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ABSTRACT

This year, at Electronic Imaging 2013, as part of the "Color Imaging XVIII: Displaying, Processing, Hardcopy, and Applications" and "Human Vision and Electronic Imaging XVIII" conferences, we hold the fifth annual special session entitled, "The Dark Side of Color". This session aims at introducing innovative thinking, opening discussion from experts working in a wide range of disciplines related with color, fostering ideas and stimulating ongoing issues and revealing common misunderstanding in color science and technology. It is comprised of a limited number of invited short presentations that are presented as summaries in this paper together with an overall description of the session point of view.

Keywords: Dark side of color, Color, Color models, Color teaching, Colorimetry, Vision, Color related phenomena

1. WHAT THIS SESSION IS ABOUT

Color is a very complex phenomenon that cannot be explained with only physics principles. The human vision system is what transforms the physical stimuli into the colors we see.

Color related topics are often taught and communicated without presenting their inner complexity, their limits and the simplifications that generally are taken at some point. Dealing with color is usually reduced to the automatic and repetitive use of pre-defined "recipes" and this can lead to the risk of loosing the overall framework and consequently a correct understanding of the technique to use.

Classic colorimetric methods, specifically designed to deal with color in aperture mode (isolated, out of visual context), have become dominant in digital color science and technology. Their use has been extended to deal with a great variety of situations in which color is considered within a visual context, thus outside of its initial scope. Color science is facing this transitional evolution in order to deal with color in context and appearance, but without substantial changes in their original foundation.

There is a need for widening the scientific debate and discuss about paradigms. This can be achieved by, for example, new questions, different attention for details; information in the margins that so far are often discounted or overlooked. These aspects are what we consider to be the "dark side of color".

The invited speakers of this session have been asked to stimulate ideas and discussions on the needs and the characteristics of possible alternative approaches and/or point of view. This session aims at suggesting paradigm shifts, lateral thinking and bottom up experimentation by re-addressing the current state of the evolving situation in color in sciences, arts and technologies.

Following these principles, every speaker has chosen a topic of his/her preference and presents open issues and problems in a short 15-minutes presentation. The presentation abstracts are reported in the following paper to give the reader a glance on the discussed topics.

We would like to stress that basically no answers are expected to arise from the presentations of this session, but more likely questions and perspective shifts.

2. THE SPEAKERS

Here are the abstracts of the speakers that will participate at this Dark Side of Color session.

2.1 "Can trichromats really know what dichromats see?" Michael H. Brill, Datacolor (United States)

Can trichromats really know what dichromats see?

Presumptively the answer would be "yes", judging from several algorithms and software applications that simulate the appearance to a dichromat of any given trichromatic image[1-4]. My purpose here is to challenge that presumption.

We know what sets of tristimuli are matches for each kind of dichromat. The confusion loci are parallel line segments through tristimulus space. But that says nothing about how to map the appearance of a dichromatic color on the appearance from a trichromatic space. It is not even necessary for the dichromatic appearance of a light to match the trichromatic appearance of one of the lights on a confusion locus. So how can one make the map?

On one level, the question devolves to the classic philosophical conundrum of my not being able to know if I see the same blue that you do. The situation is saved to some extent by the existence of unilateral dichromats. There the appearance matches between the dichromatic eye and the trichromatic eye promise to be a legitimate "Rosetta Stone". Indeed, unilateral dichromats depose the naïve model of a dichromat's color always having the appearance of one of its confusion aliases in trichromatic vision. But to be trustworthy, color-appearance matches must be made *cetera paribus*---that is, all other variables being equal. The spatial context of a scene always affects the appearance of a color in that scene, and the contexts themselves cannot be equated between a dichromat and a trichromat. You would have to ask the unilateral dichromat to match all the colors in all the possible scenes in your universe to be sure that you had a good simulation. An additional complication is that unilateral dichromats are so rare that we cannot be too fussy about assuring that the trichromatic eye is really "normal." Finally, the colors dichromats see can be as unstable as Gestalt effects like the Necker cube. If you still want to predict and simulate what dichromats see, you have truly passed…to the Dark Side of the Color.

