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What if colorimetry does not work

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Abstract

Colorimetry is a fascinating piece of science that Maxwell began in 1860. From the rigorous scientific point of view, the series of assumptions on which it is based have formed, during time, a substrate of constraints, making its use unpractical for many of today tasks in color management. In everyday applications, these constraints are often not considered, producing a series of best practices and models that carry on mismatches between measures and the actual color sensation as perceived by the observers. This paper presents a synthetic critical overview on colorimetry research and its everyday use.

Introduction

Our vision system generates color sensation using two mechanisms. One is the photon capture by cones, the other is the spatial computation of the receptor's responses.

In a naive idea of color, the first mechanism is the important one, while the second is more an annoyance than a founding principle of our color vision.

This simplification has a long history [1] and has been fostered by the gap between art and science. For an artist, spatial effects are an important mechanism to consider in order to obtain the desired result. For too many scientists they are an annoying complexity and thus not to consider.

Not only this has caused a series of understandable simplifications, but also has caused attitudes that consider these simplifications negligible in everyday practice [2]. Unfortunately, not considering spatial mechanisms does not make them disappear.

Scene type 0 (0-D): pointwise colorimetry in aperture mode

Colorimetry is a great scientific framework that, in order to deal with the great complexity of the human vision system in forming color sensation, introduced the "aperture mode" constraint.

Here are definitions of aperture mode from CIE [3] and Claudio Oleari [4].

"*Aperture mode, from which the term Aperture colour mode, perceived colour for which there is no definite spatial localisation in depth, such as that perceived as filling a hole in a screen*." [3]

"Synonymous with film colour. Perceived colour typical of the radiation that, before entering the eye, passes through the aperture of a diaphragm and the eye is focused on the edge of the diaphragm in order to avoid associating the radiation with an object or a source. In this way, the observer loses any information that denotes the object (or source), such as surface non- uniformity, polish, texture, type of lighting (grazing, diffused, etc.), and the light that enters the eye on the retina has at any point the same spectral decomposition. In this case, the field of vision is totally dark with the exclusion of the part within the aperture of the diaphragm." [4]

Or alternatively, aperture mode is defined in combination with object mode by the Optical Society of America (OSA) in the Science of Color [5]:

"Aperture Mode of Appearance: Non-located mode by which color is perceived when divorced as completely as possible from all of the spatial and temporal attributes of other modes of appearance."

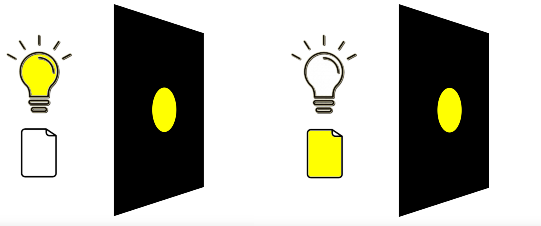

Figure 1. Under the "aperture mode" constraint a yellow light shining on a white paper (left) and a white light shining on a yellow paper (right) generate the same color signal.

Fig. 1 describe the ambiguity of the aperture mode, for which the way color signal is generated cannot be considered. In the example, the contribution of the illuminant is not distinguishable from the one of the surface. Both cases generate the same yellow.

Aperture Mode is a strong basic assumption that heavily influences research and results in colorimetry and color science in general. It follows that colorimetry is a powerful and precise model and tool for color in isolation (or aperture mode). Unfortunately, this constraint is very narrow, and rarely can be applied in real scenarios, such as digital imaging.

Many had the need to overcome this constraint in order characterize color in complex scenes.

Scene type 1: moving out from the aperture mode

After Richard Hunter's work in 1948 [6,7], CIE standardized in 1976 the CIELab color space.[8].

It carries an important novelty: its use requires to know the tristimulus or the spectral radiance of the illuminant. In principles, this information should be measured from the scene, but in a major part of the cases it is substituted by numbers from standard illuminants and rarely these data match with the scene's ones.

In this way aperture mode's constraint seems overtaken: now it is possible to distinguish the ambiguous situation of Fig. 1.

This situation is referred as "surface mode", or alternatively as "object mode", but in CIELab the color is still evaluated through a hole (pointwise), since no spatial mechanism is taken into account. For the sake of listing, in this paper we label this situation "scene type 1" (see Table 1).

Here the definition of surface-colour mode from CIE [3] and Claudio Oleari [4]:

Surface-colour mode − colour perceived as belonging to a surface from which the light appears to be diffusely reflected or radiated"

Scene type 1 is something more than the 0-D aperture mode, but not yet a 2-D situation with a spatial arrangement.

CIE presents CIELab as the first model of appearance. It is interesting to look carefully at the transition from colorimetry to appearance.

