This is a preprint of

Paper 7241-26 in SPIE/IS&T Electronic Imaging Meeting, San Jose, January, 2009

Colour Appearance and Colour Rendering of HDR Scenes: An Experiment

Carinna Parraman,*[a] Alessandro Rizzi,[b] John J. McCann[c]
[a]Centre for Fine Print Research, University of the West of England,, Bristol, BS3 2JT
[b]Dip. Tecnologie dell'Informazione - Università degli Studi di Milano, 26013, Crema (CR), Italy
[c]McCann Imaging, Belmont, MA 02478 USA

Colour Appearance and Colour Rendering of HDR Scenes: An Experiment

Carinna Parraman,*[a] Alessandro Rizzi,[b] John J. McCann[c]
[a]Centre for Fine Print Research, University of the West of England,, Bristol, BS3 2JT
[b]Dip. Tecnologie dell'Informazione - Università degli Studi di Milano, 26013, Crema (CR), Italy
[c]McCann Imaging, Belmont, MA 02478 USA

ABSTRACT

In order to gain a deeper understanding of the appearance of coloured objects in a three-dimensional scene, the research introduces a multidisciplinary experimental approach. The experiment employed two identical 3-D Mondrians, which were viewed and compared side by side. Each scene was subjected to different lighting conditions. First, we used an illumination cube to diffuse the light and illuminate all the objects from each direction. This produced a low-dynamic-range (LDR) image of the 3-D Mondrian scene. Second, in order to make a high-dynamic range (HDR) image of the same objects, we used a directional 150W spotlight and an array of WLEDs assembled in a flashlight. The scenes were significant as each contained exactly the same three-dimensional painted colour blocks that were arranged in the same position in the still life. The blocks comprised 6 hue colours and 5 tones from white to black.

Participants from the CREATE project were asked to consider the change in the appearance of a selection of colours according to lightness, hue, and chroma, and to rate how the change in illumination affected appearance. We measured the light coming to the eye from still-life surfaces with a colorimeter (Yxy). We captured the scene radiance using multiple exposures with a number of different cameras. We have begun a programme of digital image processing of these scene capture methods. This multi-disciplinary programme continues until 2010, so this paper is an interim report on the initial phases and a description of the ongoing project.

Keywords: Education on imaging systems, colour constancy, image processing, scene renditions, visual appearance, high-dynamic range (HDR) imaging.

1. INTRODUCTION

Time and effort is often undertaken to attain a high-dynamic-range (HDR) record of scene radiances that is intended to correspond to the real scene as closely and as accurately possible. However, device limitations can often constrain the luminance range and chromaticity value that can be captured and displayed. The intention of this presentation is not to dwell on the problems of gamut mapping, but to concentrate on how local and global changes in processing the image information can be important to achieve a similar appearance between a real scene and its reproduction.

The experiments comprise a still life arrangement with two different lighting conditions: the first contains a limited dynamic range, such as a standard indoor scene with a diffused uniform light using an illumination cube; the second scene contains a high dynamic range, that has directed spot lights and light reflected from coloured surfaces. For each of the two scenes a series of reference points are identified, which are representative of the different luminance range, and are widely stepped and belong to visually noticeable areas. The reflectances and radiances of these areas were measured.

This paper begins with a discussion of the rendering intent of reproductions (Section 2). The next section describes the CREATE interdisciplinary programme (Section 3). We describe the 3-D Mondrian and its illuminations in Section 4. The next step in the programme is to ask the workshop participants to study the changes in appearance caused by the LDR and HDR illumination (Section 5). We describe multiple-expose scene radiance capture in Section 6. The scenes were captured by a range of input devices, which included a high quality Leaf Aptus with a Mamiya body and a wide range of digital cameras, as well as a reflection and transmission silver-halide film cameras. In Section 7 we describe ongoing image processing of these images to digitally render the LDR and HDR scenes. The goal of the project is to produce a series of different renditions of these two scenes by using many different imaging techniques and to evaluate their similarities and differences.

A discussion about the found relationship between luminance and chromaticity values, compression and final visual appearance will conclude the paper. We will present the preliminary results in this paper. Since the project continues until 2010, we will present the complete report in future EI Colour meetings.

2. LEARNING TO USE COLOUR

For artists, the skills for the transcription of colour sensations onto canvas or paper evolved by copying and learning from the master artist, and skills were entrusted through the generations from master to apprentice. Early publications such as *Il Libro dell'Arte* (*The Craftsman's Handbook*) by Cennino Cennini written around 1390, describes the use of colour as 'the glory of the profession' [1] providing practical advice, for example, on which colours to choose to describe the folds of drapery. Whereas Cennini's manual is instructional, Alberti's book, *Della Pittura* (*On Painting*) (1435-6) provides an early insight into the phenomena of colour, for example, how colours interact when placed next to each other. Giorgio Vasari (1511-1574), in Vasari's *Vite de' più eccellenti architetti, pittori, et scultori Italiani* 1550-68, (*The Lives of the Most Outstanding Italian Architects, Artists and Sculptors*) provides a detailed account of artists' studies of colour in painting and in 'imitation of nature'. Similarly, Leonardo da Vinci's (1452-1519) *Notes on Art* provides a very detailed analysis on the use of colour [2]. For example, he suggests how a 'red also will seem most vivid when against a yellow background' (p.275) or that even the direction of the sun effects of the degree of brilliance of the greens in the meadows (p.288).

