# Using commercial glasses for CVD correction with digital displays

**Luca Armellin[1], Alice Plutino[1], Alessandro Rizzi[1]**
[1]MIPS Lab, Department of Computer Science, Università degli Studi di Milano, Milano
Contact: Luca Armellin, luca@armellinluca.com

## Abstract

The development and commercialization of aids for improving, and sometimes allegedly correcting, the discrimination of colors, in color vision deficient subjects, has increased in the last few years. Producers often claim such devices are also effective in improving the experience of color vision while using digital displays, sometimes even selling specific types intended for indoor and display monitor usage. In general, the underlying mechanism of these physical ocular filters is to reduce the amount of spectral energy in specific bands of the visible spectrum. The most common digital displays rely on the emission of three light sources limited in band occupancy, so different filter types might be more or less effective when used with digital displays rather than when observing real scenes or pigments. This paper aims to comment and evaluate the effectiveness of such filters when used with different types of digital display technologies. We discuss whether inter-device variations (namely different gamuts) might alter the chromatic sensation of users.

**Keywords:** color deficiency, color blindness, color perception.

## Introduction

The most common forms of congenital color blindness arise from a lack of a class of cones or an alteration in one of them, resulting in overlapping the spectral responses of two sets of cones (Birch, 2012; Hunt and Carvalho, 2016). The most common form is the latter and takes the name of anomalous trichromacy, a condition in which the L (protanomaly) or the M (deuteranomaly) cones exhibit a slightly altered spectral response, resulting in the two curves getting closer and thus reducing the delta between the signals produced by the two sets of cones for a given stimulus. This leads to a reduction of chromatic contrast between the L and M signals, leading to an under-stimulation of the neural pathway comprising the "red-green" opponent system (Boehm, A.E. *et al.*, 2021). In this study, we considered two glasses of two types manufactured by Pilestone and Enchroma. To make a preliminary assessment of the differences between glasses, after estimating the spectral sensitivities of the cones for an ideal protanomalous and an ideal deuteranomalous observer, we computed:

(a) The difference between the two sets of cones using both the actual spectral sensitivities;
(b) The spectral sensitivities weighted by the transmittance of the glasses' lenses;
(c) The filtering of the primaries of digital displays through the glasses lenses.

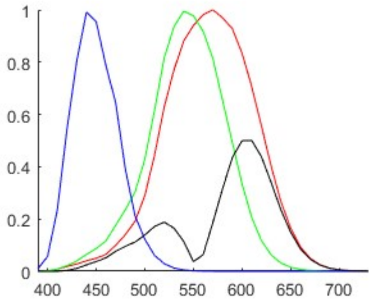
The pointwise absolute difference between the two spectra (L and M) can be interpreted as the resulting differential value generated by the two sets of cones for a monochromatic stimulus having unitary amplitude at different wavelengths. On the other hand, the delta between the filtered versions of the cones' response indicates the glasses' effectiveness in improving the separation between the signals generated by two cones for a given monochromatic stimuli. This separation can be compared with the L and M separations of the standard color observer, providing a preliminary idea of the glasses' effectiveness. In addition to these measures, the simulation of the filtering of the RGB primaries of a digital display can provide a preliminary assessment of the effectiveness of using glasses with digital displays.

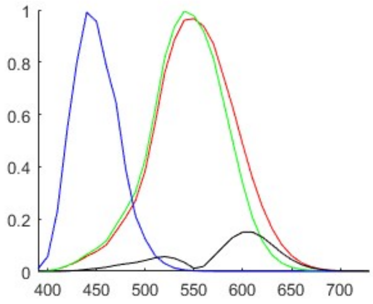
## Materials and methods

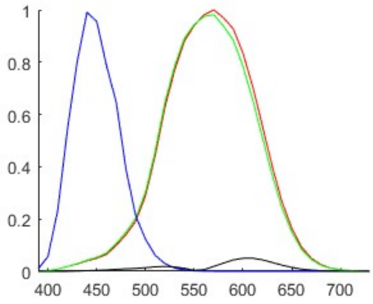
### *Cones spectral sensitivity estimation*

