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PRINCIPLES OF CORRECTION OF COLOUR DEFICIENCY BY FILTER GLASSES

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Abstract

With the aid of optimized filters we are able to shift the sensitivity curves of the L, M, S cones of the human eye along the wavelength axis.

Since the shape of receptor sensitivity curve itself cannot be changed we apply a colour filter in the path of the incoming light beam to modify the spectrum.

This is equivalent to multiplying the receptor sensitivity function with the filter transmission function.

This method also reduces the sensitivity of the receptor but the selective colour adaptation mechanism of the eye can compensate this effect within a certain range. Using this method the maximum point of the sensitivity curve can be shifted to the desired direction.

This method can be used to improve the colour vision of anomalous trichromates with shifted sensitivity curves and also to enhance the colour discrimination of the normal eye optimized for a specified task.

Keywords: colour blindness, human eye, colour filters, sensitivity functions.

1. Introduction

We have been working with colour anomaly of trichromates at the Technical University of Budapest for fourteen years, and in the last two years at COLORYTE Inc., a company established to make use of the achievements.

This is the first instance of publishing Colour Vision Deficiency (CVD) correction principles because the procedure has been patented [1] therefore any publication made prior to obtaining the patent licence would have been a novelty-killer.

In the meantime, some attempts have become known to improve colour anomaly by using colour filters. Although our method is based on filters as well, it is fundamentally different from others. These currently known methods are based much more on the increase on light-dark contrast of the different colours than on true enhancement of colour vision. These methods will improve the CVD's result on traditional colour vision tests such as recognition of ISHIHARA plates, however, they will not improve overall colour vision. A good example is a red contact lens applied in the path of light travelling to the eye. Looking through this, the reddish patches in the pseudo-isochromatic figures become bright, and the greenish patches turn dark, so the numbers in test charts become visible for a CVD patient without any improvement in his/her colour vision. Consequently, medical examination can be misled via applying such lens. Those who developed such methods based on the old conception that the reason for colour anomaly is the reduced sensitivity of the receptors (M) or (L) responsible for the perception of red or green, respectively. They concluded that if the other receptor of excessive colour sensitivity is suppressed, then colour vision must be improved [2].

Since the basic reason for colour anomaly, however, is a shift in maximum points of the receptors' sensitivity functions along the wavelength axis rather than the reduction to their sensitivity, any effort to make correction based only on sensitivity suppression will lead to a mere mock result.

The objective is to correct the sensitivity functions of colour anomalous patients' receptors by using dedicated colour filters. Since the sensitivity functions of anomalous receptors are usually shifted along wavelength, our primary aim is to shift them back to the place where they ought to be.

Our in-depth examinations have shown that the shape of curves may be distorted in addition to their shift. Therefore a general objective was made to correct sensitivity functions of colour anomalous patients in such a way, that both of their shape and maximum point would approximate those with normal receptors.

2. Methods

In our intention to apply a non-invasive method for the correction of colour anomaly, our desire is to alter the spectrum of the light reaching the eye by using a colour filter inserted in the path of light. This altering of the spectrum shall be carried out in such a way, that the anomalous receptors of the CVD person would generate a colour sensation similar to the normal persons. As it will be shown in *Fig. 1*, this is equivalent to the alteration of receptor sensitivity functions.

Let $\Phi(\lambda)$ be the spectral distribution function of the light travelling to the eye, while $p(\lambda)$, $d(\lambda)$ and $t(\lambda)$ are the spectral sensitivity functions of protos (otherwise L), deuteros (otherwise M) and tritos (otherwise S) receptors, respectively. Place a correction colour filter in front of the eye of a CVD patient just as if it was a regular eyewear, supposing $\tau(\lambda)$ the spectral transmission function of this colour filter.

The stimulus of the receptor (L) is calculated as follows:

$$P = \int_{380}^{780} \Phi(\lambda)\tau(\lambda)p(\lambda)\,\mathrm{d}\lambda.$$

Stimuli of Receptors (M) and (S) are calculated similarly.

