controller firmware, and a battery of sufficient capacity for all-day operation.

No component mass budget, power budget, or thermal budget has been developed. Providing order-of-magnitude estimates for these budgets is a prerequisite for meaningful engineering collaboration.

4. Safety Considerations

4.1 LC Thermal Stability

LC alignment layers degrade under UV exposure and above approximately 60°C. Spectacle frames can reach 60–80°C in direct sunlight (left on a car dashboard, for instance). Alignment layer failure changes the tuning response and cannot be field-repaired. A thermal management strategy or use-case restriction is required, though no thermal analysis has been performed.

4.2 Tritanomaly and Photophobia Conflict

Blocking 480 nm (the peak sensitivity of intrinsically photosensitive retinal ganglion cells, relevant to photophobia) directly undermines blue-cone CVD correction for tritanomaly patients. The combined CVD and photophobia mode cannot serve all CVD subtypes simultaneously. Clinical protocols would need to identify this conflict during patient assessment and restrict the combined mode accordingly.

4.3 Broadband Transmittance Constraint

Current polariser-free LC notch filter demonstrations achieve over 40% transmittance outside the notch band. For a general-purpose ophthalmic device usable in indoor, low-light, and night-driving conditions, substantially higher broadband transmittance is likely required. Whether this can be achieved with the proposed photonic crystal architecture is uncertain and may represent a fundamental material limitation rather than a gap that engineering alone can close.

4.4 Optical Scaling

Polymer one-dimensional photonic crystals with LC defect layers have been demonstrated in laboratory settings. Scaling to ophthalmic form factor with uniform optical performance across the full visual field (approximately 50 mm aperture with consistent spectral response at oblique viewing angles) is assumed but not evidenced. This materials engineering challenge may present unforeseen obstacles.

4.5 Electronic and Software Failure Modes

Active systems introduce risks absent from passive fixed filters: electronic component failure, software faults in the optimisation algorithm, and latency artefacts during filter transitions. Each requires separate mitigation strategies, failure mode analysis, and clinical validation. The spectral optimisation algorithm, as Software as a Medical Device (SaMD), would require clinical validation of its outputs, regulatory submission, and cybersecurity assessment.

5. Regulatory Pathway

Active tunable spectacles with embedded software would likely classify as medical devices under EU MDR 2017/745. A device with software-driven therapeutic function would fall into Class IIa or above, requiring conformity assessment by a Notified Body. In the United Kingdom, MHRA registration would be required under the post-Brexit regulatory framework.

The spectral optimisation algorithm constitutes Software as a Medical Device (SaMD) under MDCG 2019-16 guidance. This classification triggers requirements for clinical validation of algorithmic outputs, a formal regulatory submission pathway, and a cybersecurity assessment. The realistic regulatory timeline is three to five years minimum from clinical data to market authorisation.

This timeline constraint should be factored into any development roadmap from the outset. It is not a formality—SaMD classification for a novel adaptive algorithm without established predicate devices means the regulatory pathway will require primary clinical evidence rather than reliance on equivalence arguments.

6. Risk Analysis

The project faces several independently critical challenges, any one of which could prevent the concept from being realised. These are listed without a hierarchy of importance, because ranking them requires feasibility analysis that has not been performed.

6.1 Spectral Optimisation Algorithm

The adaptive correction value proposition depends on a spectral optimisation algorithm that does not exist. The problem is harder than it may initially appear because it requires modelling not just illuminant spectra but object reflectance distributions and individual cone responses. Without this algorithm, the device is limited to manual notch adjustment—and the manual baseline itself is an untested hypothesis with no evidence of superiority over existing fixed filters.

6.2 Broadband Transmittance

This is a hard physics constraint. If the photonic crystal stack cannot achieve broadband transmittance substantially above 40%, the device is restricted to outdoor daytime applications. The addressable market and clinical utility narrow considerably under this restriction.

6.3 Form Factor, Power, and Thermal Budgets

No engineering budgets have been estimated. As a preliminary framing (not a calculated budget): the IXI auto-focus glasses achieve 22 g for a simpler system, and the proposed device's additional components (spectrometer, compute module, more complex LC stack) will add mass. Whether the total can remain below 40–50 g—a rough threshold for comfortable all-day spectacle wear—is unknown. Continuous spectral sensing, periodic computation, and LC drive current all draw power, and extrapolating from IXI's all-day battery life for binary focus switching is not valid for this system's power draw. LC alignment layers degrade above 60°C, yet spectacle frames can reach 60–80°C in direct sunlight.

6.4 Recruitment and Sustainability

The project value proposition depends on assembling multi-disciplinary expertise spanning neuro-ophthalmology, LC optics, polymer chemistry, clinical trial design, computational vision, and regulatory affairs. The author is an independent researcher without institutional affiliation, laboratory facilities, or funding. The probability of recruiting collaborators of sufficient breadth and depth under these conditions is low. This structural constraint is the most likely near-term failure mode.