As described in the Introduction, to assess the differences between the distinct types of glasses, we first computed an estimate of the spectral sensitivities of the cones for an ideal protanomalous and an ideal deuteranomalous observer. Later, we computed the difference between the two sets of cones using both the actual spectral sensitivities (as can be seen in Fig. 1) and the spectral sensitivities weighted by the transmittance of the glasses' lenses (Fig.2 and Fig. 3). The black plot in Fig. 1 shows the pointwise absolute difference between the two spectral sensitivities. The spectral sensitivities for the anomalous observers (L' and M') have been computed with a linear combination of both the L and M cones, based on the equation in Eq. 1 (Lucassen M. and Alferdinck J., 2006; Martínez-Domingo, M.Á., *et al.*, 2020):

$$L' = ((1 - d) \cdot L) + (d \cdot M)$$
$$M' = ((1 - d) \cdot M) + (d \cdot L)$$







### *Glasses transmittance measurement*

The glasses that have been considered were manufactured by Pilestone and Enchroma, specifically, we had been supplied with four types of glasses from Pilestone and had acquired one type from Enchroma. All the glasses have had their transmittance computed by means of averaging the respective transmittances of each of the two lenses, which were measured using an A illuminant as a light source and an X-Rite Eye-One Pro spectrophotometer using the open-source software i1Toolz. i1Toolz is an open-source software currently under development that enables commercial spectrophotometers and colorimeters, usually destined for displays and printers' calibration and profiling, to take spectral measurements. Being the X-Rite Eye-One a spectrophotometer capable of only taking 45/0 reflectance or emission readings, using it to measure transmittance requires the use of an external light source against which the instrument, together with the software, needs to be calibrated (hence why a light source has been specified). The use of a type-A illuminant is a result of the fact that LEDs mimicking D65 or D50 light sources emit a relevant amount of energy in the blue region of the visible spectrum, which we noticed introduced errors in the longer wavelengths portion of the spectrum in the form of a transmittance even greater than 1 for some LEDs; emission measurements of the lenses illuminated on the side opposing the instrument with a blacklight showed that all of them undergo fluorescence when struck with short wavelengths of light, this is the reason why we chose to use an incandescent bulb to take all the measurements. The graph in Fig. 1 shows the spectral transmittances of the four glasses pairs made by Pilestone and the one made by Enchroma.

The graph in Fig. 2 shows the spectral transmittances of the four glasses pairs made by Pilestone and the one made by Enchroma. Pilestone's type E and D shows some common characteristics with type A and B. Pilestone type A (as well as type E) has an almost neutral density throughout the shorter to medium wavelengths, effectively emphasizing the longer wavelength above around 650 nm, resulting in a reddish color. Pilestone type B (as well as type D) shows a similar behavior, with a higher density in the medium wavelengths dropping below 480 nm. The Enchroma Cx3, on the other hand, shows some interesting differences: they still emphasize the red portion of the spectrum but also show two lows effectively acting as narrow notch filters centered at 490 nm and 580 nm.