The integrand is a trifactorial product, and seeing that production is a distributive operation, it may be grouped and bracketed in two manners. In this course $\tau(\lambda)$ may be connected to $\Phi(\lambda)$ or $p(\lambda)$, thus to attribute a different meaning to the effect of the colour filter:

$$[\Phi(\lambda)\tau(\lambda)]p(\lambda) = \Phi(\lambda)[\tau(\lambda)p(\lambda)].$$

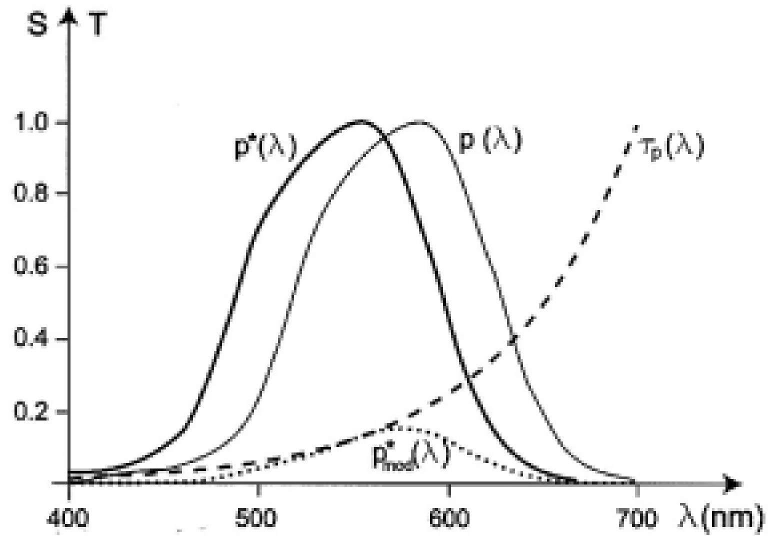

Fig. 1. Principle of correction of CVD. $p(\lambda)$ is the spectral sensitivity function of a normal (L) cone, $p^*(\lambda)$ is the spectral sensitivity function of an anomalous (L) cone shifted to the left. The form of curves are after Estevez, normalized for areas under curves to 1. τ_p is the spectral transmission function of correction filter.

One of the interpretations is

$$\Phi(\lambda) \cdot \tau(\lambda) = \Phi_{\text{mod}}(\lambda).$$

This is in accordance with physical reality and shows that the colour filter is modifying the spectral distribution of the input light by transforming it into a light of $\Phi_{\text{mod}}(\lambda)$. This modified spectral composition is the one that receptor with $p(\lambda)$ sensitivity function is able to see.

The other interpretation is:

$$\tau(\lambda) \cdot p(\lambda) = p_{\text{mod}}(\lambda).$$

This theoretical interpretation describes that the colour filter alters the anomalous sensitivity function to result in $P_{\text{mod}}(\lambda)$, a modified sensitivity function. The point of this latter interpretation resides in showing that colour sensitivity functions and therefore colour vision of a CVD person may be modified without any invasion into the eye.

Let us see what kind of $\tau(\lambda)$ transmission function is required for the colour filter. The equation describing the correction is as follows:

$$p(\lambda) = \tau_p(\lambda) \cdot p^*(\lambda),$$

from where

$$\tau(\lambda) = \frac{p(\lambda)}{p^*(\lambda)},$$

so the transmission function of the required colour filter is produced as a ratio of the two sensitivity functions. Since the value of $\tau(\lambda)$ must not exceed 1 (100% light transmission) at any wavelength, the resulting $p(\lambda)$ will describe a lower sensitivity than previously (*Fig. 1*).

Fig. 1 shows the sensitivity function of a normal (L) cone $p(\lambda)$ and an anomalous sensitivity function, which is shifted to the left, $p^*(\lambda)$. Both of them are in ESTEVEZ [3] form, normalised of areas under curves to 1. $\tau_p(\lambda)$ is the filter transmission function generated as the ratio of the above mentioned sensitivity functions. It is normalised to have a peak value of 1.

The correction happens in two steps. First the anomalous receptor is shifted to the right so its peak is at the same wavelength as the normal receptor's one. The effect is described by the following equation:

$$\tau_p(\lambda) \cdot p^*(\lambda) = p_{\text{mod}}(\lambda).$$

As it is shown, the maximum value of this $p_{\text{mod}}(\lambda)$ is lower than a normal receptor's one, but it is already at the right place.