In the 20th and 21st century, as part of a traditional formal training in art and design, all apprentices would have undertaken practical sessions on how to mix and spatially compose colours, in order to understand colour relationships and harmonies in painting from nature to convey a realistic and pleasing image. Most artists or designers would be knowledgeable about how to construct a colour wheel but probably less aware of the historical background. Some of the most influential colour studies were undertaken at the Bauhaus School in Weimar, which was founded in 1919 by Walter Gropius. Under its curriculum the study of colour was approached scientifically, with a practical objective for art, design and industry [3] Bauhaus instructors Wilhelm Ostwald (1853 -1932), Josef Albers (1888 –1976) [4] and Johannes Itten (1888-1967) [5], all produced detailed colour systems that combined practical, philosophical and technical publications on colour.

Digital world of today has not changed the inner nature of colour, but only changed the way we deal with it. From the context of digital photography, digital imaging and printing, users require access to tools in order to modify or correct images, which might include corrections to the colour, colour balance and tone. Yet, at what point can an image be considered to be correct? One can suggest also that similar tools were required for traditional analogue photography, and it was the intervention of the artist to obtain the desired emotional response, through different camera exposures, manipulation of the negative and printing to paper.

This paper aims to deepen the mechanism undergoing a satisfactory scene reproduction. To begin, it is important to distinguish between camera response and human colour response. Cameras count photons. In all but a few electronic cameras the quanta catch at a pixel on the sensor determines the final response of the camera. All pixels with the same quanta catch of photons have the same response. Human vision is markedly different. Identical quanta catch at the receptor can result in any colour appearance. For humans, there are in fact many different ways to analyse colours between the light from a scene coming to the observer's eye and the observer's response to the information. Failure to understand the different processes often causes great confusion.

First, there is the physical description of light that measures the radiant energy at each wavelength. In essence the physical description counts the photons coming to the eye; vision is not involved. Second, there are colorimetric engineering standards that attempt to calculate the visual response to those photons. These standards include luminance (V) and colour matching functions (XYZ), CIELAB, CIELUV, CIECAM. Although their goal is to calculate appearance they all require separate measurements of the reflectances of objects and the illumination at each pixel in the image. They cannot calculate the appearance of an object in a scene from just the photon count at a pixel. Third, following the ideas of the Scottish philosopher Thomas Reid [6], there is the measurement and calculation of colour sensations. These involve the measurements of appearance of objects in complex scenes and measurements of the array of photons over the entire scene. Here the goal is different from colourimetry - that assumes no information about illumination and reflectances. Instead it attempts to calculate appearance from the spatial information in the photon arrays. Fourth, there is the perceptual analysis of the coloured image involving the use of prior experience to recognize the content of the image. Finally, there are the aesthetic uses of colour and spatial relationships to convey emotional information.[7]

It is necessary to consider each of these issues separately, as for example, one should not try to evaluate the emotional impact of a particular triplet CIEXYZ values. These values can be used to predict other mixtures of photons that will match, but cannot predict which colour those matches will appear [8- 9]. The artist uses the appearances of patches of image pixels to generate the emotional responses to the image. The artist is unaware of the luminance and chromaticites of the group of photons coming to the eye.

There are many reasons and requirements that can range from the point of view of an aesthetic judgement, to convey a particular mood or emotion, or based on accuracy, which can be considered from two viewpoints: the first is based on the physical distribution of light and might require colorimetric and photometric comparison and measurement, the second considers appearance, a judgement of the scene that is based on perceptual creation of the scene that, similar to the old master painters, presents an interpretation of what is seen. Our perception, in most circumstances, does not coincide with physical measurement devices. In this paper we intend to focus on the relationship between the two aspects of the accuracy of image rendering. Should the image reproduce the scenes' photon count, or portray the artist visualization of the image? (Adams) [8-11].

How to describe and measure colour appearance is a problematic activity; there can be a considerable difference between how the radiometry of colour is measured and how the appearance of colour is perceived. For contemporary colour science, there is a requirement to accurately measure and specify a colour. However when looking at art, at photographs and at real life situations, attempts to define what we 'see' are more complex. Pixels with identical radiances can appear as radically different colours. How do we obtain a balance between what is there in reality and an appropriate interpretation of reality through colourants (dyes, pigments, inks) onto a surface (paper, canvas, film)?

Today, this formal training has taken on greater significance as artists and designers are required to demonstrate colour harmony and mixing that extends beyond paint, but to consider electronic arts, digital colour and publishing for the web. This method of colour mixing is considerably different to subtractive colour mixing of printing and painting, and requires extensive knowledge and understanding of additive colour systems.

Moreover, the interplay of imaging devices with human vision can be seen very clearly at the interface of high-dynamic range imaging and colour constancy. Humans are very good at sensing their visual environment in both high-dynamic range (HDR) and low dynamic range (LDR) scenes. Humans are largely indifferent to both the amount and spectral distribution of a scene's illumination. Camera sensors are different. Each image segment has a fixed response to the intensity and spectral composition of the light falling on them. Cameras have to incorporate additional mechanisms for automatic exposure, automatic colour balance, tone-scale mapping and HDR image processing in order to render images that approximate the human response to scenes. The best capture and re-rendering of HDR scenes are undertaken by artists who simply paint the appearances they see.

3. BACKGROUND TO THE EXPERIMENT: THE CREATE PROJECT

These experiments were a part of a recent CREATE event, which was hosted by the University of the West of England in Bristol.

