Artist's colour rendering of HDR scenes in 3D Mondrian colour-constancy experiments

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1. ABSTRACT

The presentation provides an update on ongoing research using three-dimensional Colour Mondrians. Two still life arrangements comprising hand-painted coloured blocks of 11 different colours were subjected to two different lighting conditions of a nearly uniform light and directed spotlights. The three-dimensional nature of these test targets adds shadows and multiple reflections, not found in flat Mondrian targets. Working from exactly the same pair of scenes, an author painted them using watercolour inks and paints to recreate both LDR and HDR Mondrians on paper. This provided us with a second set of appearance measurements of both scenes. Here we measured appearances by measuring reflectances of the artist's rendering. Land's Colour Mondrian extended colour constancy from a pixel to a complex scene. Since it used a planar array in uniform illumination, it did not measure the appearances of real life 3-D scenes in non-uniform illumination. The experiments in this paper, by simultaneously studying LDR and HDR renditions of the same array of reflectances, extend Land's Mondrian towards real scenes in non-uniform illumination. The results show that the appearances of many areas in complex scenes do not correlate with reflectance.

Keywords: High-Dynamic range scenes, colour constancy, measured appearance.

2. INTRODUCTION

The experiments in this paper describe the capture of appearances in a complex scene by an artist's painting. Fechner measured middle-gray lightness by asking an artist to paint it. Here an author, Carinna Parraman painted two identical sets of blocks in different illuminations. Measurements of the watercolour painting reflectances quantify the appearances of each element in the scene. These experiments continue a series of experiments designed to study the interplay of reflectance, illumination and spatial content in human colour appearance.[1] In this series we replaced the flat array of colour papers used in Land's Mondrian[2] with a collection of three-dimensional painted blocks. We replaced the 100 plus colour papers used in Land's Mondrians with eleven reflectances: 6 chromatic and 5 achromatic. We replaced the spatially uniform illumination with a pair of different illuminants: one as uniform as possible, and the other highly directional. The uniform illumination has a low dynamic range (LDR), while the directional one has a high dynamic range (HDR).[3,4] While Land used many reflectances to make a complex array of radiances, we used the shadows and gradients created by the 3-D objects to generate complexity. The three-dimensional nature of these test targets adds shadows and multiple reflections. These properties enrich the targets and make them more like real scenes. Here we measure the effects of illumination on constant reflectances. Human vision models need this data to assess how well their predictions match appearances.

3. LDR & HDR SCENES

As described in earlier papers [1,3-4] the scene consisted of two identical set of painted wooden blocks viewed side-by-side at the same time in different illuminations.

2.1 Two identical 3-D Mondrians

Each of the flat surfaces had one of eleven different paints (Red, Yellow, Green, Cyan, Blue, Magenta, White, Neutral Gray Light, Neutral Gray Middle, Neutral Gray Dark, Black). Figures 1 shows photographs of the two parts of the scene.

Figure 1 shows photographs of the LDR & HDR parts of scene.

2.2 Characterization of LDR & HDR Illuminations

Above, in Figure 1 (left) we see a photograph of the LDR Mondrian in illumination that was as uniform as possible. The blocks were placed in an illumination cube (figure 2 left). It had a white floor, translucent top and sides, and a black background. We directed eight halide spotlights on the sides and top of the illumination cube. The combination of multiple lamps, light-scattering cloth and highly reflective 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.

Figure 1 (right) is a photograph of the HDR Colour Mondrian illuminated by two different lights. One was a 150W tungsten spotlight 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 (orange stick). It stood vertically and was placed quite close (20 cm) on the left (See figure 2 right). 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. 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 target in the chamber significantly increased the range of the non-uniform display. However, human observers had no difficulty seeing the darker circular target.

