A simple way the human visual system could extract surface reflectance properties: applications to color naming and unique hues.

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Abstract

Recently, Philipona & ORegan (2006) proposed a linear model of surface reflectance as it is sensed by the human eye. They showed that it can be surprisingly well modeled by a linear and illuminant-independent operator of the 3 dimensional space generated by the human cone responses. To each surface thus corresponds one linear operator represented by a unique 3x3 matrix, whose properties, as it will be shown, correlate with the existence of focal colors. The diagonalization of each computed matrix makes easy to study its properties. Interestingly, all the matrices can be almost exactly diagonalized in a common basis of virtual sensors through a unique 3x3 linear transformation. This result suggests that, by appealing to a similar transformation, the human nervous system could easily have access to the reflection properties of surfaces.

Introduction

A colored surface can be considered as an operator that takes incoming light $E(\lambda)$ and transforms it into reflected light. Physicists describe this operator as a continuous reflectance function $S(\lambda)$, describing the attenuation of light at each wavelength of the spectrum. Human photoreceptor cones however are only sensitive to three broad ranges of light, so the sensed equivalent of the incoming and reflected light are simply three dimensional vectors corresponding to the three cone responses. The sensed equivalent of the physicist's reflectance function would thus be an operator describing the transformation of the sensed incoming 3-vector into the sensed reflected 3-vector (Figure 1). Philipona and O'Regan (2016)[3], have shown the surprising fact that the function linking these vectors is to an extremely high degree of accuracy, simply a *linear* and *illuminant-independent* transformation, that can be represented by a 3 x 3 matrix $A^{\mathbb{S}}$. We would thus have: $\mathbf{v}^{\mathbb{S}}(E) = A^{\mathbb{S}}\mathbf{u}(E)$, where:

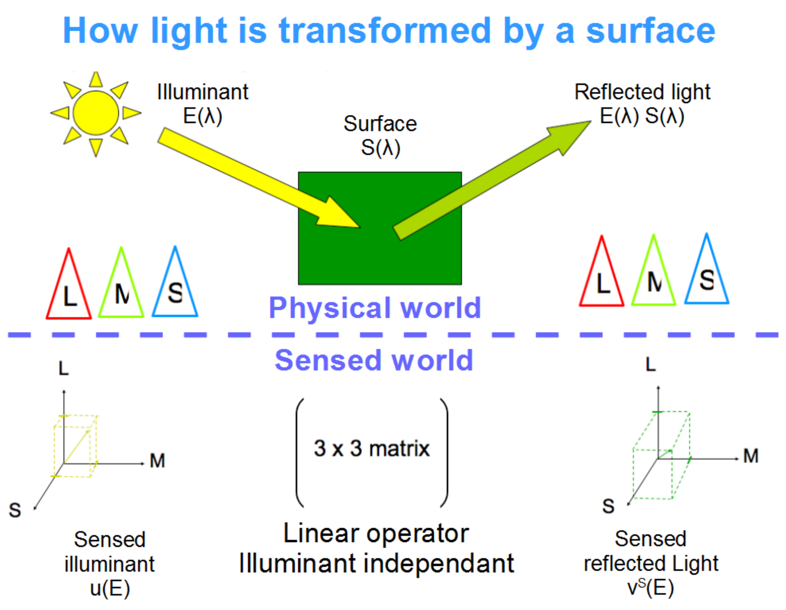

Figure 1: Sensed analogue of surface reflectance

$\mathbf{u}^{\mathbb{S}}(E) \stackrel{\text{def}}{=}$ Sensed incident light $= \left(u_L^{\mathbb{S}}(E), u_M^{\mathbb{S}}(E), u_S^{\mathbb{S}}(E)\right)^t = \int_\Lambda E(\lambda)\mathbf{R}(\lambda)d\lambda.$

$\mathbf{v}^{\mathbb{S}}(E) \stackrel{\text{def}}{=}$ Sensed reflected light $= \left(v_L^{\mathbb{S}}(E), v_M^{\mathbb{S}}(E), v_S^{\mathbb{S}}(E)\right)^t = \int_\Lambda E(\lambda)\mathbf{R}(\lambda)S(\lambda)d\lambda.$

and cone sensitivities $\stackrel{\text{def}}{=} \mathbf{R}(\lambda) = (R_L(\lambda), R_M(\lambda), R_S(\lambda)).$