2.2 "Color scales for visualization: traveling though color space" Bernice E. Rogowitz, Visual Perspectives Consulting (United States)

Color is often used to represent data in visualization and imaging. A colormap, for example, maps numerical values onto a color scale. Each color scale is a trajectory through a three-dimensional color space. But, which trajectories are the best? A popular idea is that any trajectory where equal steps in the data correspond to equal steps in the color space is sufficient to produce a good result. According to this hypothesis, equal steps around the hue circle or equal steps in luminance should produce equally good colormaps. This talk challenges this assumption and provides insight into other perceptual factors at play.

2.3 "Color spaces" Jan J. Koenderink, Technische Univ. Delft (Netherlands)

Is there a preferred way to map colors in some space? The question as such makes little sense, it is bound to have very different answers in various settings. Historically, the settings were determined by scientific considerations, mostly drawn from physics. These included extreme constraints on viewing conditions, and (by their very design) yielded

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important data for psycho-physiology, but were utterly irrelevant to "vision in the wild". Later work in experimental psychology only slightly relaxed the constraints, admitting minor structural complexity in spatiotemporal parameters, and slightly relaxed viewing conditions. Studies on vision in the wild remain rare, even today.

The most extreme conditions involved comparison of beams differing in spectral composition alone. Of course, this is impossible, but one forced consistency by mutual agreement on spatiotemporal parameters. In such cases the problem was soon solved once and for all. For generic human observers "colors" are affine subspaces of the space of radiant power spectra, an infinitely dimensional Hausdorff space. There is a single invariant, which is the "black space", which (for most people) has co-dimension three.

The psychological approach led to a number of phenomenological spaces, essentially canonizing the results of "eye measure". The Munsell space is perhaps the best known instance. In retrospect one fitted various colorimetric parameters to the eye measure results. The most widely used of such mongrel systems is perhaps the CIELAB system.

Attempts to arrive at a non-trivial color space from first principles have been rare. There were a few attempts starting from physiology, and a few starting from colorimetry. Among the latter were Ostwald's color atlas, which does not depend upon eye measure, but on pure colorimetry, and Schrödinger's theoretical attempt.

Is it at all possible to construct a useful color space from first principles? It depends on what may count as "first principles". If one only includes physics, then one is done with the complement of the black space in the Hausdorff space of spectra. This is evidently less than what is desirable. What has to be added to the "first principles" in order to arrive at interesting structures? Here one has a choice. One obvious choice is to pick some spectrum as the "achromatic source". This makes sense from an evolutionary perspective. Color vision is likely to promote you to detect deviations from the generic source. An important range of such deviations is due to spectrally selective scattering by surfaces. In the simplest case one deals with a set of "object colors", which in a given illumination and viewing geometry, have spectra that have the spectrum of a "white" object as common envelope. A "white object" is simple a Lambertian object of unit albedo. Color vision is then understood as a system that differentiates between object colors in some consistent and optimal way.

This yields sufficient structure on which to erect an interesting color space. The spectra of all object colors fill a hypercuboid in the space of spectra. Modulo the black space one obtains Schrödinger's color solid. Of course, the color space one obtains only exists up to arbitrary linear transformations, and lacks a canonical basis. However, this is easy to remedy. Since ratios of volumes are affinely invariant, it makes sense to look for a basis such that the unit cube (as defined by the basis) exhausts as much of the color solid as possible. This turns out to admit of a unique solution. Then, representing this basis as an orthonormal triad, one obtains a unique representation. It depends only on the black space (of course), and on the achromatic beam.

In this representation the color solid is very close to a cube, a "slightly inflated" cube. Color coordinates are largely in the range 0...1, with few and minor exceptions. The basic vectors lie on the boundary of the color solid, they are "optimal colors", with reflection spectra that toggle at most two times between zero and one throughout the visual spectrum. Together they exhaust the spectrum of the achromatic beam. They represent the short wavelength, medium wavelength, and long wavelengths of the spectrum. Thus the color coordinates represent the blue, green, and red components of a color. It is a spectral representation in three bins. Although a colorimetric (not eye measure) construction, the color coordinates have immediate intuitive meanings.

