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# What Underlies Focal Colours?

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## Abstract

Colour names are generally attributed to specific colour categories, of which the most representative colour is termed a focal colour. The question as to what underlies this categorization is addressed in this paper. Are the categories simply a naming convention of colours with a specific 'perceptual salience?' Results based on the wraparound Gaussian model of reflectances show that colour categories follow naturally from a perception-agnostic segmentation of colours defined in this space. In other words, a segmentation based only on colour coordinates, not perceived colours. Furthermore, it is demonstrated that the concept of a focal colour can be explained as a colour that is both (i) representative of a colour category, and (ii) relatively stable under a wide range of illuminant spectra without depending upon chromatic adaptation.


## Introduction

The study of focal and categorical colours in terms of colour naming has a long history in Philosophy and Linguistics. Focal colour is generally defined as the best example of a colour category as described by a unique colour name. Typical colour names or 'basic colour terms' as discussed in the seminal cross-cultural colour naming study of Berlin and Kay [2] are black, white, red, green, yellow, blue, and grey. Additional terms are brown, purple, pink, and orange. The universality of color names is explored by Lindsey et. al [3]. Witkowski and Brown [9] argue that 'perceptual-salience' may define some of these categories, but that raises the question as to what underlies the 'perceptual-salience' of a colour.

This paper explores two features that lead naturally to definitions of focal colours [1] and colour categories. Colour categories are found by region segmentation of the set of possible colours defined in terms of wraparound Gaussian reflectances (Gaussian-like reflectances defined on the hue circle) as a function of central wavelength and sigma in KSM ($k\sigma\mu$) coordinates [6] (details below). Focal colour as the representative of a colour category is defined in terms of its tolerance to different illuminants without any chromatic adaptation. In other words, a focal colour defined in this way is one which is both representative of a colour category and also recognizable under a wide range of natural illuminants without needing to adjust in any way for the CCT of the illuminant.

The definition of focal and categorical colours introduced here contrasts with the definition given by Menegaz et al. [5] "Color naming is about the labelling of a given set of color stimuli according to their appearance in a given observation condition" in that the proposed definition is not at all appearance-based. The proposed definition is closer in spirit to that of Morimoto et. al [7]. Their psychophysical experiments show that focal colours, defined as "the best example of a color category" are more resistant to illuminant change than non-focal colours. In other words, that focal colours defined as representative colours have the property of illuminant stability. This observation is turned around here to argue that illuminant stability in fact defines focal colours.

## KSM Wraparound Gaussian Reflectances

In order to explore the question of how colour categories and focal colours are affected by changes in the illuminant, a model of potential surface reflectances is needed. For this purpose, the set of wraparound Gaussian reflectances [4] is ideal. In particular, the KSM (scaling K, sigma S, central wavelength M) model of colour employs Logvinenko's [4] wraparound Gaussians as reflectance functions. A formal definition is given below. Two examples of such functions are plotted in Figure 1.

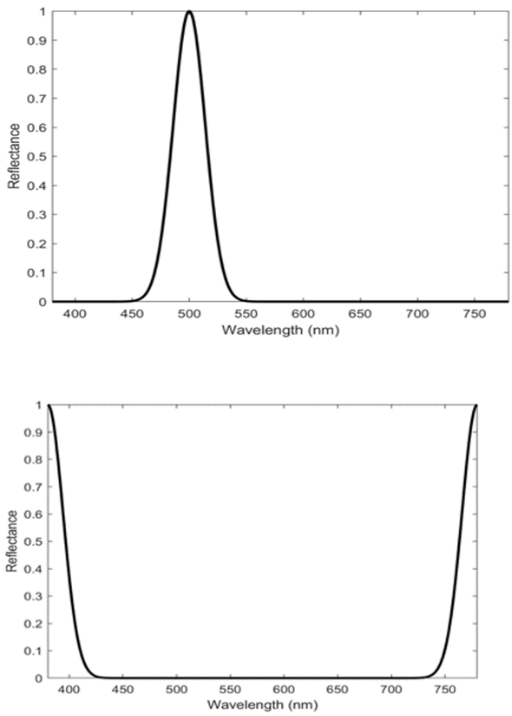


***Figure 1.*** *Upper plot shows a wraparound Gaussian with K=1 (scaling) S=20 (sigma) and M = 500nm (central wavelength); Lower plot shows a wraparound Gaussian with K=1 S=20 and M = 780nm.*

The central-wavelength parameter, M, of KSM has been shown to be a very effective hue descriptor with hue defined as the peak wavelength, M, of the wraparound Gaussian function [6]. This hue descriptor correlates with the hue names found in Moroney's large, crowd-sourced Color Thesaurus [8]. Furthermore, it also correlates as well as CIECAM02 hue does to the hue designators of papers from the Munsell and Natural Color System colour atlases. Hence, KSM coordinates provide a natural coordinate system for determining focal colours and colour categories.