For example, for a blue-green surface we might have

$$\begin{pmatrix} v_L^{\mathbb{S}}(E) \\ v_M^{\mathbb{S}}(E) \\ v_S^{\mathbb{S}}(E) \end{pmatrix} = \begin{pmatrix} 0.2590 & 0.2151 & -0.0136 \\ -0.0979 & 0.5861 & -0.0090 \\ -0.0099 & 0.0155 & 0.4212 \end{pmatrix} \begin{pmatrix} u_L(E) \\ u_M(E) \\ u_S(E) \end{pmatrix}.$$

The accuracy and applicability of Philipona & O'Regan's approach was comprehensively confirmed by Witzel et al. (2015)[5]. In further work, Flachot et al. (2016)[2] showed that this matrix can be calculated without reference to illuminants, and purely on the basis of the human cone sensitivities and the physical reflectance function of the surface. This is a simplification as compared to Philipona & O'Regan, and Witzel et al., who used linear regression over many illuminants to calculate the matrix.

Studying the sensed analogue of reflectance

Reduce the number of coefficients

The matrices A^S defining a surface's reflectance properties will usually contain 9 coefficients. To understand the properties of such matrices, it is useful to diagonalize them, so that they contain only 3 coeffcients.

$$\begin{pmatrix} 0.2590 & 0.2151 & -0.0136 \\ -0.0979 & 0.5861 & -0.0090 \\ -0.0099 & 0.0155 & 0.4212 \end{pmatrix} \xrightarrow{T^{\mathbb{S}}} \begin{pmatrix} 0.3467 & 0 & 0 \\ 0 & 0.4975 & 0 \\ 0 & 0 & 0.4221 \end{pmatrix}$$

Where T^S is a diagonalizing transformation. We now have only **three reflection coefficients** $\{r_L^{\mathbb{S}}, r_M^{\mathbb{S}}, r_S^{\mathbb{S}}\}$ for each sensed surface.