Since this representation is metric by design, it allows one to mensurate the color circle. Remember that the color circle is the locus of "semichromes", that are the colors on the boundary of the color solid that are as distant from the black-white axis as possible. One obtains a system that is very much like that of Ostwald, and differs from the conventional Munsell system by amounts that are similar to the difference one finds between the various eye measure systems (the Munsell system being just one among many). The symmetries of the RGB-cube (and thus the color solid in the canonical representation) also allow one to define "opponent colors", "warm" and "cold" color families, and so forth in a natural manner. The cone action spectra enter only by way of the black space, thus this representation is psychophysical, rather than psycho-physiological.

This color space is "natural" also in the sense that, if you plot the color coordinates as RGB- values on a standard RGB-display, you obtain a rendering that fulfills most expectations. This recommends such a system for applications oriented areas. It avoids numerous conventional definitions (which tend to appear as so much mumbo jumbo to the uninitiated), and yields a parameterization that is intuitive, and is immediately fit for many jobs.

2.4 “You can't rely on color, yet we all do” Floris L. van Nes, Technische Univ. Eindhoven (Netherlands)

Color is one of the most salient features of the visual field. Being thrilled by color, man early in his development learned how to use it, as for body paint – which continued in fashion, art, for painting artefacts. In a way, man relied on color, for embellishing and later, when coding was invented, for attaching meaning to objects having a certain color.

However, this magnificent property of all objects around us is also elusive, as soon as you want to really specify it. Notwithstanding perceptual phenomena such as color constancy one has to cope with (i) dependence of all surface colors on the color of illumination; (ii) the fact that it is not easy for one person to communicate the precise color of an object to another person – especially of the opposite sex; (iii) observing that colors from visual displays are often strongly desaturated by surround light. To mention but a few. And all this is rather poorly understood, if at all, by the general public. Sometimes even by people who are reasonably knowledgable in visual matters, such as visual ergonomists or display engineers. After all, it is not a rare occurrence that multi-colored texts, in print or on slides shown by visual scientists are illegible because the text foreground and background colors were ill-chosen.

But color is so important that people can hardly avoid to 'rely on color' – so they do. They rely on its predictability; when they buy clothes via the internet, for instance, or select a holiday destination from an alluring landscape picture on a calendar.

As to professional users: designers of modern electronic visual displays need to master many fields; colorimetry of one kind or another being one of them.

My experience of several decades has taught me that dealing with colors on displays always turned out to tax most writers of ergonomics display standards heavily – as well as the professionals in display manufacturing. Because, the organization responsible for the agreed standards for specification and measurement of all dimensions of color , the *Commission Internationale de l'Éclairage, (CIE)*, has for a long time now created chromaticity diagrams and color spaces that are complex and far from easy to use by 'practitioners' in the color display industry, and the writers of standards for their products.

Of course, quantifying facets of color is a difficult thing to do. Yet, there are many people who would applaud CIE if this illustrious organization would devote a part of its energy to the development of a color specification and measurement system with a simpler yet easily usable color space than, for instance, CIECAM02 – or its successor that may already be waiting in the wings. Perhaps CIE then should resort to the well established ergonomics method of user involvement, the users being color science practitioners. Furthermore, it would be revolutionary but recommendable if an international organization such as the CIE would start an effort to educate the population at large better in color matters. One group that could benefit from such an action are color-defective viewers. Time and again they are the victim of inappropriate color choices for all sorts of products that have been color-coded, sometimes for important information in terms of health or safety, by people who have normal color vision but lack knowledge on its intricasies, and who therefore are naive as to the perception of these choices by those with color vision abnormalities.

2.5 “How 'high-level' is human color perception? Michael E. Rudd, Univ. of Washington (United States)

Contemporary theories of human color vision invoke a large array of perceptual mechanisms, ranging from ‘low-level’ neural mechanisms like the relative quantum catches in the three cone photoreceptors to “’high-level’ cognitive mechanisms that rely on Bayesian priors and other, less easily quantified, cognitive principles. The color space models that are often used to quantify and predict color percepts in technological applications—like CIE—are closer in spirit to low-level models. A glaring deficiency of both color space and low-level physiological models of color vision is their inability to account for the strong effects of spatial context on color appearance. How “high” do we need to go to capture significant aspects of a spatial context in our theories? Is it possible to do so in a satisfying way without sacrificing the quantitative precision of the low-level models? I begin by giving some examples of approaches to color based on several different levels of perceptual analysis, from the low-level to the high-level. Then I discuss by own recent work, which attempts to explain how color percepts are constructed by the brain from information about achromatic and chromatic borders. The approach has much in common with the Retinex theory of Land and McCann, but it expands the domain of Retinex to include prior knowledge and top-down influences on color matches in addition to other physiologically-motivated "tweaks" such as the inclusion of contrast gain control between edges and distant-dependent weighted spatial integration of oriented contrast. I give some examples of how the model accounts for quantitative properties of color that are not explained by alternative models currently finding broad use in industrial settings. I close by suggesting ways in which the models that I am developing could inform the development of new classes of algorithms for both image compression and display design.

