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BRIEF COMMUNICATION

Performance enhancement in color deficiency with color-correcting lenses

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Normal color vision, predicated on three cones sensitive to red, green, and blue light, is essential for critical color discrimination in multiple occupations. Yet 8% of males and 0.5% of females have hereditary X-linked color vision deficiency (CVD): red or green cones are absent (2%) or peak sensitivity of defective cones are shifted in wavelength [1]. A novel approach using color-correcting lenses (CCLs) with notch filters improved suprathreshold red-green perception in CVDs after extended wear even without viewing through CCLs [2]. We used cone specific tests (contrast sensitivity, CS [3], visual evoked potentials, VEPs [4], color naming) to demonstrate immediate and long-term threshold and supra-threshold improvements in CVDs with CCLs.

Thirteen CVDs (9 green/deuteranomalous, 4 red/protanomalous, mean age 32 ± 14, range 13-66; CVD confirmed by Ishihara, anomaloscope, cone CS tests) provided informed consent to participate (repeated measures, before-after design). Each subject was given a CCL appropriate for their CVD (www.enchroma.com) and tested with and without CCLs at baseline and 11–14 days later after wearing the CCLs daily (mean h/day: 2.5 ± 1.8). Cone CS [3] and color naming were assessed by presenting letters visible only to red, green, or blue cones and gray luminance letters on a Surface Pro in randomized order within and between sessions. Subjects verbally identified each letter and its color with scoring (0–100) based on letters correct (0.15 log CS/letter). Cone specific VEPs [4] were recorded to an average of 75 pattern onsets without and with CCLs.

With CCLs CVDs showed immediate increase in cone CS for letters corresponding to defective cone types (mean improvement: 26, 95% CI: 7–45, $P = 0.01$; 80% improved with CCLs, $P = 0.01$, Fig. 1a). Color naming also improved with CCLs (mean improvement: 22, 95% CI: 6–38, $P = 0.006$; 70% improved with CCLs, $P = 0.006$, Fig. 1b). After 12 days of CCL wear, cone CS and color naming for defective cone types improved *without wearing the CCLs* (mean CS improvement: 15, 95% CI: 8–21, $P < 0.001$, 85% improved without CCLs, $P < 0.001$, Fig. 1a; mean naming improvement: 19, 95% CI: 7–31, $P = 0.004$; 70% improved without CCLs, $P < 0.001$, Fig. 1b). Figure 2 shows VEPs from a green CVD at baseline without and with CCLs and 11 days later without CCLs. VEPs were minimal without CCLs but showed large amplitudes with CCLs and 11 days later without CCLs.

Study limitations include lack of controls (e.g., CVD response to neutral filters with same luminance transmission as CCLs), but one color-vision normal showed no change in color test outcomes and two showed no VEP changes with CCLs. While the CCLs surely modified stimulus chromaticity and luminance [2], the cone specific CVD improvements substantiate potential application of CCL notch filters for CVD.

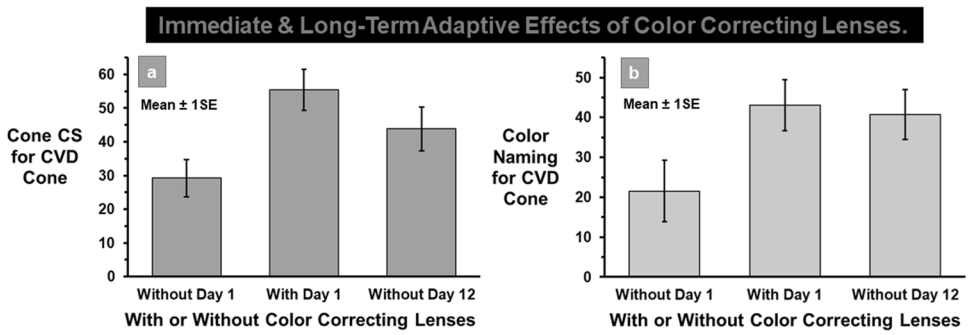

Fig. 1 Cone contrast sensitivity (CS) [3] and color naming accuracy in color vision deficient (CVD) subjects. a Mean (±1 SE, $n = 13$) cone CS for the defective cone type is shown for Day 1 without and with color correcting lenses (CCLs) showing an immediate improvement. Day 12 shows long term improvement in CS without wearing the CCLs suggesting neuro-adaptive enhancement. **b** Results comparable to those shown in **a** are shown for color naming. While results are clear, the text appropriately reports results of parametric and non-parametric within subject comparisons which use appropriate error bars and parameters for paired analyses.

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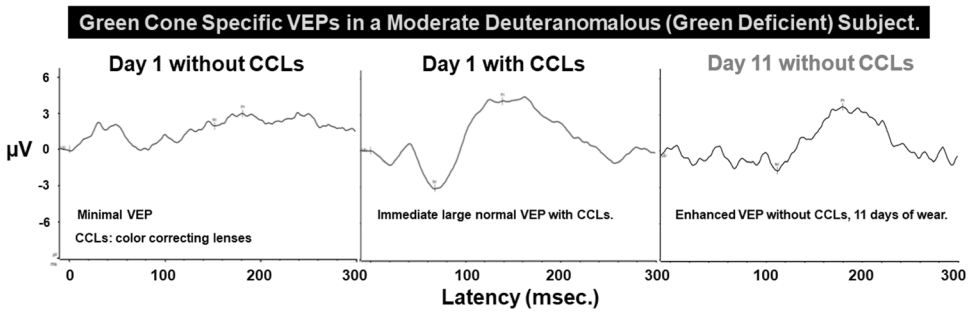

Fig. 2 Immediate and long-term enhancement in cone specific VEPs [4] with CCLs. Results are shown for a subject with moderate deuteranomalous (green cone) CVD. The left panel shows Day 1 (baseline) nearly flat mean VEP to 75 artifact-free pattern onsets of a stimulus which selectively stimulates green cones. The middle panel shows results from the same subject on Day 1 while wearing the CCLs: note the well-defined normal green-cone VEP characterized by an early negative wave followed by a positive peak. The right panel shows the VEP from the same subject after wearing the CCLs for 11 days, 2.72 h/day). Albeit delayed compared to the middle panel, note the substantial gain in amplitude compared to baseline suggesting neuro-adaptive changes. Similar VEP changes were observed in several subjects.

Immediate threshold (CS) and suprathreshold improvements (naming, VEPs) can ensue in CVDs with CCLs. Extended wear improved outcomes even without CCLs suggesting neuro-adaptive changes [2]. fMRI shows CVD defects in lower cortex with neural compensation at higher levels [5]. Hence changes reported herein may reflect top-down perceptual learning from higher to lower cortex.

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AUTHOR CONTRIBUTIONS

JR was responsible for conceptualization, conducting the investigation, formal analysis, writing, reviewing, and editing the manuscript, and project administration. FS was responsible for conceptualization, data collection and analysis, reviewing, and editing the manuscript. NT, HG, LL, LI, GA, EL, and HV were responsible for conceptualization, data collection, analysis, validation, and data curation.

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COMPETING INTERESTS

There were no competing financial interests in the conduct of this research and no disclosures to be made by any of the authors. EnChroma donated color vision correcting spectacles for use in the study but provided no assistance or guidance during any phase of this study.

ADDITIONAL INFORMATION

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