Singularities in reflection properties

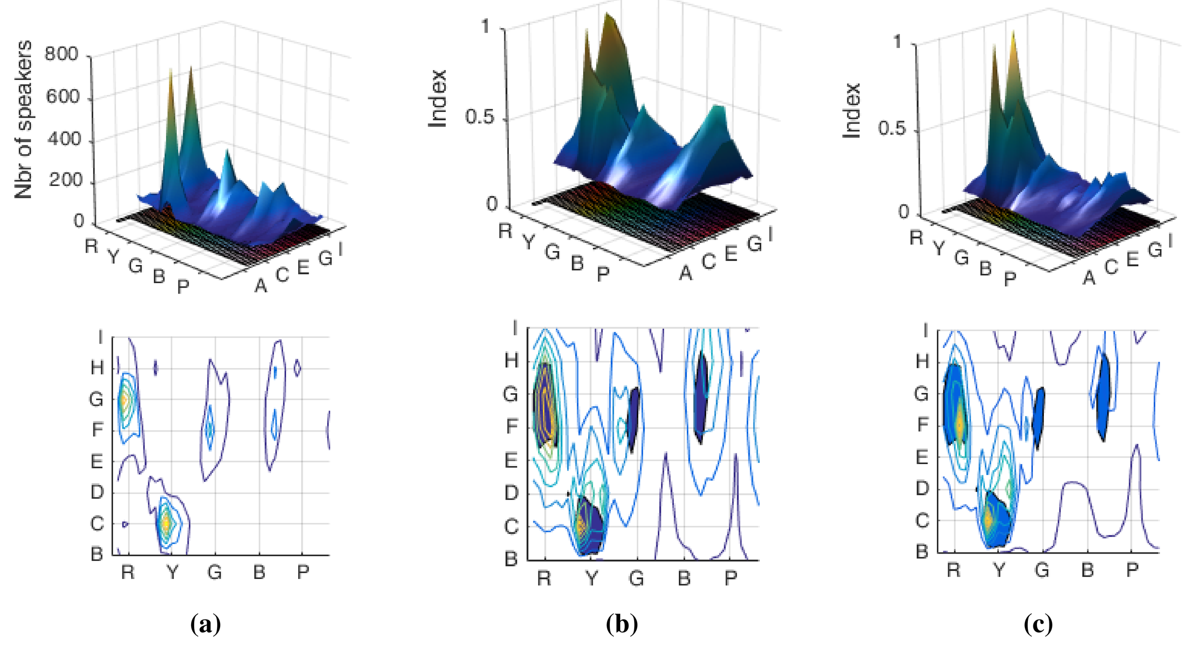

Figure 2: *a)* Results of the WCS cross cultural study on color naming. *b)* Singularities of the Munsell chips used in the WCS study. *c)* Singularities as assessed by the nervous system through virtual sensors.

The three values $\{r_L^{\mathbb{S}}, r_M^{\mathbb{S}}, r_S^{\mathbb{S}}\}$ entirely characterize the color properties of a surface. In particular, cases where all components of the incoming light are reflected equally ($r_L^{\mathbb{S}} \simeq r_M^{\mathbb{S}} \simeq r_S^{\mathbb{S}}$), would correspond to achromatic surfaces. Similarly, we expect that surfaces that reflect one component either very strongly or very weakly compared to the other two, should have a particular perceptual status. We call this kind of surface *singular*. It corresponds to the cases where $r_1{}^{\mathbb{S}} >> r_2{}^{\mathbb{S}} \simeq r_1{}^{\mathbb{S}}$ and where $r_1{}^{\mathbb{S}} \simeq r_2{}^{\mathbb{S}} >> r_1{}^{\mathbb{S}}$, where $r_1{}^{\mathbb{S}} > r_2{}^{\mathbb{S}} > r_3{}^{\mathbb{S}}$ are the reflection coefficients $\{r_L^{\mathbb{S}}, r_M^{\mathbb{S}}, r_S^{\mathbb{S}}\}$ in decreasing order. Indeed Figure 2 b) plots the singularity of the 320 Munsell chips used in the World Color Survey, which counted the number of speakers across many different cultures in the world that have a name for a particular chip's color (Figure 2 a)). The surfaces most singular in a Munsell color region highly correlate $r = 0.62$ with the surfaces whose colors are cross culturally considered as prototypes of color categories – so-called "focal colors".

The correlation between focal colors and singularities suggests that the quality of a color may come from the capacity of the nervous system to extract the information about the reflection properties of the surface it is looking at.

How could the nervous system have access to reflection properties of sensed reflectance?

Virtual sensors

So far, in order to study the properties of the matrix representing the sensed reflectance of a surface, we first computed the matrix by performing a linear regression, then did a per surface diagonalization. This seems like a long process for the nervous system. Fortunately, we can show that reflectance matrices for most surfaces can be almost exactly diagonalized in the same basis using a unique transformation T. This basis would correspond to a set of what we call *virtual sensors*, replacing the normal human cones. The basis is such that, on average, the responses of the virtual sensors are almost independent (cf Figure 3) and the off diagonal elements of the resulting transformed reflectance matrices are 50x smaller than the elements on the diagonal.

