

# ON COLOUR SPACES AND ON COLOUR PERCEPTION

## *Independence between uniques and chromatic circularity*

Alfredo Restrepo Palacios

Laboratorio de Señales, Dpt. Ing. Eléctrica y Electrónica, Universidad de los Andes, Bogotá, Colombia

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Abstract: The colour space one uses has a bearing on the type of colour image processing tasks one does. As we approach the stage of colour processing in image processing, new colour spaces may be needed. In particular, colour spaces that model properties of our perception of colour may be useful. We propose two nonlinear, tridimensional transformations of the variables of the RGB (or LMS) colour space. In the resulting spaces pure S, or pure M input, does not imply the presence of yellow. Since there is evidence of S input to the parvocellular system, we use a dimension called violet minus green; in the resulting space, as the wavelength variable sweeps the visible spectrum, a circle is obtained, making explicit a circularity of chromaticity for spectral colours.

## 1 INTRODUCTION

While experimenting with a technique for colour contrast enhancement (Restrepo et al, 2002), (Restrepo and Vega, 2005), for which colour space is triangulated with tetrahedra and points (colours) within each tetrahedron are expanded, it became clear that the technique performs better in some colour spaces than in others. In particular, for the detection of malaria parasites in thin blood films, the colour space called here Hering-2 is better than traditional RGB space (Ortiz et al, 2005).

We are particularly interested in *perceptually good colour spaces*. In RGB space, the corners of the cube although geometrically equivalent, play different roles perceptually: cyan and violet are *binary colours*, black and white are *achromatic colours* while red, green, blue and yellow are *unique colours*. We say that a colour space is perceptually better than another if it geometrically makes conspicuous perceptual aspects and does not geometrically differentiate between aspects that perceptually are of the same type. The terminology used here and that includes the terms unique colour and binary colour is the one used by researchers such as Pridmore, in (Pridmore, 1999).

Trichromacy, although a fundamental link between the wavelength and the perceptual aspects of colour, is also a source of misunderstanding, partially because it is valid both at the receptoral

(e.g. in the human retina or in a colour camera) and at the stimulus (MacAdam, 1985) (e.g. in a colour projector or a computer screen) levels. At a receptoral level, it is convenient to call the response variables of the human visual system *large*, *medium* and *small*, rather than *red*, *green* and *blue*, the terms red, green and blue being misleading there.

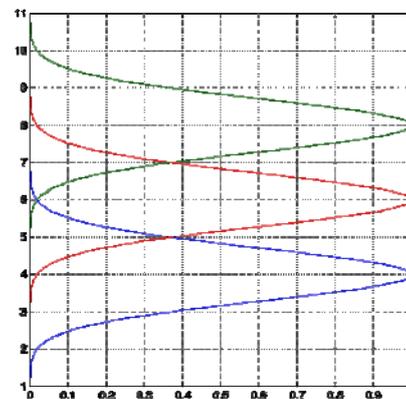


Figure 1: Assumed R, G and B functions. For the purpose of a schematic illustration of the ideas presented here, for the R, G and B functions, we use the shown bell shaped curves, on an artificial wavelength scale from 0 to 12, rather than real curves based on psychophysical data.

Likewise, in image processing, RGB is an ambiguous term, partly because of the phenomenon of metamerism. Interpreted as an input code for image processing, RGB refers to the broadband and

overlapping functions  $R(\lambda)$  (a high-pass filter at approximately 600 nm)  $G(\lambda)$  (a band-pass between approx. 500 and 575 nm) and  $B(\lambda)$  (a low-pass at approx. 500 nm), of the wavelength variable  $\lambda$ , which are the spectral transmittance functions of the 3 filters used in colour cameras. As an output code, RGB may refer to the relative intensities of three light sources of narrow spectrum (e.g. a Blue Violet LED at 430 nm, a Super Red LED at 633 nm and a Pure Green LED at 555 nm) which when combined evoke the corresponding same RGB readings in a colour camera; these narrowband lights do not usually have the colours we speak of as red, blue and green. Unique red is not a *spectral colour*, in fact, unique red, a red that does not appear neither yellowish nor bluish must include both long and short wavelengths [4]. When displaying colours on the screen of the computer, RGB values given by 1 0 0, 1 1 0, 0 1 0 and 0 0 1 correspond to “pure” red, yellow, green and blue, respectively, and if we want pure and unique coincide, the stimulus corresponding to red cannot be narrow band.