The project CREATE, which stands for Colour Research for European Advanced Technology Employment, is funded by the European Union, Framework 6 Marie Curie Conferences & Training Courses (SCF). The aim is to develop an international cross-disciplinary community within the areas of science and technology and the arts and commerce that could exchange both practical and theoretical knowledge. The intention is to foster novel ideas within a group of professional scientists and artists. (www.create.uwe.ac.uk)

The objective for the four-year project is to co-ordinate a series of themed conferences and training courses that bring together research communities to share, discuss, and teach, and build on the particular expertise of a range the collaborating institutes and experts. The participants are researchers who are in the early stages of their career.

3.1 Instructions given to the participants

The CREATE programme is part demonstration, part experiment and part interdisciplinary exploration of many issues in scene capture, image processing and rendering. The experiment, given during the recent programme, used two identical sets of painted wooden blocks in two different illumination environments. These two 3-D Mondrians were each positioned in a still life scene, placed side by side so that observers and photographers could compare them directly. The only difference was the illumination of each scene, which is described in more detail in Section 4.

Before taking the experiment, the background and rationale was presented to the participants. A description of the two three-dimensional still-life scenes was provided, which included the reasons why each illumination was chosen and their characteristics. Differences and similarities were also highlighted between the images that were captured in advance and the perception as a result of gazing at the scene.

4. SET UP OF THE EXPERIMENT

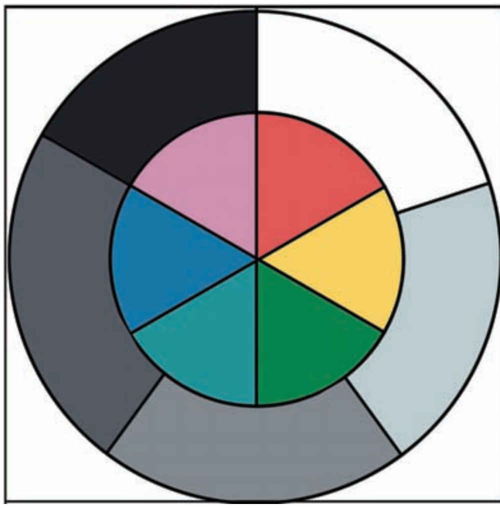
The experiment used two identical sets of objects in uniform and non-uniform illumination in the same room at the same time. Each of the flat surfaces had one of 11 different paints applied. Figure 1 shows photographs of the two scenes.

Figure 1a) shows the low-dynamic-range (LDR) scene on the left, and 1b) a high-dynamic-range (HDR) scene (right).

4.1 Characterisation of the paints for the 3-D Mondrians

Figure 2 (left) shows a circular test target with 11 painted sections. The inner circle has red (R), yellow (Y), green (G), cyan (C), blue (B), and magenta (M) paints. The outer circle has white (W), light grey (G7.5), midgrey (G6), dark grey (G4) and black (K) paints.

Figure 2 (right) lists the Munsell chip closest to each paint. This evaluation was undertaken by placing chips on top of the painted sample. In addition, the figure lists the colorimetric values Yxy measured from this text target in the uniform illumination scene. We made these measurements with a Minolta C100 meter.



Name	Munsell	Y	x	y
R	2.5R 4/14	43.2	.631	.335
Y	2.5Y 8/14	105.0	.553	.429
G	10GY 5/12	29.7	.370	.547
C	10BG 6/8	39.9	.350	.434
B	5PB 4/12	20.6	.351	.350
M	10P 6/10	65.1	.520	.359
W	N 10/	156	.464	.417
G7.5	N 7.5/	76.3	.456	.418
G6	N 6/	44.5	.456	.418
G4	N 4/	21.2	.452	.416
K	N 1/	9.12	.462	.413

Figure 2 shows the painted flat test target, along with the paints designation, its Munsell designation and the luminance and chromaticities measured on the back wall of the LDR display.

4.2 Characterisation of Illumination

Figure 3 shows the arrangement of the illumination. On the left the illumination was as diffused and uniform as possible. The blocks were placed in an illumination cube. It had a white floor, a translucent top and sides, and a black background. We directed eight halide spot-lights on the sides and top of the illumination cube. The combination of multiple lamps, light-scattering cloth and highly reflected walls made the illumination nearly uniform. Departures from perfect uniformity came from shadows cast by the 3-D objects, and the open front of the cube for viewing. This 3-D Mondrian was the low-dynamic range (LDR) scene.

Figure 3 (right) shows the highly directional illumination provided by two different lights. One was a 150W spot light place to the side of the 3-D Mondrian at the same elevation. It was placed 2 meters from the centre of the target. The second light was an array of WLEDs assembled in a flashlight. It stood vertically and was placed quite close (20 cm) to the display to the left. Although both are considered variants of white light they have different colour appearance.

The placement of these lamps produced highly non-uniform illumination and increased the dynamic range of the scene. When comparing the two scenes, the most striking differences were in the shadows. In the uniformly lit scene (figures 1a and 3a), the shadows were soft and had no obvious colour cast. Whereas in the high dynamic range (figures 1b and 3b), the cast shadows appeared to contain blue and pink and purple. This was an observation made by Goethe [12] that shadows could be coloured, which was later tested by Land. (Sorensen)[13].

