Human and Computational Color Constancy

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Abstract In this paper we present a brief review of the main issues surrounding the link between human and computational color constancy. Starting with the problem statement, it's definition, main attributes and measuring methods, we introduce the computational color constancy problem and link it to its human equivalent. Finally we conclude that a new computational color constancy algorithm could be build by means of mimicking the functional stages of the human color constancy.

Keywords: human color constancy, computational color constancy, memory colors.

1 Introduction

Human Color Constancy is a perceptual phenomenon that stabilizes the appearance of object's colors throughout changes in illumination, [14, 16, 19].

One possible ecological justification for color constancy in mammals is to facilitate scene object recognition. In Helmolt'z words: "*Colors are mainly important for us as properties of objects and as means of identifying objects*". Then a mechanism that preserves the color appearance of objects will serve this purpose [15] .

As a perceptual phenomenon, all variables affecting color constancy lie in the content of the perceived scene, e.g. scene chromaticity, three-dimensional information, object movement and some others. All these factors are called visual cues. As we will see later, the object's color is constrained by scene context and memory context.

There are also two other alternative definitions:

- The concept of *operational/relational color constancy* refers to the constancy of the perceived relations between the colors of surfaces under such changes in illumination [4, 9]. Foster et al [8] discuss the relationship between the two previous definitions and draw conditions for their equivalence.
- In computational terms: "*color constancy is achieved when a neural process transforms the signals elicited by surfaces under a test illuminant towards the signals that would be elicited by the same surfaces under a reference illuminant*" [19].

The general context where this phenomenon occurs is scene viewing. Over this process the photons reflected by surfaces are collected by sensors in the retina. This information is then translated into electrical signals and travels to the brain. Since viewing is done across time, the continuos perceived scene is a discrete succession of electric signals. Part of this information is perceived as constant, meanwhile other part is perceived as changing. Because of that, there is a pull between two processes: adaptation and discrimination [1]. According to Jameson and Hurvich [15] : " *...human visual systems are likely to have evolved a design that provides perceptual information about change as well as constancy*". What is the reason for such dual behavior? What are the key factors that govern these two processes? In this general context we will focus our study in the key scene factors that grant the achievement of color constant descriptors across time.

In the following pages we will present a short review of color constancy; it's definition, motivation and features. Also we will introduce and link human with computational color constancy [1]. In order to understand the mechanisms underlying the phenomenon of color constancy we must give a concise definition of color constancy and try to answer the right questions: What is color constancy? Which biological purpose does it serve? Where in the human visual system is it sited? Under which conditions it works and which extent does it works? We will try to give some insights into these questions.

2 Visual Cues in different neural levels

Color constancy is composed by several mechanisms situated at different neural levels in the human visual system [13, 16, 19]. However these mechanisms may have some purpose other than color constancy. The wide range of this scope is what makes specially difficult to understand this phenomenon. In order to achieve constancy the visual system extract visual cues from the scene, ranging from physical scene statistics to scene object composition. According to Brainard [16]: "*The open question of color constancy is what aspects of complex images govern the visual system's sensitivity*", and in our case adaptation. Also, we are interested to find out how much each visual cue contributes to the final color constancy achieved, and in particular how these contributions vary for different complex scenes [16].

Some authors have studied the problem using scene statistics from the physical scene description. This is, using the illuminant and surface reflectance spectral function and the sensitivity functions for each photoreceptor type [3]. From this point of view they try to extract relevant physical statistics from the scene. Also there has been other studies using other conditions, as object movement [24], chroma variance and the existence of 3D objects [11]. All these factors could be classified as bottom-up because they belong to the scene composition. However some other kind of factors have been identified, such as the effect of '*memory color'* in familiar objects [17] (i.e. the modification of perceived colors by remembered colors or memory context.) These two approaches split the perceived color formation between two information sources. On one side we have bottom-up information and on the other side we have top-down information. Traditional studies have centered their attention on bottom-up factors but recently there have been new insights into the top-down contributions.

According to Smithson [19] a color constancy model should perform three operations:

1. Identify the type of neural transformation required to undo a color conversion across illuminants.
2. Find out the parameters that rule the transformation and how these might be set from the scene.
3. Specify where in our perceptual apparatus these transformations are implemented.

Following this schema we can split the phenomena in three main stages: sensory, perceptual and cognitive [13] each with its own scene visual cues. However some cues may belong to multiple perceptual levels at the same time.

