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Daltonization by spectral filtering

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Abstract

Observers with a colour vision deficiency usually find it more difficult to discriminate between red and green colours, due to genetic variation in cone spectral sensitivity. Daltonization methods aim to enhance colour stimuli in order to increase the visual difference between them for such observers. In this work we focus on filtering the stimulus in the reflectance domain prior to conversion to colorimetry. This is hypothesized to enable a more precise tuning of the enhancement to the spectral absorptions of the observer with a colour vision deficiency. A spectral sharpening filter was developed and applied to spectral reflectances for a range of colour pairs which observers with a colour vision deficiency would be expected to find difficult to discriminate. The reflectance pairs were converted to colorimetry and presented on a colour display, where the visual difference between the pairs was evaluated by observers in a psychophysical experiment. Results suggest that a suitable filter can lead to an increase in the difference between the red-green pairs.

Introduction

Inherited colour vision deficiencies are a result of genetic variation in cone spectral sensitivity. Any of the three cones can be absent altogether or can have a different sensitivity peak to that of a normal observer. S-cone anomalies are rare, while M- or L-cone anomalies are present in approximately 8% of males and 0.5% of females [1]. In the opponent-colour mechanism of the retina comparison between M and L cones gives rise to the visual percepts of red and green, and so the effect anomalies in the cone photoreceptors is to make it harder to discriminate between these colours. A recent study [2] compared 15 subjects with normal and 15 with reduced colour vision, as evaluated by the HRR colour vision test, in estimating the magnitude of colour difference in 8 colour centres; it was found that across all the colour deficient observers there was an average 15% reduction in the perceived magnitude of difference in red and green colour centres relative to the normal observers.

This reduction in sensitivity in the red-green dimension leads to a loss of information in the visual field, depending on the degree of deficiency. Subjects with a colour vision deficiency (CVD) have difficulties in distinguishing, for example, way-finding information in maps and signs, or the individual elements in an information graphic. This information loss can be simulated by predicting the ratio of cone stimulation for the CVD observer [3], although it should be noted that such simulations do not necessarily predict the CVD observer's experience of colour [4][5].

Daltonization is the enhancement of an image in an attempt to restore missing information. Kotera [6] described a method in which the spectral information lost to the CVD observer is restored by a spectral shift followed by an achromatic-preserving correction. In this approach spectra are first found by a pseudo-inverse method from trichromatic data. In simulations the method was shown to yield images with enhanced differentiation between red and green for dichromats, although the performance with CVD observers was not reported.

A related idea is to fit optical filters to special glasses to cut the spectral stimulus in the wavelengths where the cone responses overlap, potentially enhancing differences between red and green stimuli for the CVD observer. Commercially-available EnChroma glasses that apply this notch filter approach [7] were evaluated by Gomez- Robledo et al [8], who concluded "the use of a colored filter may change the appearance of colors (depending on the shape of its spectral transmittance), but will never make color vision more similar to a normal observer's vision". A similar conclusion was reached by Moreland et al [9].

Green and Nussbaum [10] applied a similar idea, applying a notch filter to the illuminant spectral power distribution in the calculation of tristimulus values.

$$X = \sum_{380}^{780} S'(\lambda)\, \rho(\lambda) \bar{x}$$

where S' is the modified illuminant. *Y* and *Z* tristimulus values are calculated analogously.

This method was shown to make noticeable differences to selected colours, as shown in Figure 1, but was not tested on CVD observers.

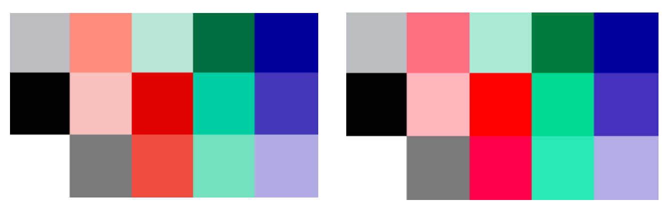


Figure 1 Test colours before and after applying a notch filter [10]

Our goal in this paper is solely to increase the difference between red and green colours for CVD observers, as this is the combination that causes most problems for such observers in signs and information graphics. Unlike Kotera's spectral shift method [6] we do not seek to preserve achromatic colours.