The NCS (Natural Colour Space) is inspired in Hering’s colour theory of opposite colour pairs (Hering, 1964), advanced towards the end of the nineteenth century and rechampioned by Hurvich and Jameson (Hurvich and Jameson, 1957). The dimensions in NCS space are *red versus green* or RG, *yellow versus blue* or YB and *lightness* or Bk&Wt. As a system inspired in the opposing colour theory, the four chromatic basic components given by [RG, YB, Bk&Wt] = [1, 0, 1/3], [-1, 0, 1/3], [0, 1, 1/3] and [0, -1, 1/3], should correspond to unique colours. An interesting asymmetry should be noted here: the two chromatic and opposing processes RG and YB differ in that a mixture of green and red is likely to produce a yellow, which lies in the chromatic YB dimension, while a mixture of blue and yellow is likely to produce a grey, in the Bk&Wt dimension, with no chromatic RG or YB component. (A mixture of *binaries* cyan and violet is likely to produce a grey, though.) Also, the chromatic RG and YB processes are opposing from the perceptual point of view, while the achromatic Bk&Wt process is a cooperative process: greys are perceptually intermediate colours between black and white.

At the perceptual level there is an independence between the *uniques* green, red, yellow and blue; the four “true colours” proposed by Alberti in 1435 (www.colorsystems.com, 2005). (Also interesting, perceptually, there are four chromatic binaries, and no “ternary” chromatic combinations.) We would like a colour system that allowed such an orthogonal quality between uniques, and have the possibility of

zeroing e.g. the RG channel but not the YB channel. (Clearly, there should be no way of silencing the achromatic, magnocellular system.) Such an independence does not exist for the dimensions of the RGB system as the response curves overlap. Even though the NCS system is perceptually a better model than RGB space, granting that the NCS and RGB systems are linearly related as  $RG = R-G$ ,  $YB = 0.5(R+G)-B$  and  $Bk\&Wt = (1/3)(R+G+B)$ , NCS space has the apparent drawback that from pure red and from pure green, a nonzero yellow results:  $YB = 0.5$ . This is a source of confusion since we might expect an independence between the Y part of the YB dimension of the NCS colour system and the RG dimension, all of the involved colours red, green, yellow and blue being uniques.

The workings of a color camera model the responses of the human L, M and S channels, at the receptor level. Pioneered by Young, polished during the nineteenth century by Maxwell and Grassmann and finally published in complete form by Helmholtz (Helmholtz, 2005), the *Young-Helmholtz trichromacy theory* served as an inspiration for the color TV camera. However, the perceptual uniques red, yellow, green and blue, result from (possibly multiple, accounting for metamerism,) specific combinations of the L, M and S responses, and not from only one of these channels responding at a time. Not even at the ganglionar level, where Hering’s theories found biological grounds, are the uniques made *explicit* (as Marr would say (Marr, 1980)) by a unique channel system of firing neurons. The NCS system and the architecture of the human visual system correlate at the ganglionar level like this: the RG dimension corresponds to the parvo system of the human visual system, the YB dimension to the konio system and the Bk&Wt dimension to the magno system. It is perhaps not until cortical area V4 that a 1-1 correspondence between our colour experience and the responses of specific neurons is found (Zeki, 1993).

It will be probably necessary to go beyond the RGB and NCS colour systems to do meaningful colour processing of images. At any rate, this path roughly follows the course of the visual system in frugivorous primates; RGB correlates with the receptor layer of the retina while NCS correlates with the ganglionar layer.

In this paper, guided by the search of mathematical models of the circular perception of chromaticity and of the independence of the uniques red and green and the unique yellow, we propose two colour systems; the starting point being the RGB system.

## 2 THE TRIDIMENSIONALITY OF COLOUR PERCEPTION

Aristotle’s model of colour is linear (Aristotle, 2001), (Aristotle, 2002), as it is da Vinci’s (da Vinci, 2002). Although Acuilonius in the fifteenth century proposed a model that is not linear and includes black and white as extrema, the first circular model of (chromatic) colour is Newton’s circle of colours, which appears in his work *Optiks* in 1704. In 1810, Otto Runge published his *sphere of colours*, the first tridimensional colour space, from a geometric point of view (www.colorsystm.com, 2005). The mathematization of trichromaticity by Grassmann gave the algebraic tridimensionality to trichromatic colour space. Hering’s opposing colour theory is also tridimensional; likewise, colour space HSI (Hue, Saturation, Intensity) is tridimensional.

Granting that a colour space should be tridimensional and even if in all currently accepted cases, topologically the space is a 3-ball, the fact remains that there are many possible tridimensional manifolds. And it is not clear whether they should have a boundary: no matter how white a region in a scene looks, it is possible to make another region look whiter. Also, other mathematical structures (such as orbifolds), besides manifolds could turn out to be more appropriate.

Besides the geometric and topological properties of a colour space, there should be also algebraic structures modelling of colour mixtures and colour independence. We are well behind such expectations; consider for example that the RGB cube is not closed under the operation of standard vector addition.