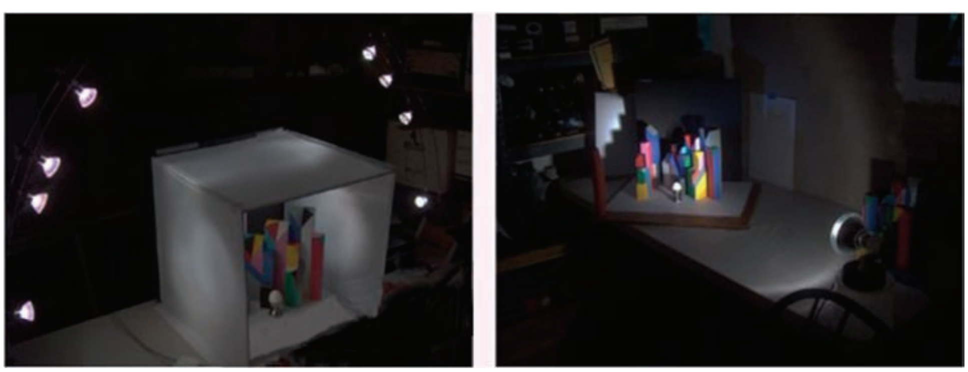


Figure 3a shows the low-dynamic-range (LDR) illumination on the left, and in 3b the high-dynamic-range (HDR) illumination on the right.

In the HDR 3-D Mondrian, the black back wall had a 10 cm circular hole cut in it. Behind the hole was a small chamber with a second black wall 10 cm behind the other. We placed the flat circular test target on the back wall of the chamber. The angle of the spotlight was selected so that no direct light fell on the circular target. That target was illuminated by light reflected from the walls of the chamber. The target in the chamber had significantly less illumination than the same paints on the wooden blocks. The presence of the target in the chamber significantly increased the luminance range of the non-uniform illumination target. However, human observers had no difficulty seeing the circular target.

5. CHARACTERISATION OF APPEARANCES

Each CREATE participant was invited to view and analyse the HDR and LDR Mondrians side by side. They were given a four-page form that identified a selection of areas in the displays (see Fig. 4). The observers were shown a painted circular test target in the floor of the display, in uniform light. This standard was explained to be the appearance of ground truth. They were told that all the flat surfaces had the same paints as the standard. They were asked if the selected areas had the same appearance as ground truth. If not, they were asked to identify the direction and magnitude of the change in appearance. The observers recorded the estimates on the forms. Due to time restrictions, the observers made these observations once only. The observer data is more a survey than a detailed set of psychophysical measurements. It served a dual purpose, as it provided data for measuring the changes observed in the LDR/HDR Mondrians, yet more importantly, it asked the participants to observe and analyse the colour shifts in the Mondrians. Such observations are crucial to understanding the role of the human visual process in our visual environment. These observations are essential in evaluating the guiding principles in image rendering. If all the objects painted with the same paint looked identical, then image rendering algorithms must fully discount the illumination. On the other hand, if shadows and inter-image reflections change the appearance of the coloured paint the strict formalism of reflectance and illumination are inappropriate for vision. The whole question of top-down vs. bottom-up colour constancy can be very effectively studied using these displays. During these experiments we asked each observer to identify if the appearance of paints changed with illumination, and how much it had changed.

5.1 Experimental details

We divided observers into small groups. We placed the ground truth reference display horizontal in front of the 3-D Mondrian. The ground truth reference was an identical copy of the paper painted with the same paints described in Figure 2 on the back wall of the 3-D Mondrian. Participants were asked to estimate the colour appearance of particular colour patches (Figure 4). There were four sheets containing 72 different colour patches to compare, and a sheet providing an explanation on how to estimate lightness, hue and chroma shifts. (Section 5.2.)

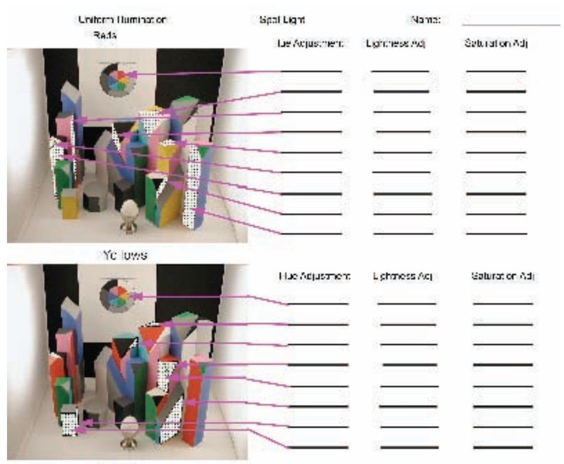


Figure 4. An example of the sheets identifying the colours required for comparison.

5.2 Magnitude estimates of luminance, hue and chroma changes

Observers estimated lightness differences on a Munsell-like scale indicating either increments and decrements, or the apparent lightness (Figure 5).

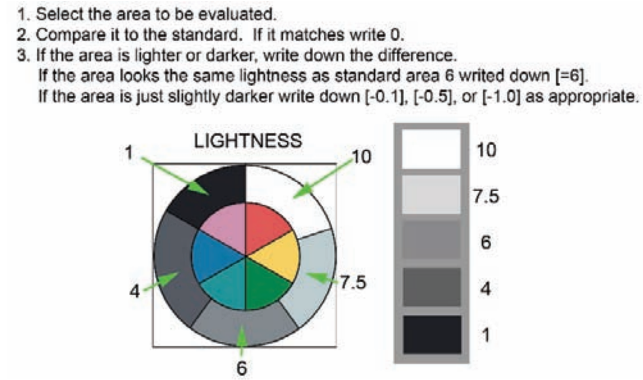


Figure 5. Description of how to estimate changes in lightness.