2.1 The Sensory Stage

The eye and specially the retina is where are sited the sensory mechanisms with the action of photoreceptors and the outer retina being his main components affecting color sensitivity. In fact, there are some authors that support the theory that the main part of color constancy is achieved in this level [21]. According to Hurlbert [13] we can divide the sensory stage in three main parts, each of them with his own temporal scale. Chromatic adaptation to the mean (60 seconds), chromatic adaptation to the variance (several minutes) and spatial contrast (25 milliseconds). And so the visual cues belonging to these levels are the mean chromaticity, chroma variance and spatial contrast. One of the results that strongly supports the use of spatial contrast in the color constancy mechanism is found by Foster and

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[1] In this paper computational color constancy is framed in computer vision context, not in computational neuroscience.

states that the ratios of cone-photoreceptor excitations produced by light from natural surfaces are statistically almost invariant under changes in illumination by natural light [7]. So they contribute to the color constancy mechanism keeping the cone-excitation ratios invariant from the surfaces across illuminant changes.

2.2 The Perceptual Stage

At this stage we require prior segmentation of the scene in order to find relevant scene elements. For instance: specular highlights, mutual reflections, movement, depth perception , 3D objects and so on. We label these kind of visual cues as ‘perceptual’. Brainard [16] studied which rate of color constancy represents each of local contrast, global contrast and specular reflections cues. But other studies [24] have been proved that movement is also a perceptual cue to improve color constancy. Also the scene depth has been proved to influence the phenomenon [11, 23]. This could be explained because scene depth facilitates subject’s illumination change recognition.

2.3 The Cognitive Stage

This level require to identify the objects prior to allow the modification of their perception by the memory processes. This influences have been studied by several authors, more recently in [17], regarding the perceived fruit color. At the end, they re-developed concept of “*memory color*”. Which was introduced by Hering and states that we see the world through the object colors that we have in our memory, which have been acquired over visual experience. In his own words: “*All objects that are already known to us from experience, or that we regard as familiar by their color, we see through the spectacles of memory color*“ [12].

There is another possible perceptual-cognitive cue, the consciousness of illuminant change as reported by several authors [2].

3 Experimental Paradigms

One way to measure the color constancy phenomenon is using psychophysical experiments. The definition of each new experiment has some common parts: the paradigm, the laboratory conditions, the stimulus and the subject’s task. For a clear exposition we will discuss separately each part but they are interrelated. In order to get a successful experiment, the correct choice of all elements is critical.

3.1 Psychophysical Paradigms

As we have seen, the color constancy effect is composed of several mechanisms. There are different psychophysical paradigms, each suited to the color constancy mechanism to be measured. The most common are *asymmetric color matching*, *achromatic color setting* and *color naming* [9, 19]. In the first paradigm two illumination conditions are presented and the subject has to match one color from one condition to the other, this matching can be across space (*Simultaneous Asymmetric Matching*) or time (*Successive Asymmetric Matching*). In the second paradigm the subject adapts under one scene illumination and then is required to adjust a test patch until

Neural Transformation	Sensory	Perceptual	Cognitive
Visual Cues	• Chromatic adapt. to the mean(1) • Chromatic adapt. to the variance(2) • Color Contrast(3)	• 3D objects • Mutual reflectance • Chroma variance • Specularities • Scene movement	• Memory Colors • Consciousness of illuminant change
Location in HVS	Retina, LGN	Cortex , V1/V2	Brain , Cortex V4
Requirements	Light	Scene Segmentation	Object Identification
Temporal Scale	(1) 60 seconds, (2) minutes, (3) milliseconds	Several minutes	Days, years

Table 1. The color constancy visual cues in the human visual system levels.

it appears achromatic. The last paradigm measures whether a surface is assigned the same color name under different illuminants. In order to report the degree of constancy achieved, all this methods measure the 'distance' between the subject's stimulus perception and the physical stimulus. Each method has its own strong and weak points, for a complete discussion see [9, 19].

Recently a new color constancy experiment was developed. It measures the boundary movement between color categories across illuminant changes [10, 18]. This experiment uses one of the last three paradigms in order to measure the perception of boundary colors.

3.2 The Laboratory Conditions

There is another useful classification among experimental paradigms: the visual environment where the property is measured. In everyday's life, color constancy is experienced in natural environments, so there is plenty of visual cues that potentially could be used. But once inside the laboratory, without all these cues, the measured color constancy is weaken [16, 19]. The big question is that we do not know exactly which are the natural relevant cues to achieve full color constancy. So there is a trade off between the naturalness of the scene and the degree of color constancy achieved and measured. When we try to translate the natural scene to a lab scene we face two problems. First we have to ensure the precise control of the illuminant spectral function and object's reflectance, while trying to keep intact the subject perceived visual cues. There are three main different laboratory setups:

1. The subject is placed in a dark room with a CRT monitor, where the stimulus is displayed [24].
2. The subject is placed in a real 3D scene and the stimulus is presented there [16].
3. The setup consists in rendering a 3D scene and present a stereo-coherent pair of images to the subject [5].