## 3 INDEPENDENCE BETWEEN RED, GREEN AND YELLOW

In the NCS space, both pure yellow (RGB=110) and pure blue (RGB=001) result in a zero valued RG channel; not so for pure red and pure green when considering the YB channel. We propose a modification of the YB dimension of the NCS consisting in modulating it with the factor  $(R \cdot G - B)$ , which we interpret as *red and green, or blue*. This makes the new variable  $Y \setminus B$  zero, for pure red and for pure green; we call the resulting transformation Hering-1:

$$\begin{aligned} RG &= R - G \\ Y \setminus B &= (R \cdot G + B)(0.5[R + G] - B) \\ Bk \&Wt &= (1/3)(R + G + B) \end{aligned} \quad (1)$$

The resulting image of the RGB cube, under transformation (2), is shown in Fig. 2.

E.g. for  $R = 0$ , the equation for the surface image of the plane G-B is given by:

$$Y \setminus B = [3/2] \cdot (Bk \&Wt)^3 - (3/8) \cdot RG^2 \cdot Bk \&Wt$$

For the computation of the inverse of Transformation 2, we must first solve the cubic polynomial in the variable B

$$\begin{aligned} B^3 &+ (4 - 7 \cdot Bk \&Wt) \cdot B^2 \\ &+ (15 \cdot Bk \&Wt^2 - 4 \cdot Bk \&Wt \cdot RG^2) \cdot B \\ &+ Bk \&Wt \cdot RG^2 - 9 \cdot Bk \&Wt + (3/8) \cdot Y \setminus B = 0 \end{aligned}$$

and then solve for R and G

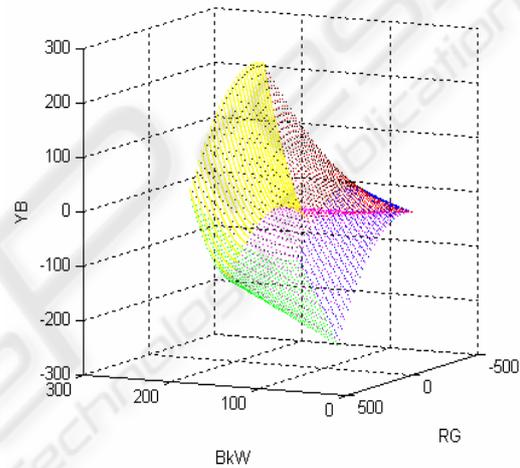


Figure 2: The image of the RGB cube under Transformation (2).

$$\begin{aligned} R &= 0.5(3 \cdot Bk \&Wt + RG - B) \\ G &= 0.5(3 \cdot Bk \&Wt - RG - B) \end{aligned}$$

Several researchers have remarked on the need for nonlinear models of the L, M and S variables for colour perception. (Larrimer, 1974), (Elzinga and de Weert, 1984); so, it is not unreasonable to use nonlinear transformations for colour spaces in image processing.

## 4 CIRCULARITY

Let us remind ourselves that there are non spectral colours; that is, colours that are not metameric to any narrowband spectral light, among them we have the greys, browns (which result mainly in contrast) and unique red (in fact, the whole *line of purples* of CIE space).

As the wavelength of a hypothetical single-wavelength light (a *spectral light*) sweeps the visible

spectrum, the resulting point in RGB space (using the functions in Fig. 1) describes a curve as the one shown in Fig. 3, that starts at the origin (pure black), parallel to the B axis and ends at the origin, parallel to the R axis. On the other hand, since unique red is not a spectral colour, a curve of visible  $\lambda$ 's in a hypothetical perceptual colour space would not be a simple closed curve (i.e. a topological circle), there would be a gap between spectral colours corresponding to large wavelengths which we perceive as reddish oranges and those of small wavelengths which we perceive as purples. Our aim here is to have a colour space where such a curve corresponding to spectral lights is closed and closes itself at a point where the variables R and B are small valued but not yet zero. (It is probably incorrect to assume that an electromagnetic radiation with spectral contents off the visible spectrum gives rise to black; *invisible* would be a more appropriate term.)

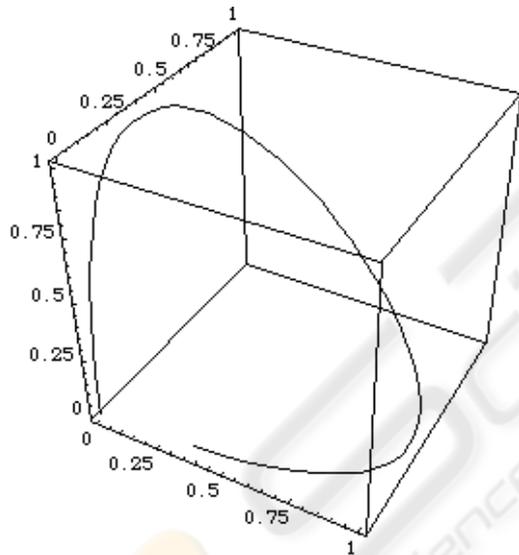


Figure 3: The image of the wavelength interval [2, 10] with respect to the functions R, G and B of Figure 1.