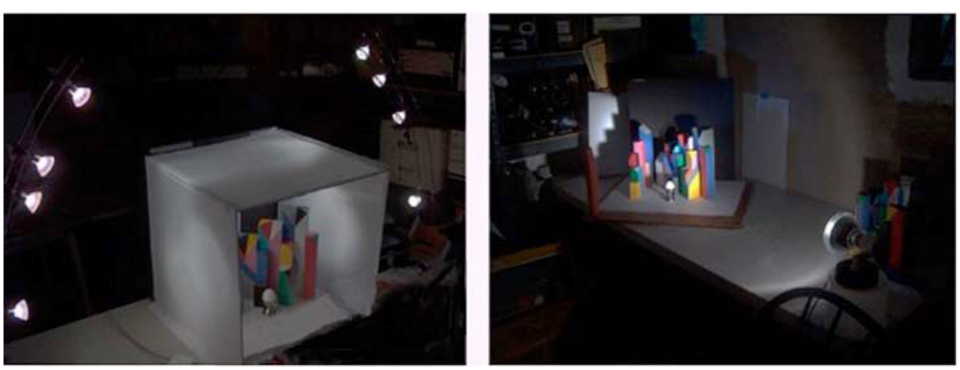

Figure 2 shows photographs of the LDR & HDR illuminations.

4. WATERCOLOUR PAINTINGS- A RECORD OF APPEARANCE

By making a painting of the appearances of each area in the LDR & HDR scene we quantify appearances.

4.1 Defining colour terms

In traditional painters terms, there are five qualities of colour: hue, value (brightness), chroma (saturation), temperature and transparency.[1] However, there are a range of interpretations, with subtle variations, agreements and conflicts according to whether the explanations are determined through psychophysics, colour science, commercial printing, or painting.[6-13] The following colour terms here are presented in the context of painting.

For artists who mix paint on a palette, define colour by hue (pure colour that is not mixed with white or black but can be mixed with another colour), tints or tinted colours are mixed with white to obtain lighter colours of the same hue and shades are mixed with black to obtain colours that are darker than the same hue.

A hue is loosely defined by generic colour terms, such as red, blue, yellow. Within these generic terms are particular colour names such as *rose madder*, *vermillion*, which can be both termed as having a red hue, in the same way that, *ultramarine* and *cobalt* have blue hues. A hue can also be described by its chemical element, such as *cadmium red*, or *cobalt blue*.

Value or the tone is a relative measurement from white to black or from lightest to darkest. The value of a colour can be described as to the extent to which a colour reflects or absorbs light. A colour by its own intrinsic value, i.e. *ultramarine* blue, absorbs less light than *cobalt* blue, which absorbs even less light than *Prussian* blue.

The saturation or chroma or colourfulness of a colour describes in terms of how the saturation is reduced by adding grey (black and white), which will result in a degrading of a colour from intense (most saturated) to neutral (grey or least saturated). By mixing two or more hues does not reduce the saturation, i.e. a purple (where red and blue is mixed) or brown (red, blue and yellow) where only hue colours are mixed (a grey is not added). This is different to comparing a hue on a digital colour wheel or spectrum where brown (as a hue) would be described as a dark orange or dark red (black would be added). Chroma is determined also by the brilliance or brightness of the colour, for example vermilion has a higher chroma than rose madder, however vermilion appears to be lighter than rose madder and so the tonal value of the colour is different.

Colour temperature is more subjective, specific colours may appear to be warm or cold, for example, red and orange suggest warmth and blue suggests cold. Within the hue colour range, vermilion appears to be warmer than rose madder, however, an ultramarine also appears warmer than a cobalt as the hue shift of the ultramarine tends towards a red hue whereas the cobalt tend towards the green. A useful example of the relationship of watercolour pigments is demonstrated by Bruce MacEvoy who has measured and plotted the colour locations on the CIECAM $a_C b_C$ plane.[14]

Translucency refers to the opacity or transparency of a colour, washes or extenders can make a colour more translucent, or some colours are inherently more translucent. Using the example of rose madder and vermilion, applying the same wash of colour reveals that vermilion is more opaque but more light is reflected through the rose madder.

4.2 Objectives for the second set of watercolour paintings

Developing a method from the previous pilot study undertaken in 2008,[1] the objective was to undertake a more detailed analysis of the appearance of colours and their colour relationships so that all the facets of the blocks could be measured and compared (see section 5)

The main objective was to match as closely as possible the appearance of colours in the scene by mixing inks and pigments according to the colours in the scene and painting them on paper. Colours and their relationships were compared and painted from the same scene and also compared between the LDR (figure 3) and HDR (figure 4) scenes.

The second objective was to paint the scene on a hue-by-hue basis, therefore, all the greens were compared to the greens in the same scene and then the greens in the LDR and HDR scene, in many cases the colours were retouched in order to ensure there was a consistency.

To compare the saturation and brightness between faces in each scene was more problematic, as this required further fine tuning through the addition or removal of layers of translucent washes of paint.