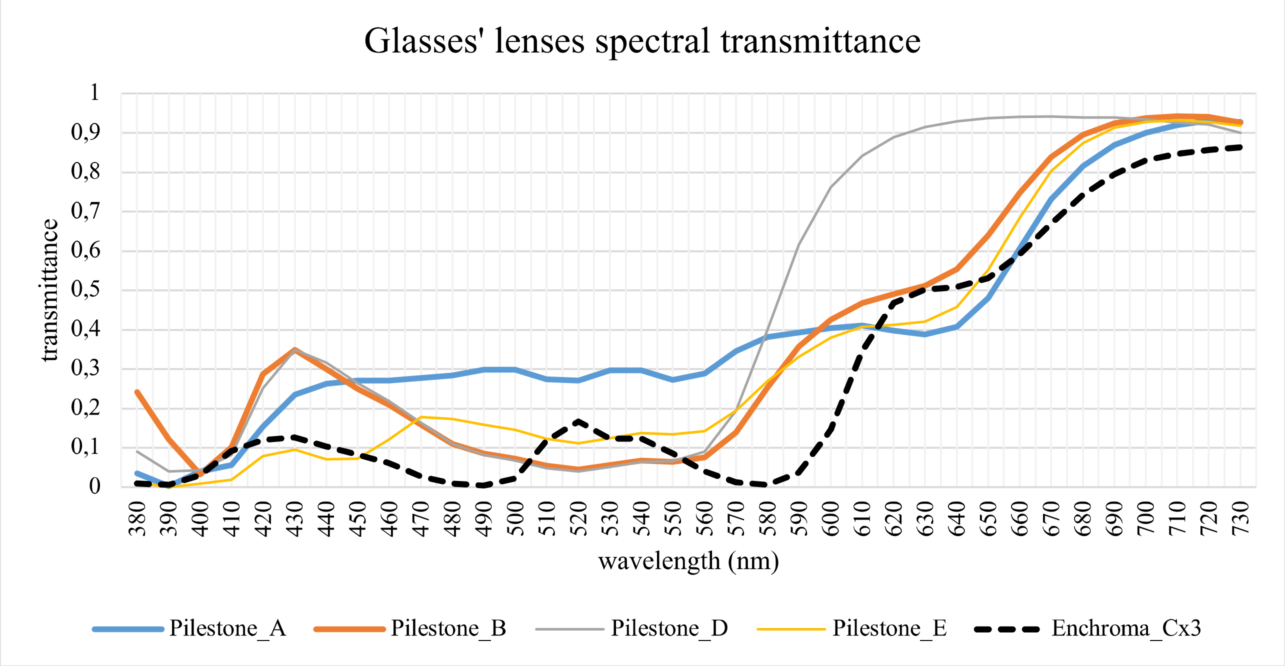


Fig. 2 – Spectral transmittances of the glasses' lenses. To make the graph easier to read, only some of the lenses have been highlighted, which are the ones on which the focus has been posed.

In Table 1, we report the average optical densities of the glasses in different portions of the visible spectrum (derived from Fig. 2). Optical density corresponds to the $\log_{10}$ of the reciprocal of the transmittance, so provide information on the average amount of light, which is filtered by the glasses, in three different regions of the visible spectrum, confirming the evaluations made to Fig. 2.

| | **Pilestone_A** | **Pilestone_B** | **Pilestone_D** | **Pilestone_E** | **Enchroma_Cx3** |
|---|---|---|---|---|---|
| **O.D. [380-730nm]** | 0.3952 | 0.4203 | 0.3423 | 0.4658 | 0.5521 |
| **O.D. [380-580nm]** | 0.6311 | 0.8342 | 0.8405 | 0.9468 | 1.1874 |
| **O.D. [590-730nm]** | 0.1947 | 0.1508 | 0.0510 | 0.1786 | 0.2349 |

Table 1 – Average optical densities in different portions of the visible spectrum, computed from the glasses' spectral transmittances shown in Fig. 2.

### ***Simulation of glasses effect on digital displays***

After measuring the glasses' transmittances, we proceeded to simulate the effect of the lenses on the gamut of digital devices. This operation aims to understand whether the optical filters would be sharp enough to increase the difference between the signals generated by the M and L cones struck with the light emitted by the primaries of different devices, as well as to see whether the gamut of the filtered device would change shape.

Given the wide variety of displays on the market adopting different technologies, primaries, and gamuts, we decided to measure only two displays, one being an Acer XR341CK and the other being one of a Google Pixel 6A smartphone. Average-priced IPS displays have a gamut covering the whole sRGB color space; hence, the first chosen display is representative of most computer displays used daily at home and office. The latter has been chosen since it has a wide gamut AMOLED display, to include a different technology in our investigation. Thus, the results of this study can apply to most displays.

The devices were measured using the same X-Rite Eye-One spectrophotometer, set in emission mode together with the i1Toolz software. The displays have been set to the maximum available brightness intensity. An HTML file showing Red, Green, and Blue *(#FF0000, #00FF00, #0000FF)* squares have been loaded, and each of the squares measured for emission using the spectrophotometer, for which the spectral readings are shown in Fig. 3.