Evaluation of Daltonization methods was described in Simon-Liedtke et al [11], where it was recommended that tests should include psychophysical experiments.

Spectral Daltonization filter

In this paper we explore an extension of the notch filter approach described in Green and Nussbaum [10]. Since spectral reproduction workflows are increasingly needed and feasible [12], our goal is to apply the filter to the spectral stimulus (reflectance, emission or transmission) without necessarily having to convert to trichromatic values or to apply the illuminant of the intended viewing condition. To achieve this we aim to define an adjustment vector that when multiplied by the vector of spectral reflectance, emission or transmittance yields a modified vector, ρ'(λ), of spectral values:

$$\rho'(\lambda)=v(\lambda)\rho(\lambda)$$

where v(λ) is the spectral adjustment vector

For a normal observer v(λ) is a unity vector, while for a CVD observer there are non-unity values at selected wavelengths. The adjustment vector can include values below unity to attenuate the stimulus in selected wavelengths in order to increase the separation between L, M and S cone responses. Unlike a physical filter, the vector can also include values above unity at wavelengths at which it is desired to enhance the stimulus. The approach also allows the adjustment vector to be finely tuned and make adjustments to the spectral stimulus vector that are not possible by a 3x3 matrix, and hence go beyond what can be achieved by operations on trichromatic data.

Experimental

Two experiments were performed to test the concept. The first experiment was performed by normal observers who used special glasses to simulate the appearance of the Daltonized colours to CVD observers; while in the second normal observers judged colours adjusted by computational simulations. A small number of CVD observers also performed the second experiment, without the use of simulations.

In the first experiment, four adjustment vectors were defined, with absorption regions centred on the overlaps between the CIE 1931 standard observer colour matching functions. Three colour pairs consisting of a red and green together with tints of these colours were selected from a set of reflectance spectra for offset printing [13], as shown in Figure 2.

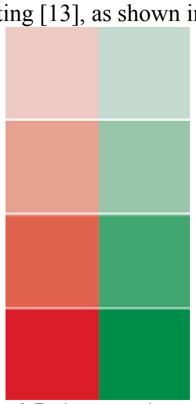


Figure 2 Red-green pairs used in phase 1 of the experiment

Four adjustment vectors applied to each reflectance, the adjusted reflectances were converted to colorimetry and the colour pairs presented on a calibrated EIZO ColorEdge CG241W colour display with a 160cd/m^2 white point. The experiment was conducted in a dim viewing environment (50 lux) and a total of 12 normal observers judged dichromat simulations of the four sets of colour pairs. The observers viewed the colour pairs using Variantor UA 3604 dichromatic simulation glasses from Cambridge Research Systems, UK, for protanopes and deuteranopes. The task of the observers was to report the number of the grey scale anchor pair (from 1 to 6) where the magnitude of difference is most similar to the difference of the test colour pair.

The results are shown in Table 1. It can be seen that all the filters resulted in an increase in perceived difference for almost all of the colour pairs.

Table 1. Average observer judgements of colour difference for four sample pairs

	Unfiltered	Filter 1	Filter 2	Filter 3
Pair 1	2.33	2.92	2.67	5.08
Pair 2	3.25	3.58	3.17	4.33
Pair 3	4.58	4.83	4.83	5.67
Pair 4	5.5	5.75	5.75	5.58

In the second phase, a set of three colour pairs was chosen from the PRMG-based reference palette [14], and the closest colours selected from a set of reflectance spectra [13]. These are shown in Figures 3 and 4.