Observers were asked to estimate hue changes starting from each of the six patches of colours [R, Y, G, C, B, M]. Participants were asked to consider the change in the hue as a percentage difference between the original hue R and the hue direction Y. For example, 50%Y indicates a hue shift to a colour halfway between R and Y (Figure 6). 100%Y meant a complete shift of hue to Y.

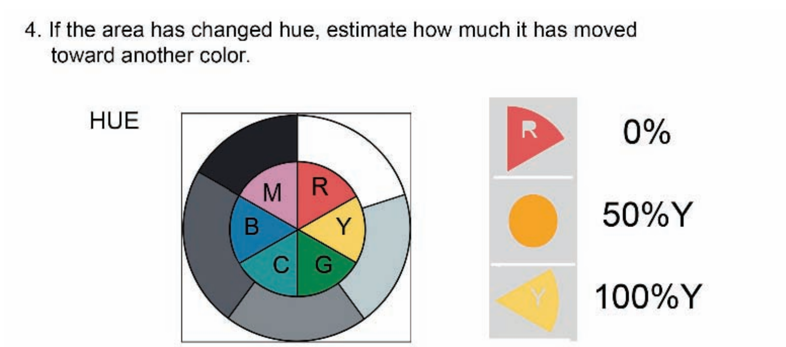


Figure 6. Description of how to estimate hue changes

Finally, we identified chroma = 100% as identical to the reference colours [R, Y, G, C, B, M]. We also identified chroma = 0% as completely washed out, achromatic grey. Observers used values greater than 100% to describe more saturated appearance than the reference (see figure 7).

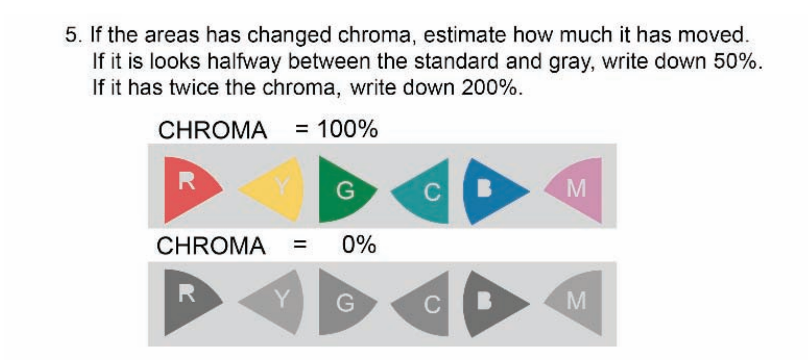


Figure 7. Description of how to estimate chroma differences

5.3 Observed Results.

In all there were 33 participants who completed the survey of 72 painted surfaces. The data was collected in mid October, and the analysis of those magnitude estimates is ongoing. Results will be presented at the meeting.

There are a variety of very different ways to calculate appearance for a complex image. One group of methods are extensions of colorimetry, such as CIECAM models. Despite their complexity, these calculate only the predicted appearance of a pixel, given both the spectral radiance distribution of light coming to the observer, and the spectral distribution falling on the object. A second group of models analyses the information from all the pixels in the image in order to estimate the illumination, and to discount it. These processes, when successful, calculate the reflectances of the surfaces of objects. The third group of models attempts to calculate appearance. This group is uninvolved in illumination and reflectance, but rather uses edges and gradients to synthesize images that match what humans see [16].

These 3-D Mondrians provide an excellent test bed for evaluating these approaches to colour appearance. Figure 8 shows a region of the 3-D Mondrian that has white paint. In the HDR illumination observers reported white, gray, pink and yellow appearances from the same white reflectance. The discrepancies from white were caused by shadows and light reflected from coloured surfaces.