The ranges of appearances in the two scenes were observed:

The shadows were more complex in the HDR scene than in the LDR scene. The shadows in the HDR scene contained different colours[15]; faces of blocks reflected coloured shadows onto the adjoining blocks, flat faces of blocks were disrupted by cast light and cast shadows which resulted in an angular appearance; faces of blacks appeared lighter in the HDR than in the LDR scene and some light areas appeared darker than in the LDR scene; the black areas in the HDR scene no longer appeared black but reflected a range of colours. The shadows in the LDR shadows appeared more diffused; shadows were softer with less hard edges; shadows here did not appear coloured. These shadows could be described as darker versions of the hue colour. However, this did not mean that if by adding black one could achieve the shadow version, but required the addition of other translucent layers. The hues in the LDR scene appeared to be more similar with less distinction between the different angles of the faces. The diffused light appeared to increase the overall saturation of the colours.

4.3 Suggested methods for painting scenes.

A range of inks and watercolours were utilised. The widest range of watercolour pigments and inks are made by Windsor and Newton.[5] However in order to obtain highly saturated pinks, watercolour inks made by Dr.Ph.Martin's were used. The most direct approach was to choose a pigment that closely matched the appearance of the block facet and to paint in an unmodified form – this occurred rarely. The second approach was to mix two hues to obtain a secondary colour. As more colours were added there resulted in a loss of brilliance. Based on the rules of economy the best approach was to modify the hue of the primary colour by adding tiny degrees of another until a colour match is obtained. Before applying the paint to the area of the picture, it was tested on the paper as a brushstroke along side a range of other mixed and tested colours. As in most cases the relationship of paint on paper differed greatly to the appearance of paint on palette.

The bright directional lighting in the HDR scene resulted in a range of shadow effects, hard angles and multiple reflected colours onto juxtaposed faces. The question was, how to paint a black highlight that appeared a greenish yellow? This could be achieved by layering thin layers of colour over the top of another, or by applying an undercolour as a foundation for another, which is a method for achieving a natural result and referred to by Italian Masters as abbozzo. For the rendering of the shadows and the coloured reflections in the HDR scene, the decision was to treat the shadow as an altogether different colour and mix it as if it were a new facet. Where there were defined shadow areas in the HDR scene, these areas were given their own location point (see section 5 and figure 5) and measured. The more naturalistic approach of applying layers of translucent colour was employed for the LDR scene.

The colour appearance of the blocks facing the blue LED light appeared cooler than the facets of the blocks facing the yellow tungsten spotlight. Therefore an *ultramarine* or a warm hue was mixed into colours and painted on the faces that were facing the spot-light, whereas the facets of the blocks facing the blue LED light were painted with cobalt or turquoise blue.

The faces on some of the larger areas were not a uniform colour, which graded from light to dark, or one colour another, which required a wash or a series of layers of translucent colour. In many cases, yellow or blue was mixed into the white to paint the facets of the white blocks in the HDR scene; deep red, *Prussian blue* and yellow were added to the black. It is rare for printmakers to print only a black, as a print will appear flat and dull.

In fact the painting of the facets in the LDR scene proved to be more problematic. This might have been due to the appearance of hues within a very narrow range of colour differences. When compared, each hue appeared to be very different but it was difficult to demonstrate these subtle changes in paint.

Figure 3 shows the watercolour painting of the LDR part of the scene.

Figure 4 shows the watercolour painting of the HDR part of the scene.