In order to speak of a curve in a hypothetical colour perception space we need the mathematical concept of continuity. The perceptual correlate of such a continuity is grounded in MacAdams' ellipses (MacAdam, 1999). His finding gives geometrical meaning to the fact that a small enough change in the spectral contents of a light goes unnoticed; it gives fuzziness to the concept of equivalence in colour space.

A new transformation, called Hering-2 is obtained by further transforming the variables Y\B and RG of the Hering-1 colour space. As has been pointed out (Stromeyer et al, 1998), there may well

be an input from the S channel to the parvo channel; thus, instead of a red-versus-green process, we propose a *violet. versus. green* process given by

$$V\sim G = 0.5(R+B) - G$$

In addition, modulating the YB variable of the NCS system with *red or blue, and green*, we also get zero for pure green and for pure red, in a new variable called Y~B. We get circularity for spectral colours in this way.

$$Y\sim B = 10G(R+B)(0.5[R + G] - B)$$

A factor of 10 has been added to make clearer the resulting circularity in a plot. Thus, we have the transformation Hering-2 given by:

$$\begin{aligned} V\sim G &= 0.5(R+B) - G \\ Y\sim B &= 10G(R+B)(0.5[R + G] - B) \quad (2) \\ Bk\&Wt &= (1/3)(R + G + B) \end{aligned}$$

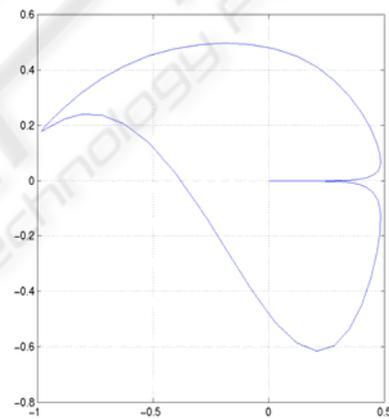


Figure 4: The image in the V~G - Y~B plane of the wavelength interval [0, 12] with respect to the functions R, G and B of Figure 1.

Under this transformation, in the V~G - Y~B plane, the curve corresponding to the spectral lights, for the interval  $\lambda \in [0, 12]$ , is as shown in Fig. 4; a closed curve is obtained. The curve in Fig. 4 is not meant to include black, (the origin) as the curve closes on itself before the three variates R, G and B are all zero.

To invert (3), we obtain B, using a rational function, then we find R and G, as shown below.

$$B = \frac{\frac{3}{10} * YB - 9 * Bk \& Wt^3 + 2 * VG^2 * Bk \& Wt + 30 * VG * Bk \& Wt^2}{3 * VG * Bk \& Wt - 9Bk \& Wt^2 + 2VG^2}$$

$$R = 3*Bk\&Wt + (2/3)*VG - B$$

$$G = Bk\&Wt - (2/3)*VG.$$

## 6 CONCLUSION

Two transformations of the R, G, B data, intended to model the perceptual independence between unique colours, and the perceptual circularity of our colour perception, up to spectral colours, are given. As the perceptual properties are surely advantageous to frugivory primates, it is probable that the given implementations will be of use in computer vision, they have shown to be useful in the detection of malaria in images from thin blood films. We have explored *colour standardization* by triangulating colour space and expanding colours within each tetrahedron (Restrepo et al, 2002), for the recognition of malaria (Ortiz et al, 2005), we had that Hering-2 is a more meaningful space.

Regarding the perceptual independence between reds and greens on the one side and yellows on the other, it probably has advantages regarding the detection of mature fruits. It is difficult to speculate as to the ways and advantages in which circular chromaticity is achieved in the human visual system; for one thing, it is probably not convenient to have to close a chromatic circle using black; a symmetry in the way the L, M and S channels are treated by the neural circuits of the visual system may represent savings in genetic code and neural wiring.

Unlike NCS space, in RGB space the *achromatic line* is not geometrically conspicuous in the cube and it is hard to speak of the circularity of the *chromatic colours*.

Colour, as a perceptual entity is meant to give us information about the surfaces of the objects in a scene and, as such, is largely independent of the spectral contents of the illuminant. Even though mathematically, pointwise, colour is a vector statistic of a spectral density, it is a very sophisticated measure when taken in the context of the surrounding colours in a scene. We can only try and speculate about the advantages brought about by the workings of our visual perception.

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