Wraparound Gaussian 3-parameter functions $g(\lambda; k, \sigma, \mu)$ having central wavelength $\mu$, standard deviation $\sigma$ and scaling $k$ are defined as follows (note $\theta \equiv 1/\sigma^2$):

If $\mu \leq (\lambda_{max} + \mu_{min})/2$:

For $\lambda_{min} \leq \lambda \leq \mu + \Lambda/2$

$$g(\lambda; k, \theta, \mu) = k\, e^{-\theta(\lambda-\mu)^2} \quad (1)$$

For $\mu + \Lambda/2 \leq \lambda \leq \lambda_{max}$

$$g(\lambda; k, \theta, \mu) = k\, e^{-\theta(\lambda-\mu-\Lambda)^2} \quad (2)$$

On the other hand, when $\mu \geq (\lambda_{max} + \mu_{min})/2$:

For $\lambda_{min} \leq \lambda \leq \mu - \Lambda/2$

$$g(\lambda; k, \theta, \mu) = k\, e^{-\theta(\lambda-\mu+\Lambda)^2} \quad (3)$$

For $\mu - \Lambda/2 \leq \lambda \leq \lambda_{max}$

$$g(\lambda; k, \theta, \mu) = k\, e^{-\theta(\lambda-\mu)^2} \quad (4)$$

where $\lambda_{min}$ and $\lambda_{max}$ are the ends of the visible spectrum, $\Lambda = \lambda_{max} - \lambda_{min}$ and $\theta = 1/\sigma^2$. For $0 \leq k \leq 1$, $\lambda_{min} \leq \mu \leq \lambda_{max}$ and positive $\theta$, we have a Gaussian-like reflectance function of the sort in Figure 1 (i.e., it has a single peak and is everywhere between 0 and 1).

Although the function definitions are piecewise and a bit complex, intuitively they simply describe a Gaussian-like function centered at $\mu$ on the hue circle. We will refer to the triple $k\sigma\mu$ as KSM (i.e., K for $k$, S for $\sigma$, M for $\mu$) coordinates, where $\sigma$ stands for standard deviation, $\mu$ for peak wavelength, and $k$ for scaling. KSM space is complete in the sense that for any XYZ a corresponding KSM wraparound Gaussian can be found [4].

For a given S, we have wraparound Gaussians of an identical shape with their peak wavelengths varying with M. If these wraparound Gaussians are treated as reflectance functions and illuminated by an illuminant such as D65 the colour will vary with M. Similarly, for fixed M but varying S, we have Gaussians all peaking at M but broadening with increasing S. A plot of the colours of all the SM pairs ($1 \leq S \leq 200$; $380 \leq M \leq 780$) illuminated by D65 is shown in Figure 2.

## Norm of Derivatives Segmentation

For a given S, the colour varies with M—somewhat like it does in a typical hue circle of monochromatic lights—and is similar to the colours of the wraparound Gaussian reflectances defining a row (especially one of the lower rows) of the SM plot shown in Figure 2. The colour band in Figure 3 depicts the hue circle for monochromatic lights. It is a circle because the right-hand side is usually wrapped around to join the left-hand side. Across the hue circle, there appear to be clear colour categories of red, green, and so on. Are these categories simply the result of having common names for them or is there some underlying reason for the division into those categories? Are the boundaries between the categories fixed by their names or are there natural boundaries based on how quickly the colour signals are changing with changing M?