5. MEASUREMENTS OF APPEARANCES – WATERCOLOUR REFLECTANCES

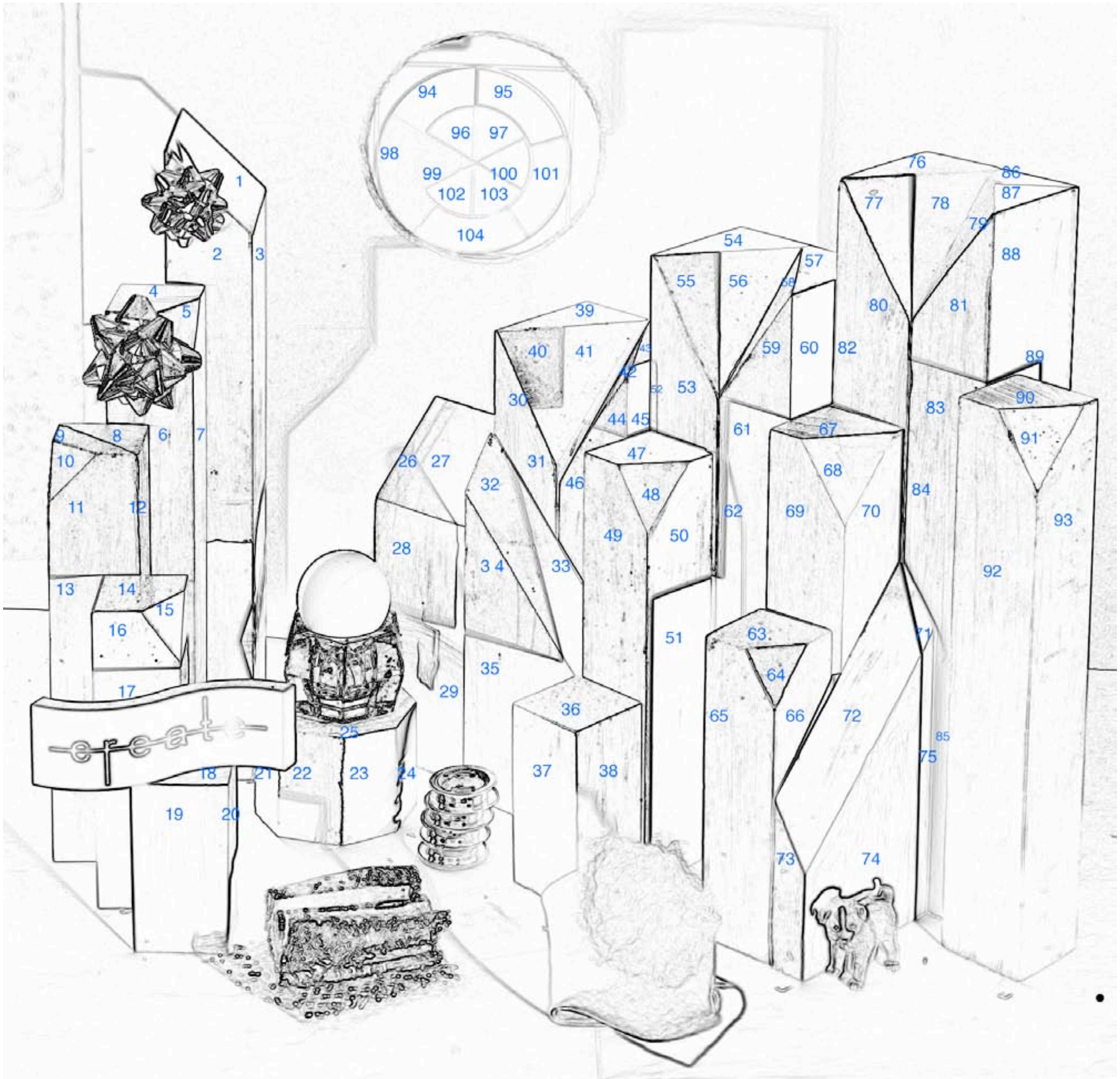

Figure 5 shows the location in the watercolour paintings where Spectralino reflectances were measured.

We measured the reflectance spectra of both LDR and HDR paintings at each of the 104 locations identified in Figure 5 using a Spectralino meter. The meter reads 36 spectral bands, 10 nm apart over the range of 380 to 730nm. We calibrated the meter using a standard reflectance tile. The average reflectance for all wavebands for the all LDR samples is 39.9%. The average reflectance for all wavebands for the all HDR samples is 32.2%. The average reflectance for all measurements is 36.0%. We considered how to represent these reflectance measurements taking into account human vision. Analysis of % reflectance over weights the high-reflectance readings, while analysis using log reflectance over weights the low-reflectance values. Experiments that measure equal changes in appearance show that the cube root of reflectance is a good approximation of equal visual weighting.[16] This non-linear transformation of reflectance has been shown to correlate with intraocular scatter.[17] We used the L* function (equation 1) to scale Spectralino reflectance value for each waveband in the following plots of painting spectra.

$$116 * (reflectance)^{1/3} - 16 \tag{1}$$

We plotted the watercolour spectra for all reproductions of the red painted block in both the LDR and HDR scenes (figure 6, top). In the LDR reproduction, all but one of the facets had very similar measured reflectances. This showed that appearances correlated well with the objects reflectance, with one exception. In the HDR reproduction the painting had a wide variety of measured reflectances, showing that the non-uniform illumination had considerable influence on limiting colour constancy.