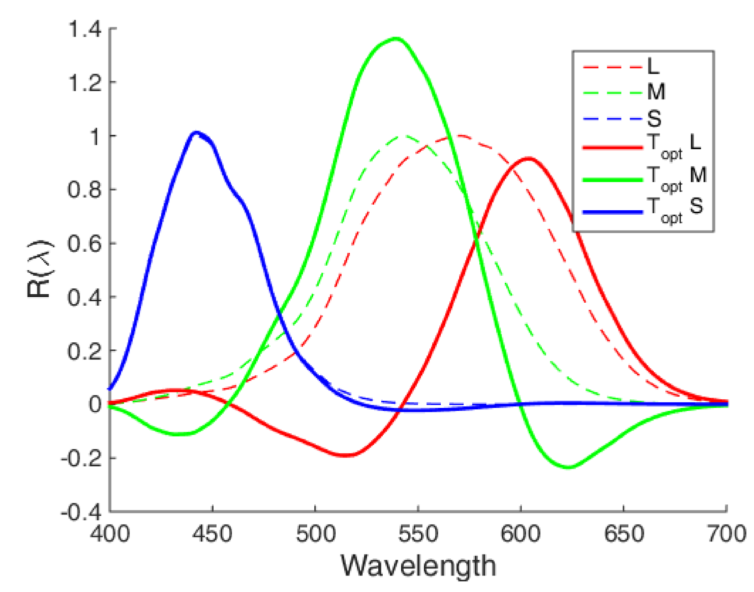

Figure 3: Virtual sensors

Thus, the nervous system could obtain the sensed reflection coefficients for a surface simply by dividing the sensed reflected light by the incoming light separately within each virtual color channel:

$$\{r_i^{\mathbb{S}} \simeq \frac{\tilde{v}_i^{\mathbb{S}}(E)}{\tilde{u}_i^{\mathbb{S}}(E)}\}, \qquad i = L, M, S.$$

Singularities and Unique Hues

Using the notion of virtual sensor, for each Munsell chip it is possible easily to obtain its three reflectance coefficients by taking a particular illuminant, and calculating the reflected light divided by the illuminating light in each virtual sensor channel. Using these reflectance coefficients we can then calculate the singularities without any matrix estimation by linear regression or subsequent diagonalization. Figure 2 c) shows that the original pattern of singularities observed in Figure 2 b) and the correlation with focal colors is conserved. This result gives a theoretical grounding to the spectral sharpening of Finlayson et al. (1994)[1] and the possibility of the existence of a von Kries like normalisation in the Human Visual System.

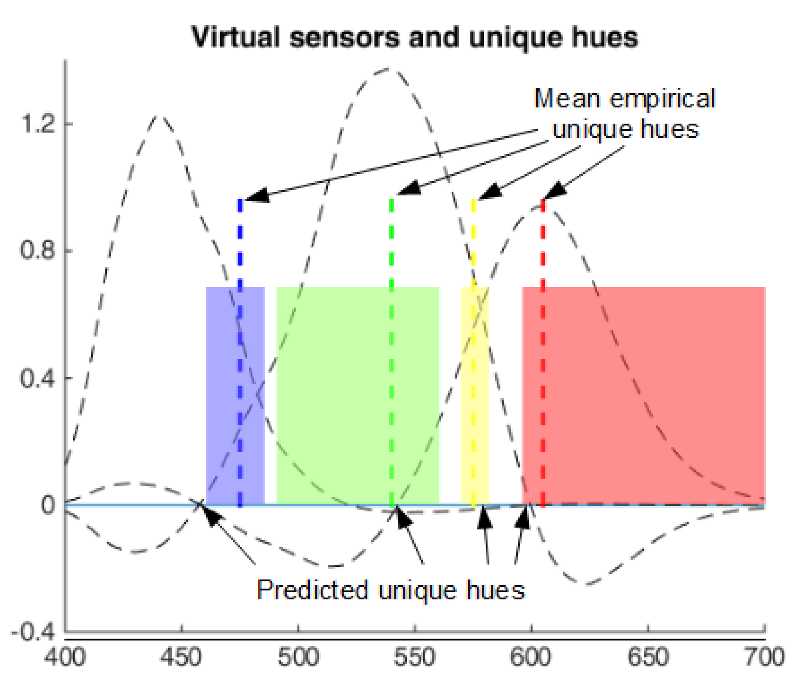

Figure 4: Comparison between mean empirical unique hues (with range) and predicted unique hues.

In addition, preliminary results show that the virtual basis may also be a hint to explain the existence of unique hues (cf Figure 4). It is indeed striking how the wavelengths, for which one of the sensors is either very sensitive or very unsensitive compared to the other two, correspond to the mean mesures of unique hues we can find in the literature [4], except maybe for the blue one.

Conclusion

This study shows that the fact that certain colors are perceived as "focal", and that certain hues are perceived as "unique", may come from the attempt of the nervous sytem to assess the reflection properties of surfaces by using the cone responses provided by the human eye. Further investigation is needed to characterize the possible relation between what we here call virtual sensors and the existence and identity of unique hues.

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