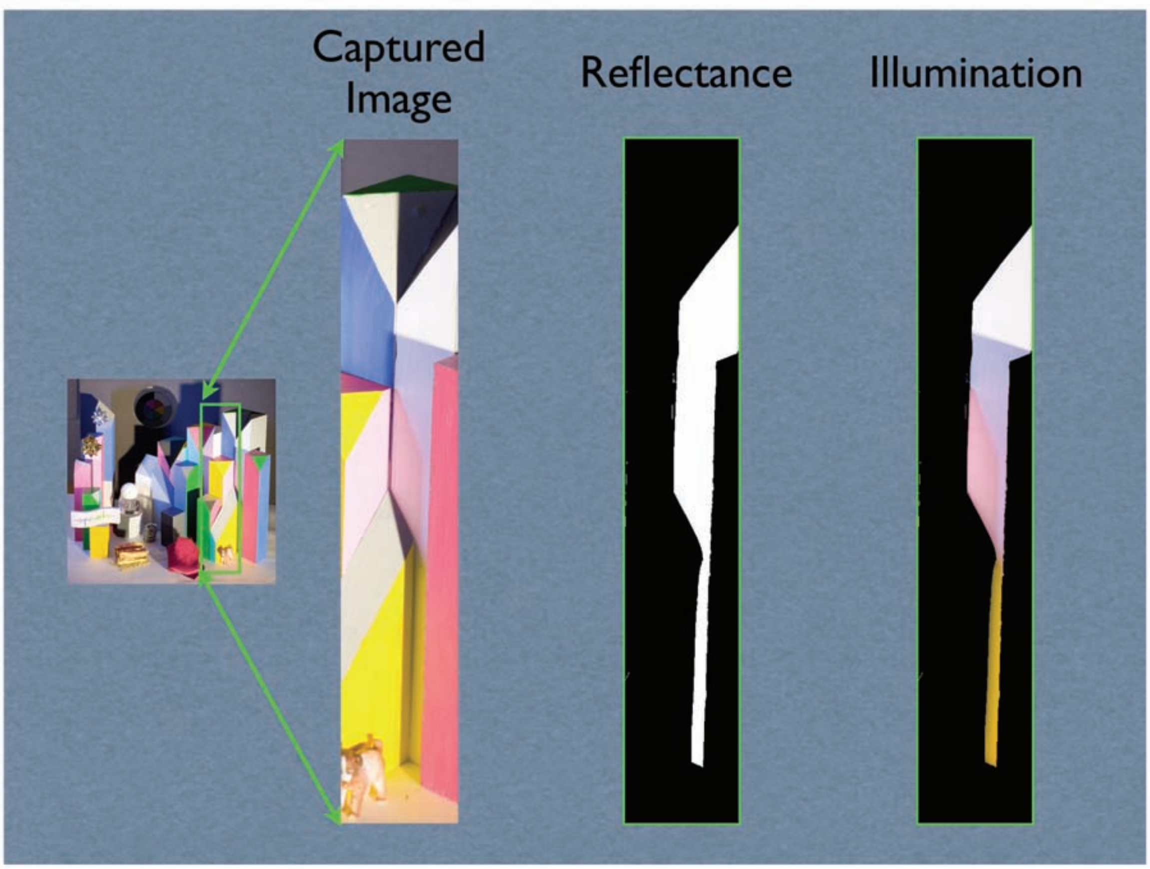


Figure 8 shows the entire HDR image, a region of interest, the reflectance of the vertical white painted surface, and the colour of the direct illumination (top), shadow (lower area), reflected pink illumination (lower), and reflected yellow illumination (bottom).

Reviewing the three theoretical approaches, we see that with CIECAM models the radiance coming to the eye, and the radiance of the illumination are the same because of the white reflectance object. Although difficult to measure, when we obtain the values of the radiances and illumination radiance CIECAM models will predict that the white, the gray, the pink and the yellow will all appear the same white. The second group of models calculates the illumination and discounts it. It is very difficult to imagine how one could compute the illumination on each surface in the LDR, let alone the HDR image. If this extraordinary challenge could be solved, it would make the same prediction as CIECAM models. It would also predict that the white, the gray, the pink, and the yellow all appear the same white. The third group of models uses the edges, assigning them high visibility, and gradients, assigning them low visibility, to synthesize an appearance image from the array of all radiances. Since these models are not concerned with measurement, or calculation of illumination, the appearances in Figure 8 are not an issue for spatial comparison models. They predict white grey, pink and yellow appearances.

Figure 9 shows a region of the 3-D Mondrian that has N4 and K paint. In the LDR illumination observers reported that the top was significantly lighter gray, than the right vertical side. This was despite the fact that the two faces have the same painted reflectance. Again the discrepancies were caused by differences in illumination. In the HDR illumination observers reported that the top was significantly darker gray, than the right vertical side. As with the LDR image the two faces have the same painted reflectance. However, in the HDR image, the illumination on the right vertical face is greater than that on the top. The appearance of the edge between the top and side of the block reverses with change in illumination.