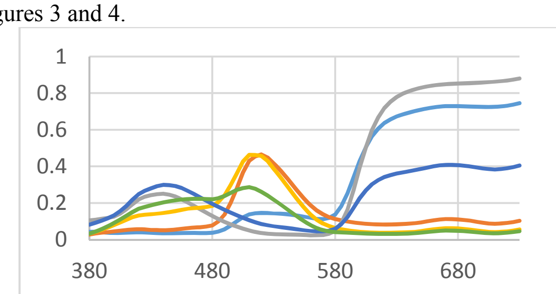


Figure 3 Test reflectances

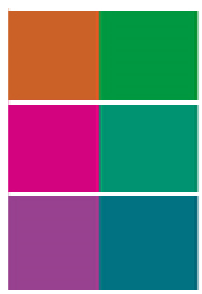
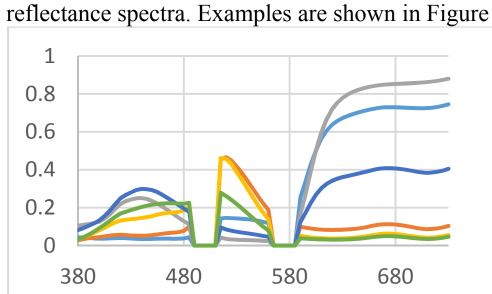


Figure 4 Red-green pairs used in phase 2 of the experiment

A set of four Daltonization spectral adjustment vectors with different properties was defined. These had either one or two absorption bands centred on the overlap between cone fundamentals at 480 and 555 nm, and some additionally had enhancement regions adjacent to the absorption bands to increase the reflectance. These adjustment vectors were applied to the test reflectances, resulting in new reflectance spectra. Examples are shown in Figure 5.



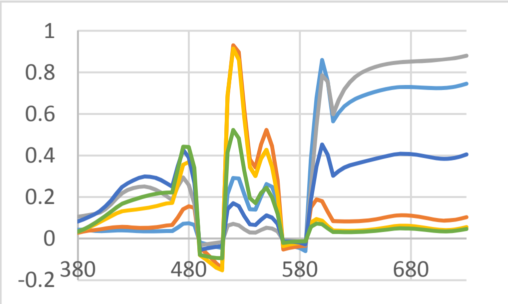


Figure 5 Examples of test reflectance spectra from Figure 3 after application of two of the adjustment vectors

After application of the spectral Daltonization vector, the test reflectances were converted to XYZ (with D65 illuminant) and the CIELAB difference between the sample pairs was found to be increased by up to 8.4 ΔE*ab. Although CIELAB ΔE*ab is not intended for such large differences it gives an approximate indication of the magnitude of increase in red-green colour difference.

In the absence of a spectral reproduction capability, the effect of the adjustments was evaluated psychophysically by converting the reflectances to XYZ (using the D65 illuminant) and subsequently sRGB in order to view them on a display.

An experiment was performed in which observers assessed the colour difference between the red-green pairs using the greyscale anchor method commonly used in colour difference experiments [15]. This viewing set-up is shown in Figure 6. The experiment was conducted in a dim viewing environment (50 lux) on an EIZO ColorEdge CG248 display calibrated to sRGB.