Here a definition from W.D. Wright:

"Where does colorimetry end and appearance science begin? An interesting question. My short answer would be that colorimetry ends once the light has been absorbed by the colour receptors in the retina and that appearance science begins as the signals from the receptors start their journey to the visual cortex. To elaborate a little, tristimulus colour matching is governed solely by the spectral sensitivity curves of the red-, green-, and blue-cone receptors (if we may be allowed to call them that), whereas the appearance of colours is influenced by all the coding of the signals that takes place along the visual pathway, not to mention the interpretation of the signals once they arrive in the visual cortex." [9]

The hidden assumptions beyond appearance

Wright definition of the boundary between colorimetry and appearance is pretty much agreed by the community. In table 1 there is a list of possible scene typologies with the relative scholar approach.

The problem arises from the hidden assumption of this transition. Moving from aperture mode to object mode, corresponds to the shift from XYZ colorimetry to color appearance. This transition does not include spatial mechanisms, but it should. In table 2 there is a synthetic summary of Wright separation and the characteristic of the Human Vision System (HVS) involved.

A possible reason of this lack is to reduce model complexity. However, the goal of simplicity does not hold since the rejection of spatial complexity forces model to become more and more complicated, dealing with different set of parameters and definitions, distinguishing for every possible scenario.

Scene type 2 (2-D): the importance of spatial mechanisms

A wide family of spatial configurations like the ones in Fig. 2 are named visual illusion. Fig. 2 reports some examples of different spatial effects. On the left a simultaneous contrast configuration, where the perceived brightness of each gray patch changes in the opposite direction of the background. In the center an assimilation configuration, where the perceived brightness of each gray patch changes in the same direction of the background. On the right, the Kofka ring [10], where the perceived brightness of each gray patch changes according to the type of edge formed by shifting the patches. Similar effects in color are obtained when using colored patches.

The name "visual illusions" confirms a bias. These spatial configurations generate different sensations from the same gray. The generated sensations are real, not illusory.

The name visual illusion refers to the fact that they contradict the idea that color sensation comes just from the stimulus at the point, regardless the spatial arrangement of the other stimuli in the observed scene.

They are good examples of the need to consider also spatial mechanisms, in particular edges, in the formation of color sensation.

If one uses CIELAB (appearance) to measure all the gray patches, the result would be always the same, like using XYZ colorimetry. No spatial configurations are accounted, but the many gray patches have a different appearance. Not because of different stimuli, because of different spatial arrangements.

Table1 Scene type characteristics

	Description	Model	Input	Goal	Output	HVS
Scene type 0	single light spot	XYZ	single light spot	Aperture Mode	Colorimetry Match	cone
Scene type 1	single light spot	CIELab	single light spot + illuminant	Object Mode	Appearance	cone + spatial
Scene type 2	a 2D scene	CIECAM	single spot taken isolated from a 2D scene + illuminant + parameters	Object Mode	Appearance	cone + spatial
Scene type 3	a 3D scene	?	?	Object mode	Appearance	cone + spatial

Table2 Mode characteristics

mode	visual description	visual mechanism
aperture mode	XYZ colorimetry	cone
object mode	appearance	cone+ spatial

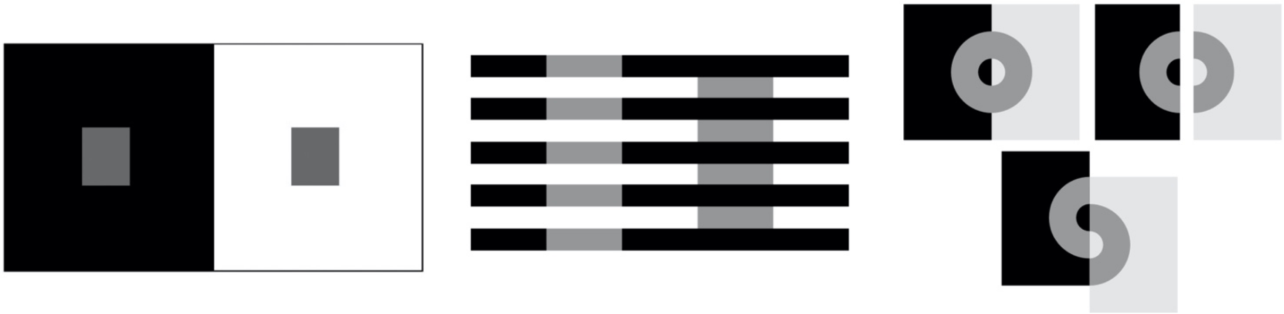

Fig. 2 Example of different spatial effects: simultaneous contrast (left), assimilation (center) and Kofka ring (right).