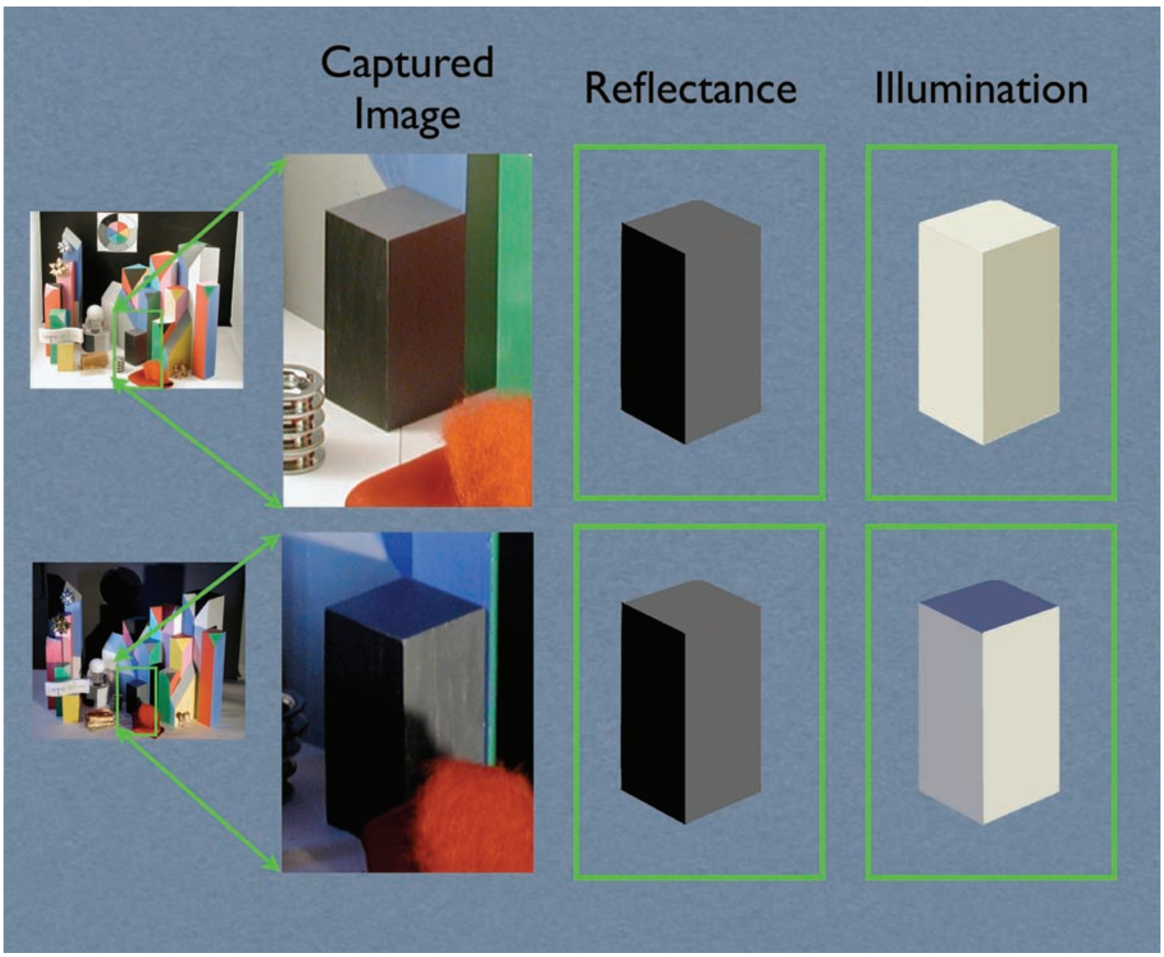


Figure 9 shows the entire LDR and HDR images, the pair of regions of interest, the reflectances of the dark block's painted surfaces, and the colour and relative intensities of the illuminations.

In Figure 9 the relative appearance of lightness of the top and side surfaces changes with illumination. In LDR the top is lighter; in HDR the top is darker. As seen before in Figure 8, appearance correlates with the edges formed by the complex interaction of reflectance and illumination. Finding illumination, either measured or calculated, is not helpful in predicting appearance.

6. SCENE CAPTURE

We used a variety of cameras to capture the radiance array from the 3-D Mondrians. We made digital images using multiple exposures with a Nikon 990, Leaf Aptus 75S (33 Megapixel back) with a Mamiya 645AFDII Body, a 35mm film camera with colour negative and transparency films. The Leaf captured each scene using 9 different exposures. These images are available on the web at http://web.mac.com/mccanns/_CREATE_08/Welcome.html and www.create.uwe.ac.uk. Moreover, each CREATE participant was invited to photograph each scene with their own camera.

A single exposure captures all the scene information in the LDR scene. A single exposure cannot capture all the information in the HDR scene, with the exception of the colour film negative. These images are posted so that CREATE participants and others can uses the scene capture information to render both scenes. Here the goal is to apply the same algorithm to both LDR and HDR scenes. See the web page for more information. Figure 10 shows six different exposures for both LDR and HDR scenes.

Figure 10 shows digital photographs of the low-dynamic-range (LDR) scene on the top, and photographs of the high-dynamic-range (HDR) scene on the bottom. Each photograph had twice the exposure of the one on its left. The photo on the far right had 64 times more exposure than the one on the far left. The exposure varied from 1/30 to 1 second.

7. NEXT STEP: IMAGE PROCESSING

CREATE participants will process the captured images and render the two LDR and HDR scenes.

The experimental instructions for the future, is to work towards a final print that is as perceptually close as possible to the real scene. Each participant will create one print. In order to minimise a gamut mapping problem, the same parameters will be used for all printed output. These common parameters will include, printing from the same hardware, operating system, colour space, printer, paper and paper profile; and where this is not possible it will be reported.

In preparation for printing, each collaborator will be asked to modify the image to match the appearance by using any tools, artistic media, or software, or HDR pipelines that they judge to be necessary. Participants will be asked to record all software and methods, so that retro analysis of the method can be studied. Each participant will be asked to describe their reproduction intent and their process.

Each print will undergo the same radiometric analysis as used to calibrate the scenes. We will evaluate the results in terms of the differences in radiometry: between illuminants; between originals and reproductions; and between reproduction techniques. A second set of experimental measurements will evaluate how independent observers rank the prints, in term of reproduction accuracy, and in terms of observer preference.

8. DISCUSSION

The results confirmed the following points. The geometry of illumination has a large effect on appearance. Different way of distributing light on objects changes the amount of light of single points. When illumination changes edges, or introduces edges, between neighbouring areas on the retina, then illumination changes colour appearance. Shadows, when sharp, create edges producing large changes in appearance. Shadows, when diffuse, create gradients, producing very small changes in appearance.

The illumination on the LDR scene attempted to provide uniform illumination. Perfect Lambertian surfaces and absolute uniformly diffused illumination exist in integrating spheres, but are not found in real, three-dimensional scenes. This explains the small changes in appearance in the LDR image. We view most real object experience in everyday life in illumination between the LRD and the HDR cases. The differences between the two scenes in the appearance, tells us something about the behaviour of our vision system concerning illumination and reflectance. In other words, we can say that the illuminant is not discounted, and that reflectance is not extracted in a very large number of circumstances.