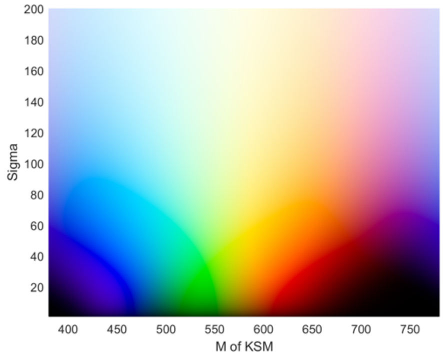


***Figure 2*** *shows the colours under D65 illumination of the wraparound Gaussian reflectances as a function of Sigma and M (central wavelength of the Gaussian).*

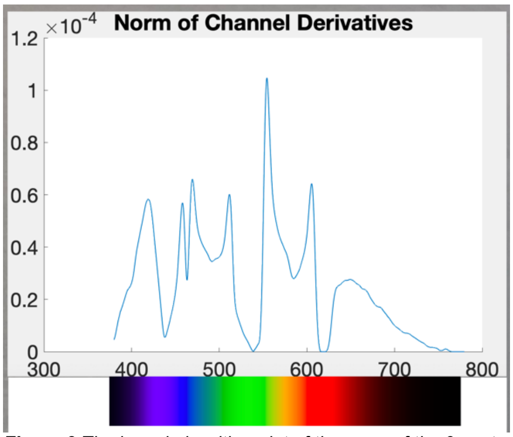


***Figure 3*** *The hue circle with a plot of the norm of the 3-vector of channel-wise derivatives. Valleys of the curve roughly correspond to many standard colour names with the peaks indicating the boundary between colour groups.*

Since colour is 3-dimensional, standard greyscale edge-detection strategies such as first and second derivatives and gradients do not apply. The graph above the colour band shows the norm of the 3-vector of the colour channel derivatives. This is a form of colour-based edge detection with large changes in the norm indicating 'edges' between colours along the hue circle. As can be seen from the figure, the valleys of the curve roughly correspond to many standard colour names with the peaks indicating the boundary between colour categories. These divisions are not based on any notion of colour perception or colour naming; rather, they are simply a reflection of how rapidly or slowly the colour signal 3-vector is changing as a function of wavelength.

Replacing monochromatic illuminant spectra with reflectance spectra, Figure 4 shows the analogous plot for S=20 from the SM plot. The colour band replicates the S=20 row in order to make the colours visible. There are fewer colour boundaries than in the hue-circle case since the wraparound Gaussian reflectances now have breadth and are no longer in any sense monochromatic in the way that lights can be.

Of course, a row of SM with S = ε, ε ->0, would represent all the colours of the standard hue circle since the Gaussians would effectively be Dirac delta functions; however, unlike monochromatic lights of non-zero intensity, a monochromatic reflectance will reflect only an infinitesimal amount of light and is therefore simply black.

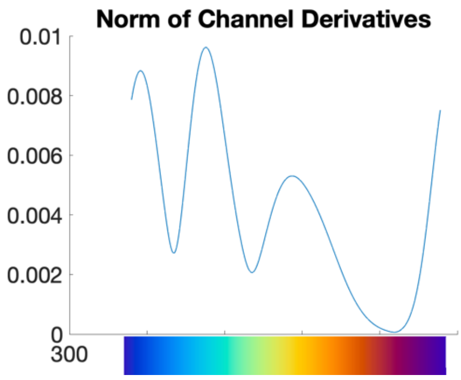


***Figure 4.*** *Plot of the norm of the 3 channel derivatives for S = 20 as a function of M (wavelength). The coloured band shows the colours for wraparound Gaussian reflectances of S = 20 under the equal-energy white illuminant. As in Figure 3, valleys of the curve once again roughly correspond to many standard colour names with the peaks indicating the boundary between colour groups.*

## Clustering Reveals Colour Categories

As is apparent from the colours in the SM plot shown in Figure 2, a single row (i.e., fixed S) does not generally intersect the full range of colours. Do the colours on the SM plane group into recognizable groupings? To answer this question, K-means clustering is applied to the colours on the SM plane. As one can see from the region boundaries plotted in Figure 5, the colours do group into natural colour categories such as red, green, yellow, blue, orange, purple, white and black. The colours on this SM plot are based on D65 as the illuminant. Figure 6 shows the segmented regions, each filled with the colour K-means determined to be the most representative of the region as a whole.