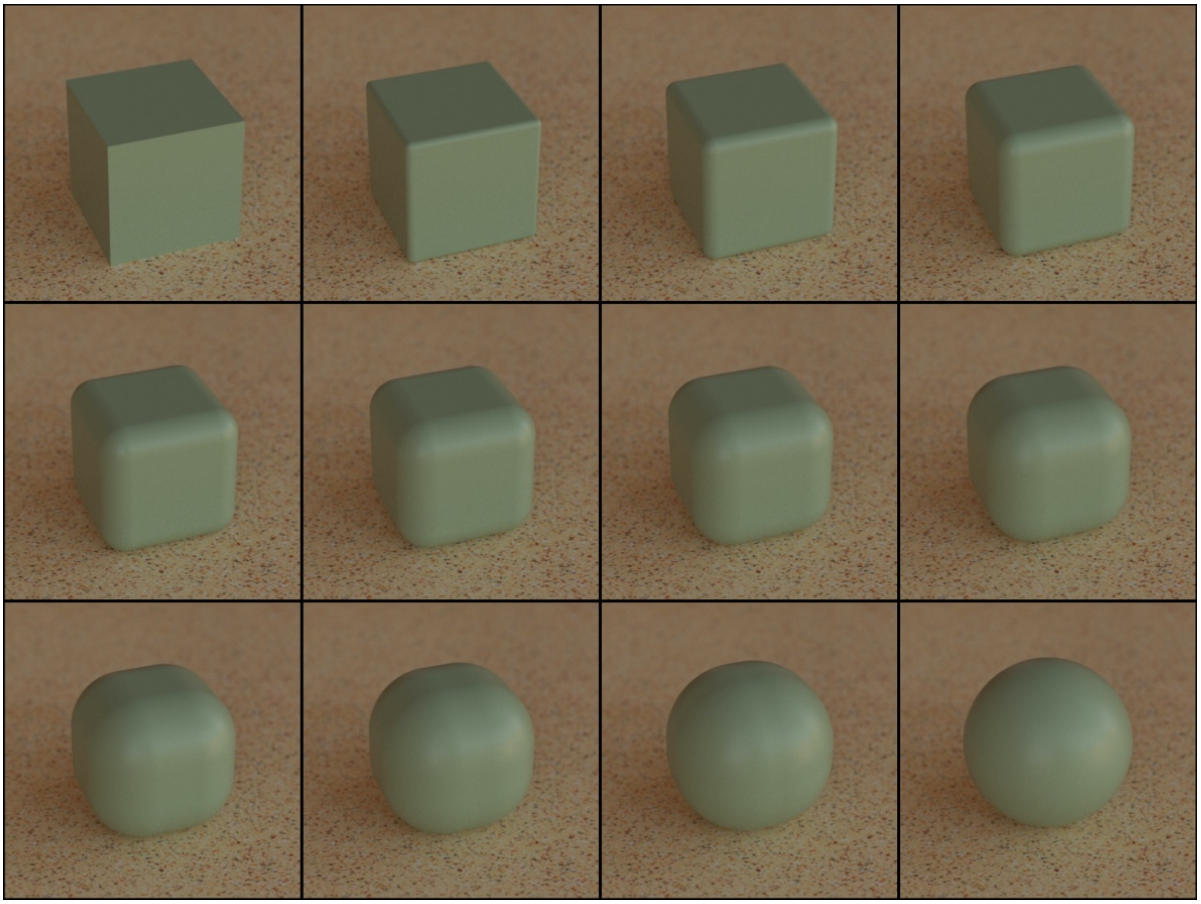

Fig. 3 Examples of changes in a 2-D rendering of different 3-D objects.

Fig. 4 Examples of changes in a real 3-D scene.

Scene type 3 (3-D): Color in Real World

Real 3-D scenes can be more complicated. We have spatial mechanisms as well, since a 3D configuration generates a 2D projection on the retina. In addition to this fact, the physical complexity increases.

Uniform distribution of illumination is practically non-existent in nature. Illumination likely changes at every point in a scene and this can strongly affect the resulting color signal and appearance.

Fig. 3 reports a theoretical situation, computed in computer graphic, where BRDF is know and carefully applied for the computation of each point. Moreover, light source is stable and uniform, surfaces perfectly flat, and thus every light bounce is neat and straight. Regardless all these unrealistic assumptions, the figure reports a wide variability in light-surface interaction.

In real 3D scenes the BRDF of every surface is usually unknown and less regular, since object and illuminants are not perfect. Moreover, estimating BRDF is usually an ill-posed problem and cannot be computed by a single image.