In the second step, areas of the three curves become equal due to the chromatic adaptation mechanism. This happens in a few minutes meanwhile the patient casts through a pair of colour filter glasses, looks at white objects thus adjusting his/her receptors' sensitivity functions to equalise the areas below their curves by using brain control. This second step is necessary for total correction. Now the $p(\lambda)$ curve, which is similar to a normal L cone will show the sensitivity function of the corrected receptor instead of the $p_{\text{mod}}(\lambda)$ curve which describes the status prior to the adaptation.

Further particulars of chromatic adaptation will be studied by using *Figs. 2* and *3*. A case is shown in *Fig. 2*, where a normal trichromate views a white object in a room illuminated by pink light featured as $\Phi(\lambda)$. Receptors of this viewer's eyes modify their sensitivity in order to satisfy the equations

$$\int \Phi(\lambda) \cdot t(\lambda)\,\mathrm{d}\lambda = \int \Phi(\lambda)\,\mathrm{d}(\lambda)\,\mathrm{d}(\lambda) = \int \Phi(\lambda) p(\lambda)\,\mathrm{d}\lambda,$$

in other words to equalise the areas below the modified receptor curves.

The situation is the same for *Fig. 3*, when the viewer looks at a white surface in a room illuminated by bluish light and adjusts himself/herself to it. For the human eye this phenomenon will take place automatically but within certain natural limits, while for a camera, an additional correction filter needs to be applied to provide correct colours for the photo.

The three receptors of a colour anomalous patient are illustrated in *Fig. 4*. To the effect of correction glasses, of course, the right side of the (M) cone will also be distorted to a small extent.

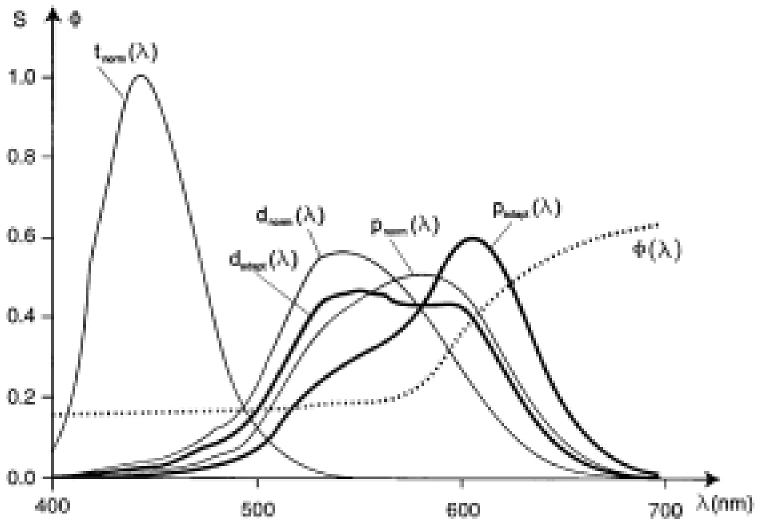

Fig. 2. Chromatic adaptation to a pink illumination, $\Phi(\lambda)$ is the spectrum of a pink illumination. $p_{\text{norm}}(\lambda)$, $d_{\text{norm}}(\lambda)$, $t_{\text{norm}}(\lambda)$, are spectral sensitivity functions of L, M, S cones of a normal viewer, $p_{\text{adapt}}(\lambda)$, $d_{\text{adapt}}(\lambda)$, $t_{\text{adapt}}(\lambda)$ are spectral sensitivity functions of L, M, S cones adapted to the $\Phi(\lambda)$ illumination.

The filter curve shall be designed carefully in a way that it exerts its effect primarily around the maximum sensitivity range of the receptor subject to modification. Therefore in practical realisations next to the maximum sensitivity of the adjacent receptor it is already substituted by a constant (the calculated value of $\tau(\lambda)$ is usually realised till the intersection point of the curves).

3. Results

The correction for another type of colour anomaly – one of the protanomalies – is shown in *Fig.* 5. (Note: for correction purposes we have divided potential colour anomalies into more types than the classical nomenclature).

In our case the sensitivity functions of these colour anomalous receptors are illustrated in *Fig.* 5*a*, while *Fig.* 5*b* demonstrates the related correction filter.