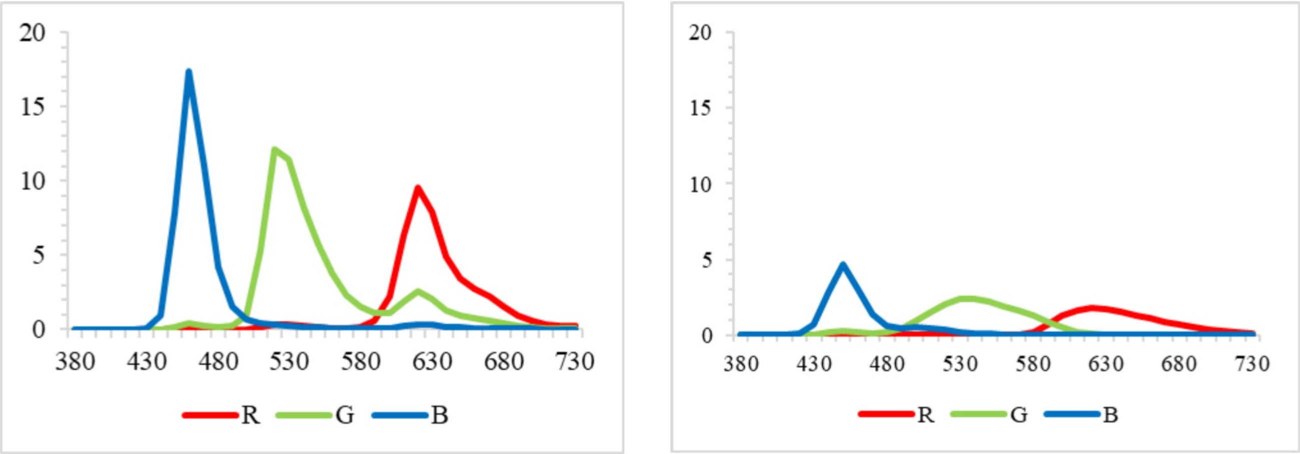


Fig. 3 – Spectral emissions of the primaries of the two displays. Google Pixel 6A on the left, Acer XR341CK on the

Fig. 1 – Ones of a protanomalous observer (center) and those of a deuteranomalous observer (right). In black is shown