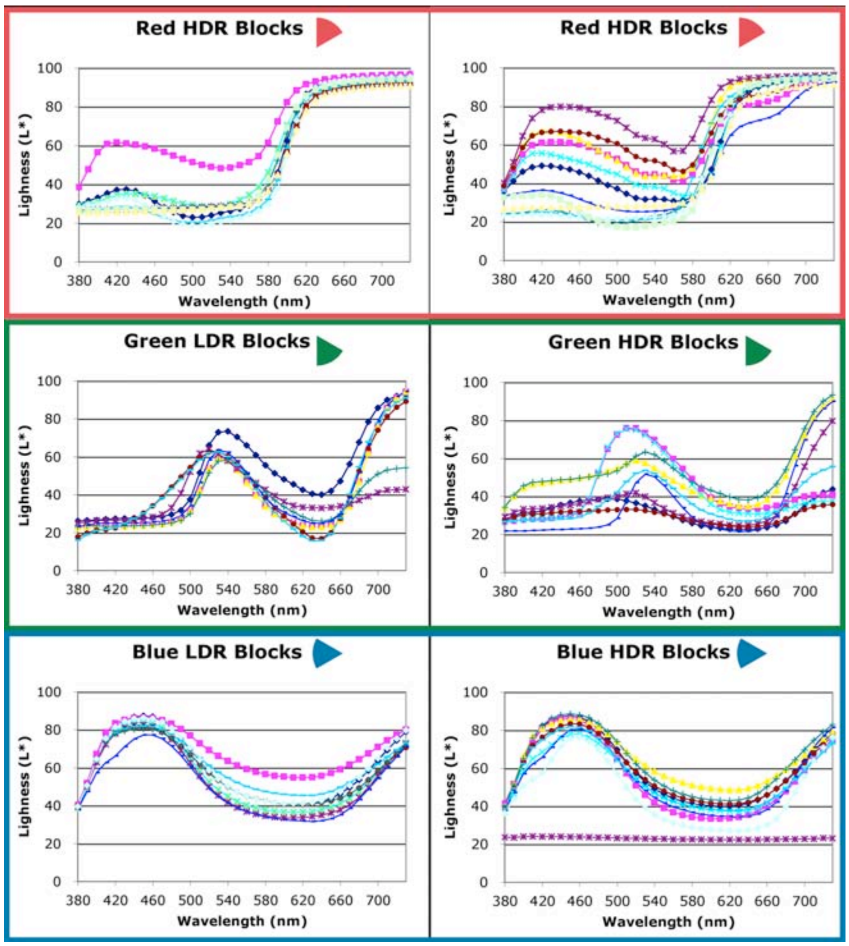

Figure 6 shows the reflectances of red, green and blue facets measured from watercolour LDR & HDR paintings.

We plotted the watercolour spectra for all reproductions of the green painted block in both the LDR and HDR scenes figure 6, middle). In both the LDR and HDR paintings, we see again a wide variety of reproduction spectra again showing that the non-uniform illumination had considerable influence on limiting colour constancy.

We plotted the watercolour spectra for all reproductions of the blue painted block in both the LDR and HDR scenes figure 6, bottom). In this case the HDR reproduction, had very similar measured reflectances in all but one of the facets. The LDR reproduction had more variability in measured reflectances than the HDR painting.

It is important to study the photographs in figure 1 and the paintings in figures 3 & 4 to see that these results have more to do with the position of the blocks and their illumination than with the block's paint colour.