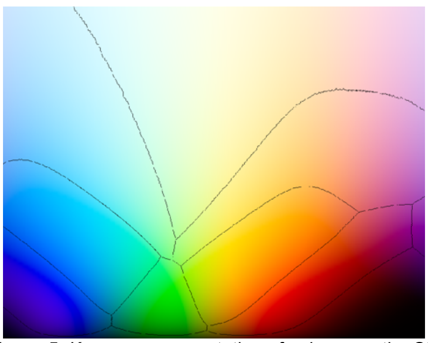

***Figure 5.*** *K-means segmentation of colours on the SM plane into 9 regions of potential categorical colours.*

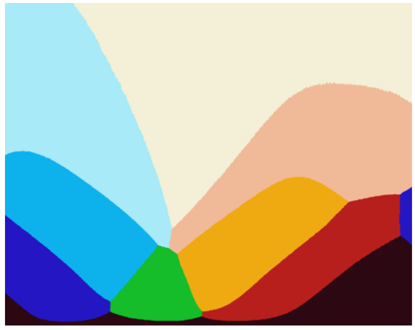

***Figure 6.*** *Region areas from Figure 5 coloured based on the most representative colour for each region as determined by K-means. Note that the blue and black regions wrap around from the right to the left corresponding to the usual idea of a hue circle, which is a feature of using wraparound Gaussian reflectances of the sort shown in Figure 1.*

Figures 7 and Figure 8 are similar to Figures 5 and 6 but with CIE A illuminating the wraparound Gaussian reflectances. Many of the categories are similar for both illuminants (CIE A and D65), especially those for blue, green, orange, purple and black.

Clearly, there is a significant degree of stability in the colour categories even under very different illuminants, and these categories correspond quite well with standard colour names. This is evidence (not proof) of the hypothesis that colour names follow from the natural divisions of the colour triples based on the rate at which they vary in different parts of colour space rather than on some linguistic agreement on names. This is explored further in the next section.

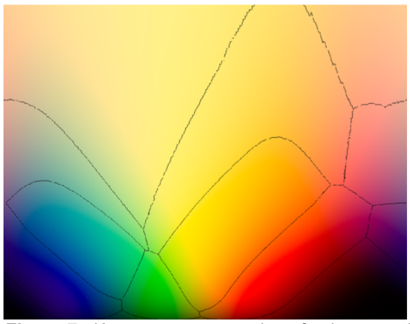

***Figure 7.*** *K-means segmentation of colours on the SM plane under illuminant A into 9 regions of potential categorical colours.*

***Figure 8.*** *Regions coloured corresponding to Figure 7 based on the most representative colour for each region as determined by K-means. Note that several of the regions wrap around from the right to the left corresponding to the usual idea of a hue circle and is a feature of using wraparound Gaussian reflectances of the sort shown in Figure 1.*

## Illuminant Tolerance of Focal Colours

A comparison of the regions in Figures 5 and 6 shows that although the segmentations under D65 and CIE A differ, there is, nonetheless, a large degree of overlap between them. A candidate for a focal colour is the colour of any SM reflectance that remains in the same region when the illuminant changes.

Does M of KSM remain stable if the illuminant is changed? To answer this question, we create Gaussian reflectance functions, with K=1 but different M and S values, and measure how much M and S change under different illuminants.

1. For a given S (sigma) and M (central wavelength), a Gaussian reflectance function, G(λ), such as those shown in Figure 1 is created.
2. The sRGB (results using CIELAB are qualitatively similar) of G(λ), illuminated by blackbody radiators of temperatures T = 2000, 2500,…,10000 are computed.
3. Assuming that the light is D65 during the KSM calculation even though it is instead a blackbody radiator from Step 2, calculate the KSM triples corresponding to the colour coordinates from Step 2.
4. Plot the resulting SM coordinates as black dots connected by black lines to the initial SM coordinate (marked by a circle) defined in Step 1. See Figure 9.