A real scene is the one reported in Fig. 4 [11] where inter-reflections, scattered subsurface light, and illumination edges and non-uniformity cause much bigger shift in appearance.

There is also another important complexity to deal with: The type of 3-D input data. In fact, we often refer to 3-D by mean of 2-D images, like in the example of Fig. 3 and 4. A 2-D representation of a 3-D object is not the same as looking directly to the 3-D object. This concept has an important tradition in the world of art. Here the tribute to Magritte of Fig. 5 helps us to recall this important point.

A spatial mechanism is worth a thousand words

In the search for the ecological reason of the existence of spatial mechanisms in our vision it is interesting to make some hypothesis. Like many complex biological systems, the reason can manyfold. One useful property is that color constancy comes for free if one implements spatial comparisons [11,12].

Fig. 5 A tribute to René Magritte. It is an iconic way to recall the importance of carefully specify (and possibly calibrate) the visual stimulus as input to the appearance model.

A big problem in taking a picture or looking at a scene is that in both cases a lens is used and thus in both cases there is glare in the acquisition. Glare changes the scene values that arrive on the retina or on the sensor plane [13,14]. It is an unavoidable departure that affects the scene values at each point according to their spatial arrangement and magnitude. The loss of contrast in the retina can be severe, another useful advantage is that spatial comparisons counteract glare [12,15,16].

Due to spatial mechanisms vision is much more robust.

Conclusions

This paper has presented a concise series of comments about XYZ colorimetry, appearance models and their application. The main goal is to underline and recall the assumptions and constraints beyond their use. Since these constraints are often not considered, taking them into consideration can help in understanding possible mismatch between theoretical and actual measurements and color sensations in many applications.

XYZ colorimetry works fine in aperture mode, but if we really want to address the object mode mimicking human vision, we need to use spatial mechanisms.

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Author Biography

Alessandro Rizzi is Full Professor at the Department of Computer Science at the University of Milano (Italy), teaching Colorimetry, Multimedia and Movie restoration.

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He is the head of the MIPS Lab at the Department of Computer Science. He has been one of the founders of the Italian Color Group, Secretary of CIE Division 8, IS&T Fellow and Vice President. In 2015 he received the Davies medal from the Royal Photographic Society.

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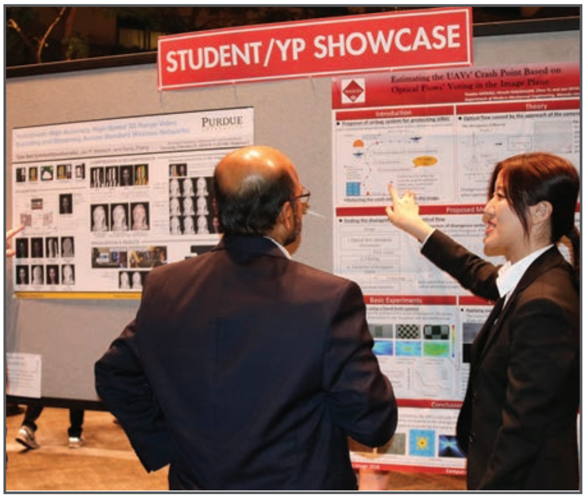

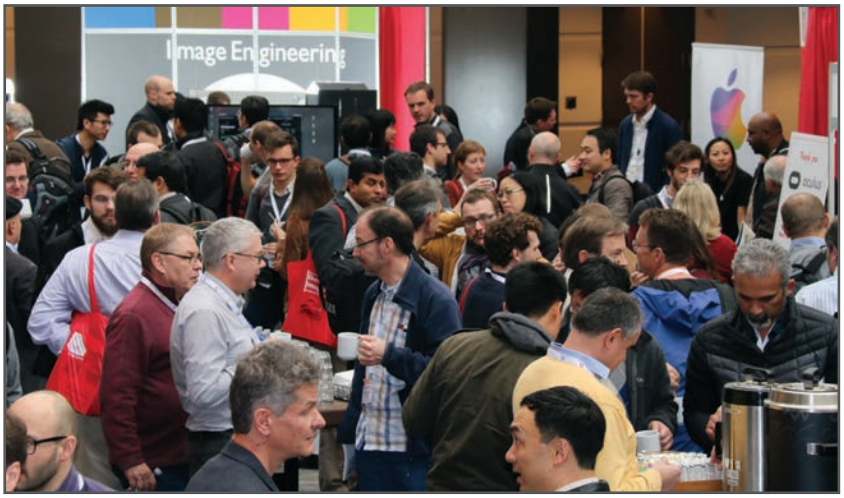

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