Each setting has his own requirements in order to precisely calibrate the scene colors and the subject's response. In the 'CRT setting' the stimulus can be presented in 2D, or 3D. Using RADIANCE[2] software we can calibrate correctly the presented colors in 3D rendered scenes [5, 11].

3.3 The Stimulus

The stimulus are presented to the subject along the experiment. After that, the subject's response is measured, usually by means of a electronically device with several buttons. In order to measure a single color constancy mechanism the stimulus selection and time exposure are critical factors.

3.4 The subject's task

In every psychophysical experiment a good subject instruction is the key factor to succeed in measuring the perceptual property. As reported by several authors the subjects instructions could affect the results[19, 20]. In the color constancy context there are two different questions that

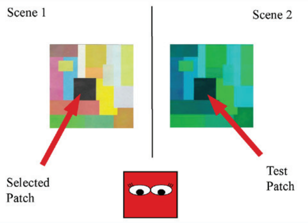
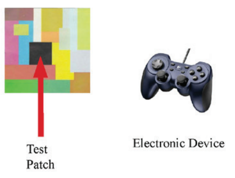
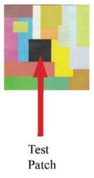
	Asymmetric Matching	Achromatic Matching	Color Naming
Lab Setting			 Color Categories: white, black, grey, green, red, yellow, blue, brown, purple, pink and orange.
Subject's Task	Match the color *Test Patch* from Scene 2 to the *Selected Patch* from Scene 1.	Transform the *Test Patch* color to achromatic using an electronic device.	Assign a color category to the *Test Patch*.

Table 2. The color constancy paradigms.

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[2] http://radsite.lbl.gov/radiance/book/

may modify the outcome. First we can ask to the subjects to make a patch on the screen ‘look as if it were cut from the same piece of paper‘ or ask to match ‘hue and saturation‘. In the first questions they show better color constancy [19].

4 Computational Color Constancy

The computational color constancy definition is more precise than the human one. Given one image, our central problem is to estimate the real object’s color coordinates in some color space. Then we can use these estimates for object recognition or color categorization. Illuminant change is a natural problem for the tasks described. Therefore there are two main computational approaches to fix these problem [22] :

- *Color Normalization* creates a new version of the image being independent through light changes.
- *Color Constancy* tries to estimate the illuminant color in order to transform the image to a canonical version of the scene reflectance.

In general, the ultimate goal of a color constancy algorithm is that the computed color for an image pixel is constant irrespective of the illuminant used [6].

The computational color constancy problem, that is illuminant estimation, is not solved. Over the last decades there has been many algorithms developed. It can be divided into two main groups: physical methods and statistical methods. The first ones are based on the fact that image must fulfill some physical properties. These methods use a more general model of image formation that the one used in the Statistical group. Statistical methods assume that surfaces are Lambertian and this group can also be split in three types:

1. Methods based in simple statistics: Grey World, White Patch, Shades of Grey and Grey-Edge.
2. Gamut Mapping methods as C-Rule.
3. Bayesian Methods as Color-by-Correlation and Voting Methods.

In order to evaluate color constancy algorithms there are two main ways: color-based object recognition and ground truth [6]. The first method evaluates the performance of color-based object recognition algorithms after applying to the image a color constancy algorithm. On the other hand the ground truth, when it is available, is much easier to check.

5 Conclusions

The human color constancy is a complex problem that needs further studies in order to completely understand all the phenomenon. But the localization of several mechanisms situated at different levels in the human visual system is a big step that allows to study each mechanism in isolation via the right psychophysical experiment.

The Computational and human color constancy processes begin with the same physical information but after this common departure their totally differ in information processing despite trying to solve similar problems. We must not forget that a digital image is not what a human has in his retina when is viewing scene. There are many differences between the two processes and the visual system is far more complex than any algorithm or camera device. Also we must remember that the visual system has two eyes, and so two visual approximations for the same scene, and that does not happen in the computational field where we only work with one image. So the two problems are modeled essentially in different ways.

When the final aim is the same, it seems natural to build an algorithm that mimics the human visual system. This algorithm should follow a human based design in a functional level. This means that it should have sensory, perceptual and cognitive levels. The bulk of the computational color constancy algorithms do not use these scheme, despite trying to get out the same perceptual effect. This implies the combination of multiple cues including the scene geometry, and not only the chromatic content of the images. This idea points to a new lines of research in the computational color constancy field.

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