By applying this filter, *Fig.* 5*c* is resulted, and then, with the time of adaptation elapsed, final results come up as it is shown in *Fig.* 5*d*.

As it is seen, the correction does not reach hundred percent, but a remarkable improvement is made.

The rate of this improvement is well demonstrated in *Fig.*6, where chromaticity diagrams of normal trichromates and our particular colour anomaly are shown. As it is clearly visible in this figure, the colour anomalous patient has a reduced

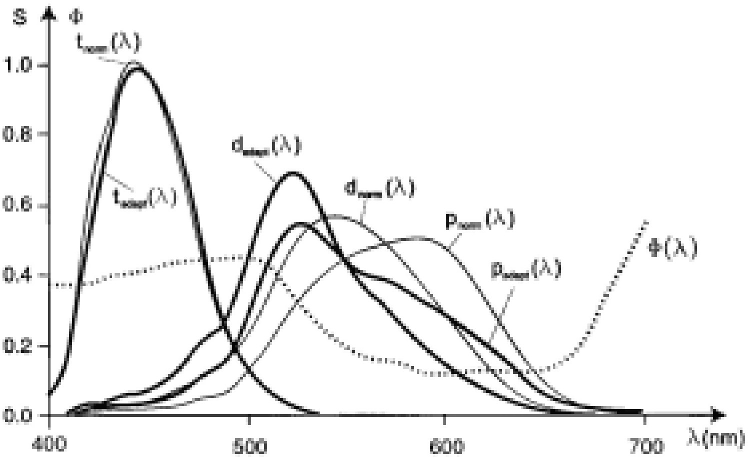

Fig. 3. Chromatic adaptation to a blue illumination $\Phi(\lambda)$ is the spectrum of a blue illumination. $p_{\mathrm{norm}}(\lambda)$, $d_{\mathrm{norm}}(\lambda)$, $t_{\mathrm{norm}}(\lambda)$, are spectral sensitivity functions of L, M, S cones of a normal viewer. $p_{\mathrm{adapt}}(\lambda)$, $d_{\mathrm{adapt}}(\lambda)$, $t_{\mathrm{adapt}}(\lambda)$ are spectral sensitivity functions of L, M, S cones adapted to the $\Phi(\lambda)$ illumination.

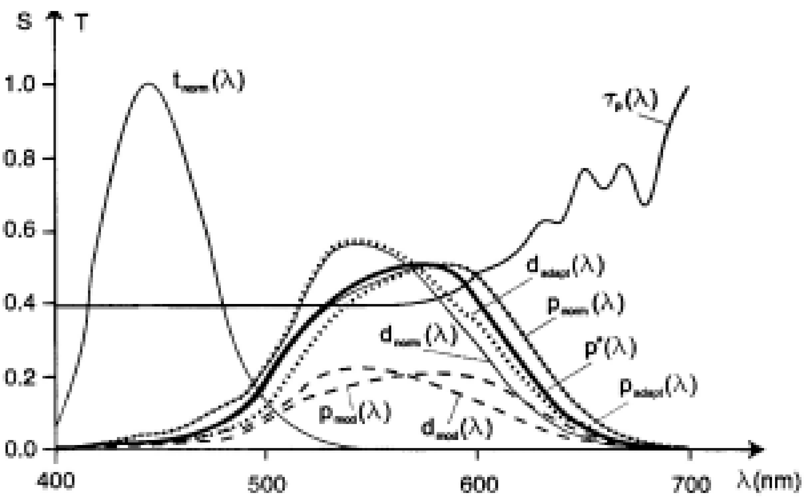

Fig. 4. How filter glasses correct

colour space, however, thanks to the effect of correction, his/her $p - d$ diagram approximates to a normal trichromate's one.