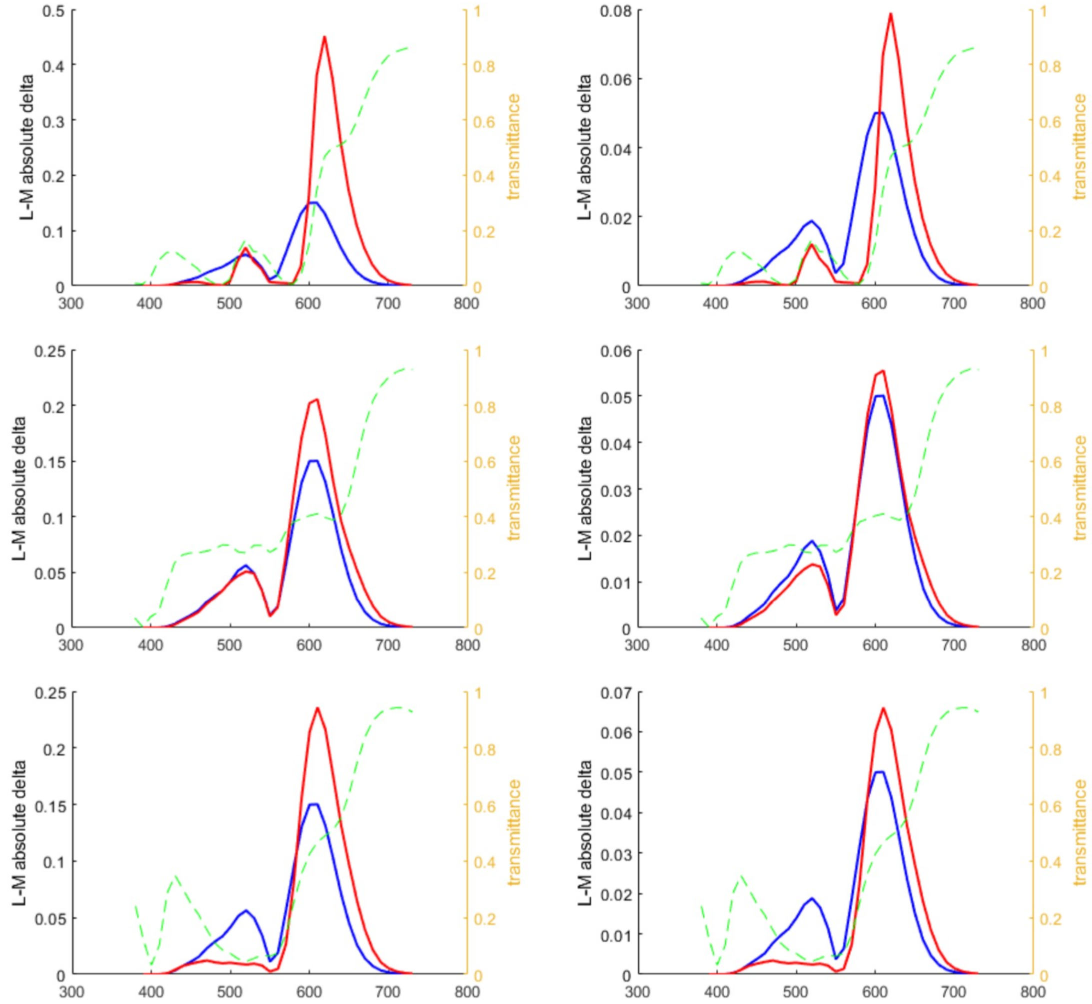


Fig. 4 – In blue is the absolute difference between the L and M cones' sensitivities (as can be seen also in Fig. 1). In red, the absolute difference between the sensitivities weighted by the transmittance of the glasses, in green the transmittance of the glasses. The left column refers to the protanomalous observer, the right to the deuteranomalous one. Top row refers to the Enchroma glasses, center row to the Pilestone type A, bottom row to the Pilestone type B.

## Results

### L and M cones sensitivity differences generated by the glasses

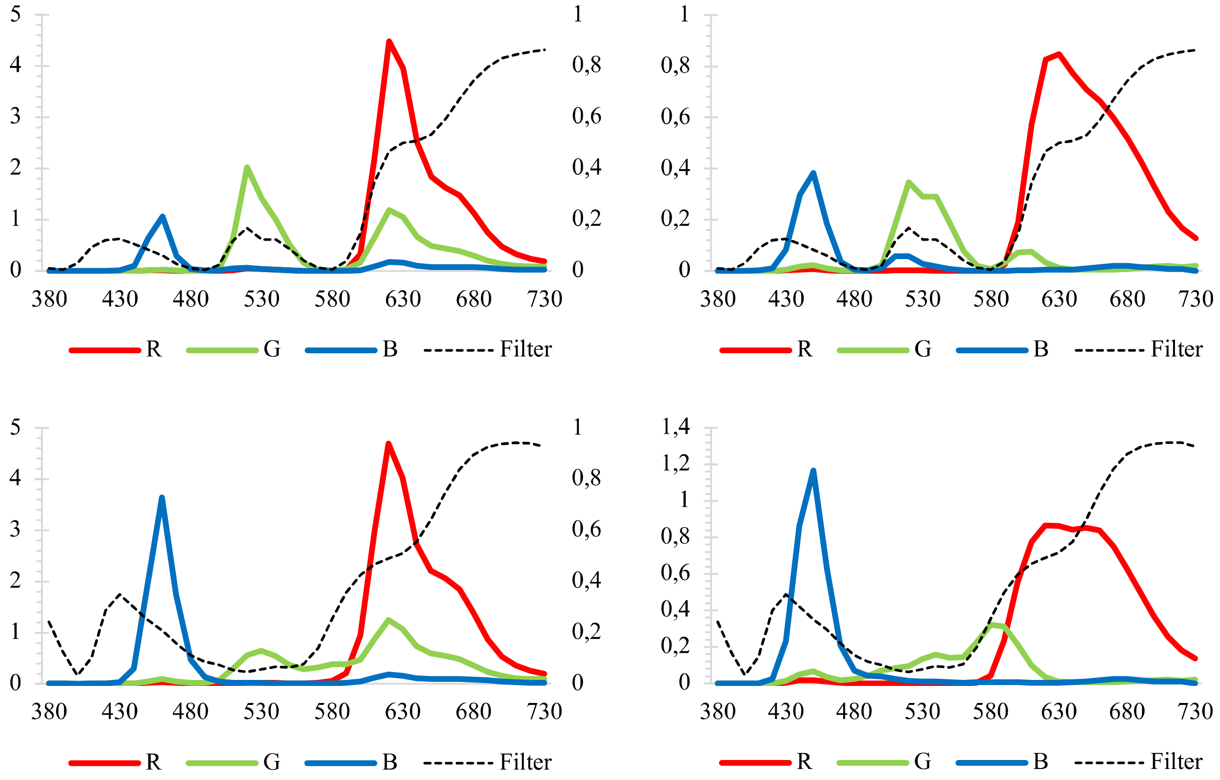
After estimating the spectral sensitivities of the cones for an ideal protanomalous and an ideal deuteranomalous observer, computing the difference between the two sets of cones using both the actual spectral sensitivities, we obtained the spectral sensitivities weighted by the transmittance of the glasses lenses. The delta between the filtered versions of the cones' response indicates the glasses' effectiveness in improving the separation between the signals generated by two cones for a given monochromatic stimuli.