2.6 **"Complex spatiochromatic interactions in a real world art laboratory"** Scott Daly, Dolby Labs., Inc. (United States)

Andy Goldsworthy is an environmental artist whose theme for several decades has been the artistic manipulation of in situ natural materials to form impermanent outdoor sculptures. One common thread is the re-organization of objects by their color, turning natural and consequently more random distributions into highly ordered arrangements. In doing so, the colors of the natural materials seem to change as a result. The real-world artwork invokes various physical and perceptual phenomenon, serving as laboratory for color science. In this talk, we will take one these artworks, titled *St. Abbs, the Borders, 1985,* and qualitatively investigate the physical and perceptual contributors to the intriguing effect. These processes range from atmospheric haze, multiple reflections, spatiochromatic CSF, white-point anchoring, chromatic induction, etc. They will be abstracted in an attempt to create a two-dimensional synthetic version of the essence of Goldsworthy's three-dimensional natural chromatic illusion.

3. THE PREVIOUS DARK SIDE SESSIONS

Here is a list of the speakers and topics that have participated at the previous Dark Side of Color sessions.

3.1 **The dark side of color I** (2009)

"Well asked questions" Reiner Eschbach
"Pictorial information as transcribed by the artist or designer" Stephen Hoskins
"Consider the Size: And Other Display Features" Garrett M. Johnson
"Adaptation! … What Adaptation?" John McCann
"The Opposite of Green is Purple?" Nathan Moroney
"Now...what color was that again?" Sabine Süsstrunk
"Stepford – the city for Colour Engineering" Stephen Westland

3.2 **The dark side of color II** (2010)

"Color naming: color scientists do it between Munsell Sheets of Color" Giordano Beretta and Nathan Moroney
"Size matters: The problem of color-difference estimation for small visual targets" Robert C. Carter and Louis D. Silverstein
"Controlled versus uncontrolled viewing conditions in color evaluation" Reiner Eschbach
"Mind over Matter" Jennifer Gille
"Globalization of color" Paul Hubel
"The appearance of illusions and the delusion of reality" John McCann

3.3 **The dark side of color III** (2011)

"The Color Side of Dark" Raja Bala
"What a bad signal from this strange device!" Alessandro Rizzi
"HDR Imaging and Color Constancy: Two Sides of the Same Coin?" John McCann
"Is the future of digital printing paperless?" Giordano Beretta, Eric Hoarau, Jun Zeng

"Can less be more?" Jan Allebach
"Can displays go wild?" Gabriel Marcu

3.4 **The dark side of color IV** (2012)

"The dark side of CIELAB" by Gaurav Sharma and Carlos Eduardo Rodriguez-Pardo
"Complexitites of complex contrast" by Eliezer Peli
"It's not the pixel count, you fool" by Michael A. Kriss
"Color imaging and aesthetics: is there the cheshire cat ?" by Elena A. Fedorovskaya
"Dark texture in artworks" by Carinna E. Parraman
"Harmonious colors: from alchemy to science" by Giordano B. Beretta, Nathan M. Moroney

4. REFERENCES

1. H. Brettel, F. Vienot, and J. D. Mollon, Computerized simulation of color appearance for dichromats, J. Opt. Soc. Am. A 14, 2647-2655 (1997).
2. P. Capilla, M. A. Diez-Ajenjo, M. J. Luque and J Malo, Corresponding-pair procedure: a new approach to simulation of dichromatic color perception. J. Opt. Soc. Am A 21, 176-186 (2004).
3. H. Kotera, A study on spectral response for dichromatic vision, Proc. 19th IS&T Color & Imaging Conference, pp. 8-13 (2011).
4. http://www.vischeck.com/daltonize/