6.5 Clinical Optimisation Parameters

Controlled clinical trials with tunable filters have not been conducted. The clinically optimal notch depth, width, and centre wavelength for each CVD subtype (protanomaly, deuteranomaly, tritanomaly) under standardised illuminants remain unknown. It is not established that a single notch filter is sufficient for meaningful CVD correction—protanomaly and deuteranomaly may require multi-notch or band-pass profiles. The single-notch design assumption should itself be tested clinically before committing to a specific photonic crystal architecture.

6.6 Manual Adjustment Baseline

The fallback position—manual user adjustment of notch parameters—is proposed as a near-term alternative to algorithmic adaptation. No evidence has been presented that patient-controlled notch tuning produces better clinical outcomes than existing fixed filters. It is possible that a manually tunable filter is functionally equivalent to, or worse than, existing fixed products (owing to added weight, cost, complexity, and reduced transmittance). The manual baseline should be considered an untested hypothesis, not an assumed fallback.

7. Invitation to Collaborate

This whitepaper is issued as an open invitation to research collaboration. This project is not seeking funding at this stage.

The author acknowledges the structural challenges of this invitation: the project requires expertise across multiple disciplines, is unfunded, has no institutional backing, and lacks a demonstrable prototype. The realistic path forward may begin with a single collaboration—most likely in LC optics or computational colour vision—to produce a feasibility demonstration or simulation result that could then serve as the basis for broader recruitment or funding applications.

Expertise is sought in the following areas: neuro-ophthalmology and colour vision science, particularly clinical assessment of CVD correction efficacy; liquid crystal optics and electrochromic materials, particularly broadband transmittance optimisation; polymer photonic crystal fabrication, particularly scale-up to ophthalmic apertures; clinical trial design for ophthalmic devices; computational vision and spectral optimisation; and medical device regulatory affairs under EU MDR and MHRA frameworks.

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8. References and Standards

External References

Birch, J. (2012). Worldwide prevalence of red-green color deficiency. Journal of the Optical Society of America A, 29(3):313–320. DOI: 10.1364/JOSAA.29.000313.

Stovner, L.J. et al. (2022). The global prevalence of headache: an update, with analysis of the influences of methodological factors on prevalence estimates. Journal of Headache and Pain, 23:34. DOI: 10.1186/s10194-022-01402-2.

Digre, K.B. & Brennan, K.C. (2012). Shedding light on photophobia. Journal of Neuro-Ophthalmology, 32(1):68–81. DOI: 10.1097/WNO.0b013e3182474548.

Gómez-Robledo, L. et al. (2018). Do EnChroma glasses improve color vision for colorblind subjects? Optics Express, 26(22):28693–28703. DOI: 10.1364/OE.26.028693.

Regulatory Standards

EU MDR 2017/745 — Regulation on medical devices. Official Journal of the European Union.

MDCG 2019-16 — Guidance on cybersecurity for medical devices.

Internal Project Documents

Project Labradorite: Commercial Applications of Synthetic Labradorescence (Deep Research Report, February 2026).

Strategic Evaluation and Commercial Roadmap for Project Labradorite (Technical Analysis, 2026).

Critical Evaluation and Strategic Enhancement of Project Labradorite (External Review, 2026).

Improvements to Project Labradorite (Enhancement Brief, 2026).

Appendix A: Document Metadata

Appendix B: Glossary

Appendix C: Methodology and Transparency Statement

Author Context and Expertise

This work is grounded in 30 years of multi-sector experience in Systems Engineering. The analytical framework reflects professional history, focusing on practical application.

Digital Methodology and Accessibility

In the spirit of transparency, I utilised a suite of Generative AI tools—specifically Claude, Google Gemini, and ChatGPT—to assist in the production of this paper. These tools were employed as force multipliers for data synthesis and editorial accessibility. As a writer with dyslexia, I leverage these models as assistive technology to refine grammar and streamline sentence structure.

Verification and Integrity

While AI assisted in processing data, the intellectual oversight is entirely human. I performed manual validation of all citations and accept full responsibility for the accuracy and originality of the final output.

Appendix D: Raw Author Notes

The concept for ambient-adaptive tunable ophthalmic filters emerged from Project Labradorite, which investigated commercial applications of synthetic labradorescence. The original approach exploited the passive angle-dependence of thin-film optical stacks (Bøggild stacks) for CVD correction, but external critique identified binocular disparity and chromatic constancy violations that made this approach clinically untenable. The pivot to active electronic tuning addressed these specific physiological risks while opening new engineering and algorithmic challenges.

The author's primary insight is the recognition that fixed spectral filters cannot serve a heterogeneous patient population under variable lighting conditions—a systems engineering observation rather than a clinical one. The core intellectual contribution is framing CVD correction as a real-time spectral optimisation problem rather than a static filtering problem, and honestly characterising the substantial unsolved challenges this framing reveals.

Several claims from earlier drafts were retracted or substantially qualified during the review process. An unverifiable meta-analysis reference was removed. The term "metameric matching algorithm" was corrected to "spectral optimisation algorithm" to reflect the actual computational problem. Unsupported engineering figures were removed. Intermediate alternatives between fixed and tunable filters were acknowledged. The overall effect of the review process was to make the paper substantially more honest about what is and is not known, at the cost of a less compelling narrative arc.

Appendix E: Change Log