Looking at the plots in Fig. 4, the most significant increase in delta between the two curves is obtained when filtering using the Enchroma glasses, at least for the wavelengths above 600nm. At the same time, the Pilestones do not seem to have such a relevant impact. It can also be noted that the filters leading to a greater separation between the L and M signals tend to reduce, if not filter out completely, the energy in certain portions of the spectrum, as can be seen comparing the type A Pilestone glasses with the Enchroma. Given the results in Fig. 4, only the Enchroma and Pilestone type B glasses will be taken into consideration in the following sections, being the effect introduced by type A the least significant.

### Glasses effect on digital displays

On a purely colorimetric and pointwise approach, wearing glasses for color vision deficiency while looking at a digital display can be modeled as filtering the digital displays' primaries through the glasses' lenses. Thus, weighting the spectral emissions of the primaries by the spectral transmittance of the glasses gives a clue on the changes the visual signal coming from the device towards the retina undergoes when viewed through them (Fig. 5).

Fig. 5 – Resulting spectral emission from the primaries as filtered by the lenses. Enchroma on the top row, Pilestone type B on the bottom row. Google Pixel 6A on the left, Acer XR341CK on the right.



It is to be noted that the peaks and valleys in the spectral transmittance of the lenses alter the shape of the emission spectra, effectively changing the chromaticity of the stimuli reaching the retina;

thus, the Introduction of a digital filter (whether it is obtained via an RGB overlay or using calibrating the device to a different white point then the native one) cannot be considered equivalent to the observation of the same display through the actual physical filters embedded in the lenses. Looking at the chromaticity plots in Fig. 6, it is clear that the gamut of the device viewed through the filters is altered, more pronouncedly in the case of the Enchroma glasses. Another observation regards the volume of the gamut, which is reduced for some pairs of display and lenses, resulting in the same pair of RGB triplets producing two chromatic stimuli closer one to the other.

Regarding the effect that glasses have on the color signal emitted from a display and reaching the retina, a modification is introduced in the chromaticity of the primaries and not only on their intensity. Clearly, the effect produced by using glasses cannot be achieved by overlaying a digital filter or performing an ad-hoc calibration of the device. Anyway, the system comprising both a real display and a pair of glasses can be simplified by a system composed of just an ideal display with custom primaries and a non-standard white point. Given some constraints (e.g., having the observer look at the display in a dark environment free from other stimuli) this simplified system is virtually equivalent to the one comprising both the display and the glasses; thus, looking at it adopting a