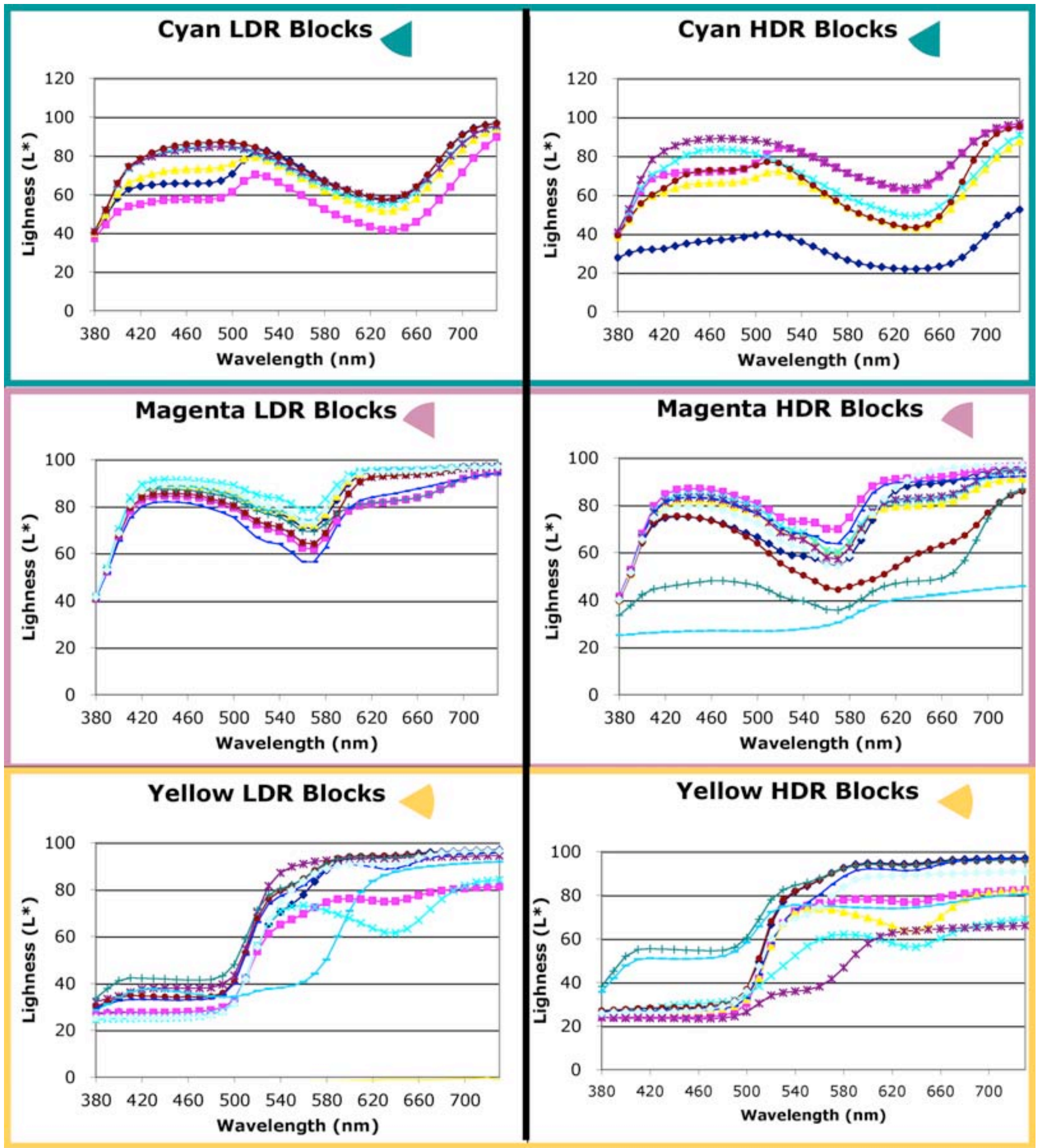

Figure 7 shows the reflectances of cyan, magenta, and yellow facets measured from watercolour LDR & HDR paintings.

Figure 7 compares the LDR and HRD painting reflectances for cyan, magenta and yellow blocks. The cyan reproduction of the HDR scene showed greater variability in lightness of similar spectra. The magenta reproduction of the HDR scene showed greater variability in lightness and spectra. The yellow reproduction of both the LDR and HDR scene showed variability in lightness and spectra. Again, the study the photographs in figure 1 and the paintings in figure 3 & 4 show that these results have more to do with the position of the blocks and their illumination than with the block's paint colour.