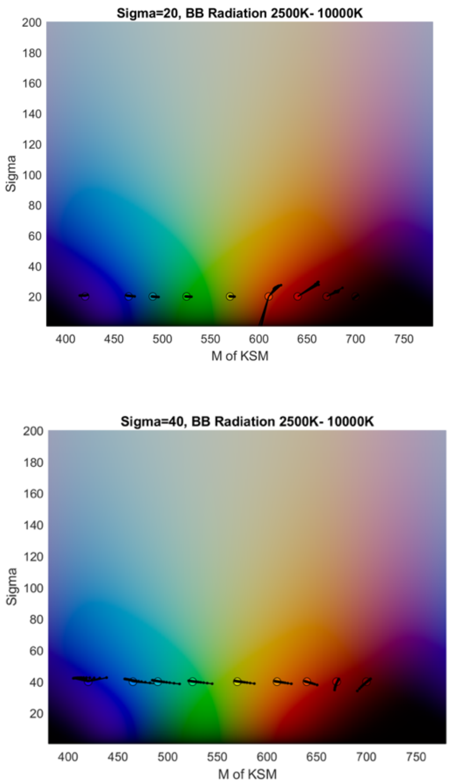


***Figure 9**. Black 'lines' plotted on top of the SM plane for D65 are samples of the range of D65-based SM coordinates as the illumination is varied from 2,500K° to 10,000K°. Top: Sigma = 20, narrow reflectance function; Bottom: Sigma = 40, broader reflectance function.*

As is clear from Figure 9, the changes in the SM coordinates are relatively small despite the fact that computing the KSM coordinates under the D65 assumption is equivalent to having no chromatic adaptation whatsoever.

Candidates for focal colours are those that remain within a single colour category's boundaries despite changes in the illuminant. In other words, expressed in KSM coordinates, focal colours can be defined as those that remain stable in terms of representing a colour category under a wide variety of illuminants. The existence of such colours is illustrated in Figure 10 in which the black lines indicate the change in SM coordinates for a change in illuminant from D65 to blackbody temperatures 2500, 3000,…,10000 for different points in colour space. The points in the violet, blue, green, yellow/orange, red and purple segments are candidate focal colours since, even without chromatic adaptation, they remain within the same colour category despite dramatic changes in the illumination. The three colours in the upper pale regions are affected much more dramatically by the illumination and, hence, are not likely candidate focal colours, at least not without accurate chromatic adaptation. Figure 11 illustrates the analogous real-world case of the failure of a white surface to continue to be named or classified as 'white' under different illuminants even in the presence of chromatic adaptation.

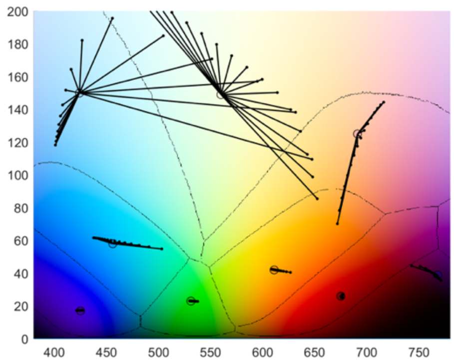

***Figure 10.** Black lines indicate the change in SM coordinates for a change in illuminant for the cases of blackbody temperatures 2500, 3000,…,10000 for different points in colour space. The points in the violet, blue, green, yellow/orange, red and purple segments are candidate focal colours since, even without chromatic adaptation, they remain within the same colour category despite dramatic changes in the illumination. The three colours in the upper pale regions are affected much more dramatically by the illumination.*

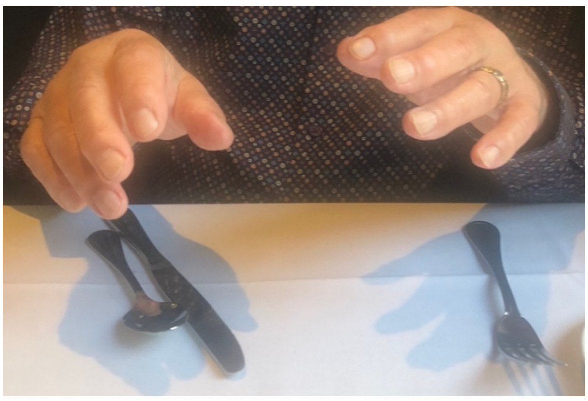

***Figure 11.** An example of the problem of white as a focal colour showing that the 'white' tablecloth is either pale orange or pale blue depending on the incident light, but not truly 'white' anywhere. The situation shown in Figure 10 is similar for S > 150 (i.e., very broad wraparound Gaussian reflectances).*

## Conclusion

Colour categories and focal colours are shown to arise naturally from segmentation of KSM colour space into regions based upon the edges in the space of colour signal triples and/or regions based on clustering similar colour signal triples together. Furthermore, focal colours can be in part defined by their tolerance to illumination change even in the absence of chromatic adaptation. Unlike many previous studies on colour naming, categorical colour and focal colour, no particular underlying assumptions about cultural naming conventions or the mechanisms of colour perception are needed.


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