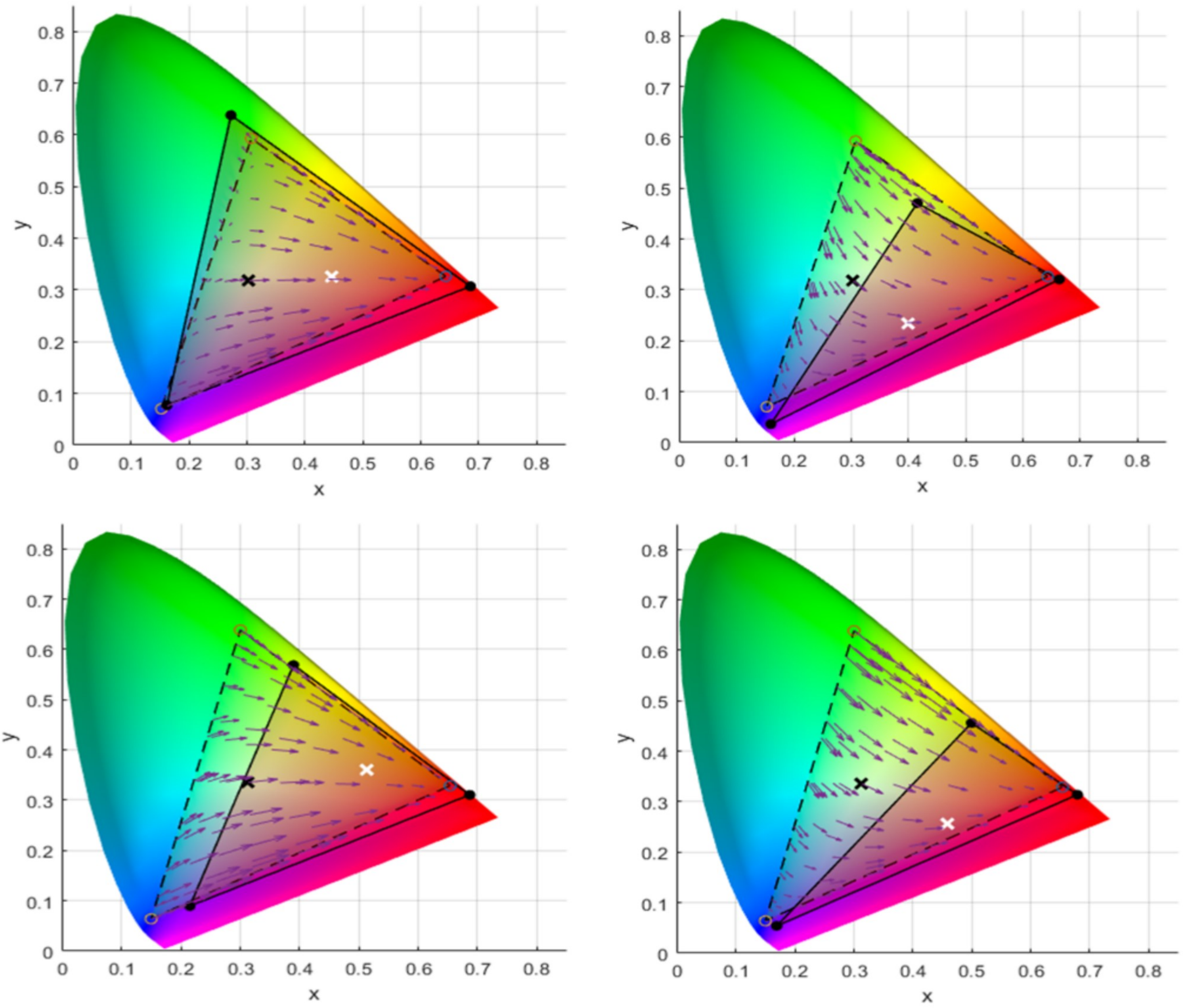


Fig. 6 – Changes in gamut of devices viewed through the glasses. At the top row is the Acer XR341CK, and at the bottom is the Pixel 6A. At the left is the Enchroma, and at the right is the Pilestone Type-B. The dashed triangle represents the actual gamut, the solid one the resulting gamut viewed through the lenses. The black cross shows the native white point (R,G,B set to the max), and the white cross is the resulting white point seen through the lenses. The arrows (on a scale of 1:5) show the direction towards which the chromaticity shifts for the same RGB triplet.

purely colorimetric and global approach, the observation of a display A through these aids is no different from the observation of any other physical display B (with different characteristics than A) without the glasses.

It is also worth noting that the same RGB triplet effectively produces a different perceived chromaticity if the display is viewed with or without the glasses. Looking at the gamut plots in Fig. 6, it is possible to choose two RGB triplets to lead to two colors falling on the same confusion line for a given deficiency when viewed without the glasses but not through the lenses. This can certainly improve the discrimination of confused colors, but the same principle holds true in reverse, with the result of having new RGB triplets falling on the same confusion lines that would not fall without the glasses on otherwise. In this regard, another aspect worth noting is that the average direction in which the colors are shifted (Fig. 6) is much closer to the direction of the confusion lines for dichromatic protan observers than the deutan and tritan ones, possibly leading to a less pronounced effect for certain types of color vision deficiency.

### *Preliminary perceptive experiment*

Considering the obtained results, a preliminary perceptual test has been conducted on three deuteranomalous subjects using a modified version of the online serious game *Qolour.it*. Each participant was shown the same stimuli and configuration in random order. 100 plays were made with the glasses on and 100 without the glasses. The plots in Fig. 8 show the distribution of the errors in both cases. Here, the circle width is proportional to the relative amount and severity of the errors committed (as a sum of the estimated Delta-E based on the profile of the device), the arrows show the average direction along which the errors have been committed, the two plots share the same scale. Even though this is just a preliminary test, it seems to suggest that glasses might be effective in improving the discrimination ability for some colors while worsening it for others.