There are two important differences between capturing the scene with a camera, and watching the scene. The first is the dynamic range. A single camera shot cannot grab the entire visual information in one shot, while our vision system is perfectly able to see all the patches in the HDR scene. The second is that cameras process pixels, while humans process spatial relationships. Most cameras use digital acquisition to perform global tone mapping. All pixels with the same input, have the same output. The human vision system is able to function over a wide range of luminance levels because it is indifferent to the quanta catch at a pixel. Rather, it processes the scene's information to synthesize the appearance from the spatial relationships of receptors responses to the entire scene.

9. CONCLUSIONS

We asked members of the CREATE project to participate in a multidisciplinary experiment in order gain a deeper understanding of the appearance of coloured objects in three-dimensional scenes. The experiment employed two identical scenes, which were viewed and compared side by side. Each scene was subjected to different lighting conditions. First, we used an illumination cube to illuminate all objects from all directions, to make a low-dynamic-range (LDR) image. Second, we used a directional spotlight and WLEDs to make a high-dynamic range (HDR) image of the same objects. The scenes contained identical three-dimensional painted colour blocks arranged in the same position in two still lifes. The blocks were painted with only 6 hue colours and 5 tones from white to black. Observers were asked to consider the changes in the appearance of a selection of colours according to lightness, hue, and chroma, and to rate how the change in illumination affected appearance. We measured the light coming to the eye from still-life surfaces with a colorimeter (Yxy). We captured the scene radiance using multiple exposures with a number of different cameras. We have begun a programme of digital image processing of these scene capture records. Participants will continue to make their individual rendering of these scenes for future analysis. This multi-disciplinary programme continues until 2010, so this paper is an interim report on the initial phases and a description of the ongoing project.

ACKNOWLEDGEMENTS

We would like to thank all the participants of CREATE, Andy Johnson of Calumet, and staff at the Centre for Fine Print Research University of the West of England Bristol.

Alison Davis, Stephen Westland, János Schanda, Cecilia Sik Lanyi, Reiner Eschbach, Gabriel Marcu, Paul Thirkell, Peter Walters, Paul Laidler, David Huson, Steve Wilkinson, Bridgett Connolly, Ondrej Panak, Mary McCann, Huw Robson, Louise Jennings, Steve Hoskins, Yu Wang, Markus Reisinger, Kelson dos Santos Araujo, Sheona Beaumont, Bernard Staig-Graham, Maja Stanic, Ferenc Szabo, Daniele Torcellini, Giorgio Trumpy, Vassilios Vonikakis, Aditya Sole, Sally Semple, Ildiko Rozsovits, Esther Perales, Marius Pedersen, Peter Nussbaum, Peter McCallion, Lyndsey McDougall, Donata Magrini, Barnabas Mader, Albrecht Linder, Andrew Lerwill, Vesela Koleva, Pesal Koirala, Kalle Kataila, Philip Henry, Sofia Hengst, Caroline Harrison, Elza Tantcheva, Vien Cheung, Julie Caves, Lara Boselli, Cristian Bonanomi, Veronica Marchante.

REFERENCES

[1] Bomford, D. and Ashok, R. *Colour*, London, The National Gallery, p.40 (2000)
[2] MacCurdy, E., Ed. The Notebooks of Leonardo Da Vinci, London, Jonathan Cape (1938)

[3] Ball, P. and Ruben, M. "Color Theory in Science and Art: Ostwald and the Bauhaus." *Angewandte Chemie International Edition* 43(37): 4842-4847 (2004)
[4] Albers, J. *Interaction of Color*. New Haven ; London, Yale University Press (1963)
[5] Itten, J. *The Elements of Color*. Ravensburg, Otto Maier Verlag (1961)
[6] Reid, T. Works of Thomas Reid. New York, Duyckinck, (1822)
[7] J. J. McCann, 'Simultaneous Contrast and Color Constancy: Signatures of Human Image Processing', Chapter 6 in *Color Perception: Philosophical, Psychological, Artistic, and Computational Perspectives*, Vancouver Studies in Cognitive Studies, S. Davis, Ed, Oxford University Press pp 87-101, (2000)
[8] Land, E. H. 'The Retinex', *Am. Scientist*, vol. 52, pp. 247-264 (1964)
[9] G. Wyszecki and W. S. Stiles. *Color Science: Concepts and Methods, Quantitative Data and Formulae*, New York Wiley (1982)
[10] Adams, A. *The Camera*, Little Brown & Company (1980)
[11] Adams, A. *The Negative*, Boston: New York Graphical Society, Little Brown & Company, Boston (1981)
[12] Adams, A. *The Print*, Little Brown & Company (1983)
[13] Adams, A. *Examples: The Making of 40 Photographs*, Boston: New York Graphical Society, Little Brown and Company (1984)
[14] Eastlake, C. L. *Goethe's Theory of Colours*; translated from the German with notes, by C. L. Eastlake. London, John Murray (1840)
[15] Sorensen, R. *Seeing Dark Things*, Oxford University Press, 153-168 (2008).
[16] Rizzi, A. and McCann, J.J. "On the behavior of spatial models of color", in *Proc,IS&T/SPIE Electronic Imaging 2007,* SanJosè (2007)