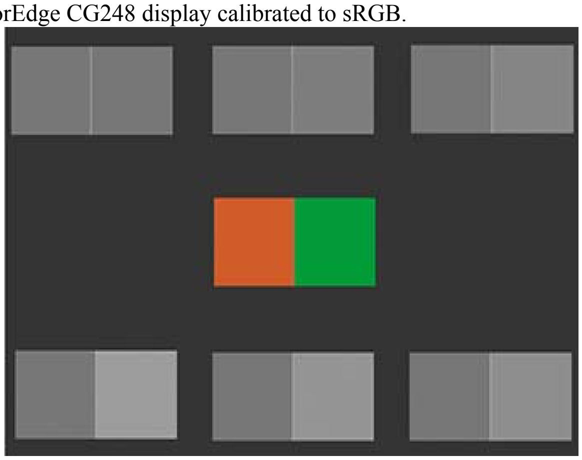


Figure 6 Viewing set-up in phase 2 experiment

A panel of 22-24 normal observers judged dichromat simulations of the colour pairs. These were prepared using a well-known simulation algorithm [16], implemented with ICC profiles [10] for both protanopes and deuteranopes. These normal observers also judged the Daltonized images with the Variantor deuteranope simulation glasses used in the previous phase. As in the first experiment, the observers were asked to report the number of the grey scale anchor pair (from 1 to 6) where the difference is most similar to the difference of the entered colour pair. The CIELAB ΔE*ab differences for the red-green pairs after applying the Daltonization were found to be increased by up to 4.6 and 10.6 for the protanope and deuteranope simulations respectively, relative to the un-Daltonized colours.

Three strong deutans and two strong protans (as indicated using Ishihara and HRR pseudo-isochromatic plates) also performed the experiment on the Daltonized colours without the computed simulations or the simulation glasses. The protans performed the experiment remotely using a similar (but unmeasured) display and viewing set-up.

The judgements of the normal observers were averaged to give a visual difference ΔV, and these are shown in Tables 2 and 3 for the deuteranope simulations and the deuteranope glasses respectively.

Table 2. Observed colour difference after Daltonization – dichromat simulation, no glasses

	No filter	Filter 1	Filter 2	Filter 3	Filter 4
Pair 1	3.95	3.53	3.17	3.73	3.30
Pair 2	3.87	3.89	3.57	3.48	4.52
Pair 3	3.39	3.65	3.26	3.96	3.09

Table 3. Observed colour difference after Daltonization – no simulation, deuteranope glasses

	No filter	Filter 1	Filter 2	Filter 3	Filter 4
Pair 1	4.09	4.22	4.19	4.45	4.18
Pair 2	4.41	4.18	4.45	4.45	4.41
Pair 3	4.31	4.18	4.32	4.36	4.32

It can be seen that simulations of the effect of the Daltonization filters did not lead to an increase in perceived colour difference ΔV in the simulated colour pairs, whereas for the pairs viewed through the deuteranope simulation glasses there is a small increase in ΔV for filters 2-4.

Tables 4 and 5 show the results for the CVD observers. It is interesting to note that for the deutan observers the original, unfiltered pairs were given a higher colour difference score than by the normal observers, and the filters were generally unable to increase the perceived difference. For the two protan observers Filter 1 (two spectral notches and no enhancement) gave the best performance, with an average 18% increase in the difference category.

Table 4. Observed colour difference after Daltonization – deutan observers

	No filter	Filter 1	Filter 2	Filter 3	Filter 4
Pair 1	6	5.33	4.67	5.67	5
Pair 2	5.67	5.67	5.67	5	5
Pair 3	4.67	5.33	5	4.67	4

Table 5. Observed colour difference after Daltonization – protan observers

	No filter	Filter 1	Filter 2	Filter 3	Filter 4
Pair 1	4	4	4	3.5	3
Pair 2	3.5	4	5	3	3
Pair 3	2.5	3.5	4	2	2.5

Conclusions

The method of Daltonization by adjustment of spectral reflectance can produce an increase in colour difference to CVD observers, without making objectionable changes for normal observers, and the direction of hue change is expected to reduce red-green confusion. The spectral adjustment vector can also increase lightness differences between red and green, making them more discriminable. Comparing the dichromat-simulated colours there was a consistent increase in colour difference, but in the psychophysical evaluation the increase in perceived colour difference was relatively small and was not consistent across the colour pairs tested. For the small number of CVD observers in the study, there was no increase in perceived difference for deutans (the most common form of CVD), while there was an increase for the protans.

In the workflow adopted in this experiment the reflectances were converted to colorimetry for evaluation on a display, but the method supports spectral reproduction.

Since the psychophysical results do not show a consistent increase in perceived colour difference, more work is needed to define optimal adjustment filters based on testing with larger numbers of colour-deficient observers, and using custom filters for individual CVD conditions.

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