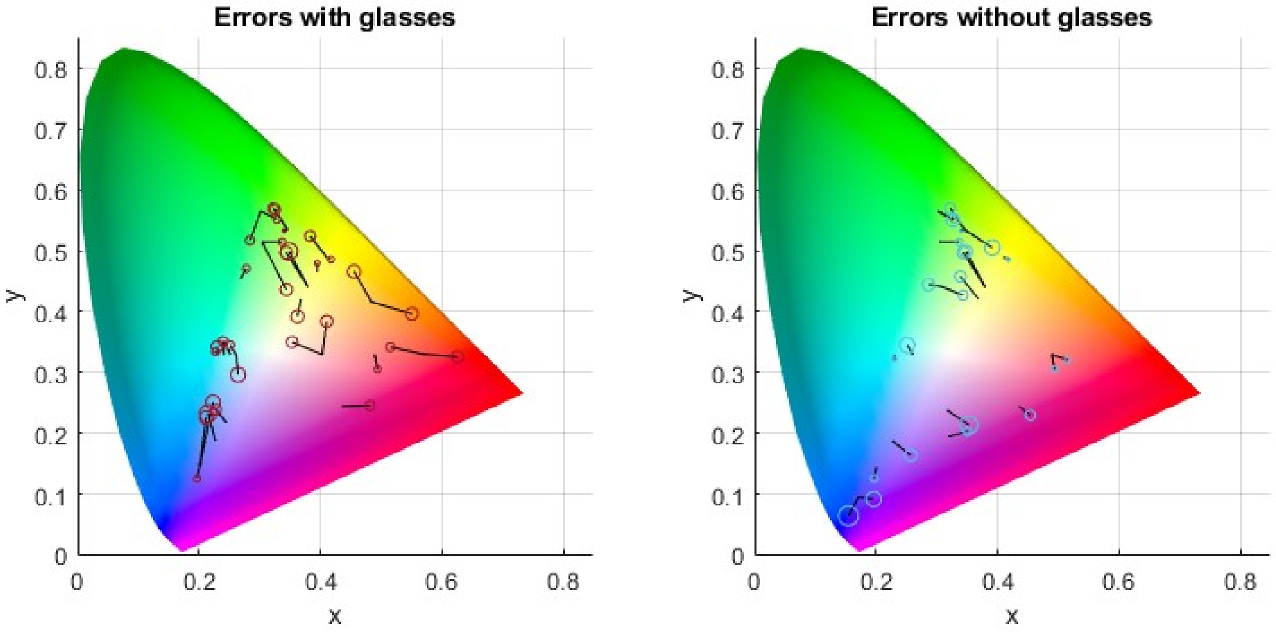


Fig. 8 – Distribution of the averaged errors committed by three deuteranomalous observers over 200 plays each of the online game Qolour.it, both with and without the Enchroma glasses on. The same Google Pixel 6A has been used to administer the test.

## Conclusion

Physical aids aimed at color-deficient people are diverse and try to reach the goal of adopting different filters with peculiar spectral responses. Some of the solutions on the market resemble colored filters, which emphasize the longer wavelengths. In contrast, others are designed to trade the color information at certain wavelengths for better channel separation. Several studies in neuroscience and ophthalmology confirm that color vision is extraordinarily complex and can not be reduced to pointwise channel transduction. Color perception also depends on brain signal processing, which is mainly spatial (McCann, 2017), and different experiments have demonstrated this effect (Rizzi, et al., 2014; Eschbach & Nussbaum, 202; Eschbach & Nussbaum, 2022). From this consideration, it is mandatory to underline the importance of defining new approaches in describing color deficiencies in developing aids and color vision tests.

In this study, we do not investigate the CVD glasses improvement in color perception. Still, we provide a colorimetric analysis of two types of glasses used for color vision deficiency aids to better understand the mechanisms behind those accessories. Thus, to make a preliminary assessment of the differences between glasses, we assessed the differential value generated by cones L and M for a monochromatic stimulus, the delta between the filtered versions of the cones' response, and the filtering of the RGB primaries of some representative displays through the glasses lenses. These analyses, together with a preliminary perceptive experiment, allow us to assess that, in some cases, CVD glasses can improve the color discrimination of color-deficient people, but just in specific conditions and for a particular set of colors.

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