It is considered as colour vision correction, when L, M and S curves of a colour anomalous (CVD) person approximate corresponding functions of normal

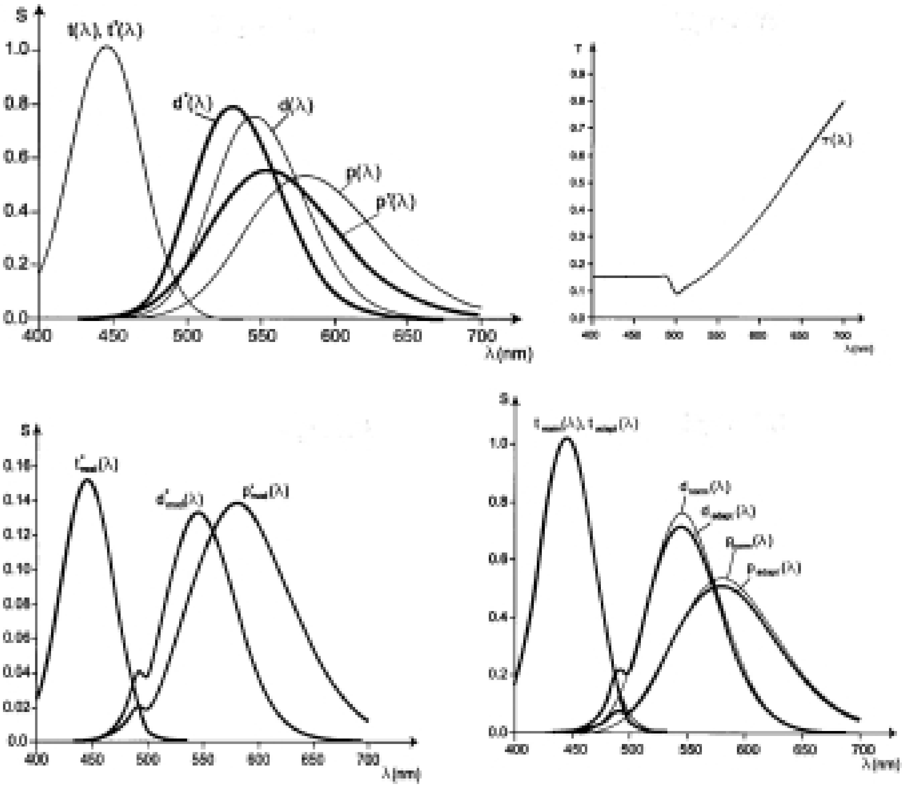

Fig. 5. Case study: Correction for an actual type of colour anomaly
a.) Spectral sensitivity functions of a CVD case $p(\lambda), d(\lambda), t(\lambda)$ are curves of L, M, S cones of the normal viewer, $p^*(\lambda), d^*(\lambda), t^*(\lambda)$ are curves of L, M, S cones of the anomalous patient. b.) Spectral transmission function of correction filter for patient related to *Fig. 4a*. c.) Corrected curves before adaptation. d.) Corrected curves after adaptation.

trichromates. In our procedure we apply colour filters which are spectrally designed to reach this goal, therefore it is anticipated that colour vision of the patients corrected with these filters will really improve rather than a mere increase in the contrast is produced.

To apply this method it is necessary to have an instrument capable for diagnosis, which L, M and S curves of colour anomalous patients can be measured with. Such an instrument has been developed, named PDT–2000 Sensometer. Colour filters corresponding to each type of colour anomalies are under development, preliminary tests are promising. Their specific applications will be reported in another paper. Framing an objective technique of measurement to check correction rate is under development. The anomaloscope seems to be insufficient, since it is working

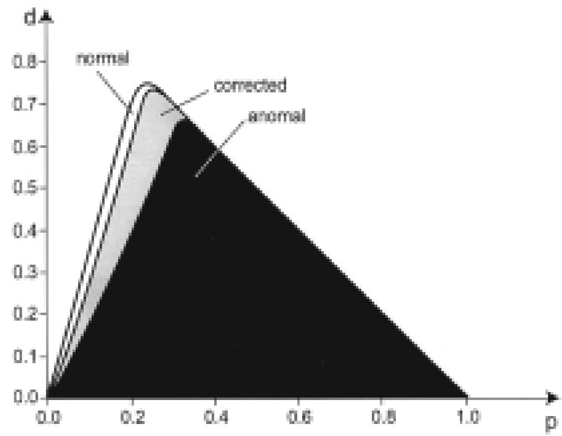

Fig. 6. Case study. Chromaticity diagrams ($p - d$) in normal, anomalous and corrected anomalous cases. p and d are chromaticity coordinates of PDT colour system.

only at discrete monochromatic wavelengths and in many cases it is more important for us to detect the modifications at other wavelengths, too.

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