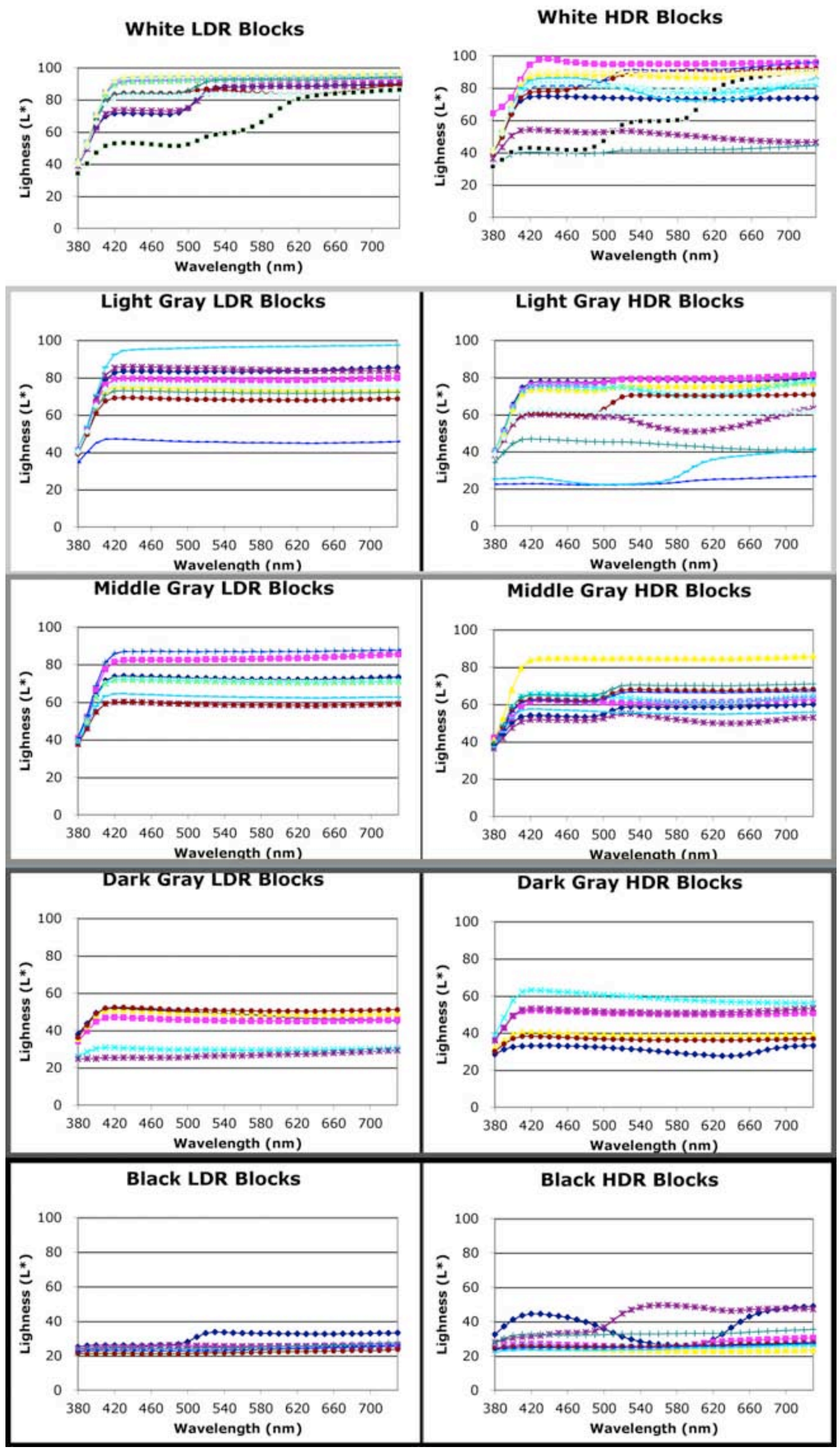

Figure 8 shows the reflectances of white, greys, and black facets measured from watercolour LDR & HDR paintings.

Figure 8 compares the LDR and HRD painting reflectances for the five achromatic value blocks. Again, we see a complex pattern of departures from perfect colour constancy with significant departures caused by the specific illumination pattern. Again, the study of the photographs and paintings shows that these results have more to do with the arrangement of the blocks and their illumination than with the block's paint colour.

6. DISCUSSION

INTERACTIONS OF REFLECTANCE & ILLUMINATION IN CONSTANCY

Since the writings of Ewald Hering [18], a central theme in colour constancy has been the idea that humans see object, rather than the light from objects. Since the works of Herman von Helmholtz[19] we have discussed the idea of discounting illumination. This is consistent with everyday experience in that objects do not seem to change dramatically when we move them through the world of different illuminations. The limits of this observation were measured in these experiments because we viewed together 11 painted surfaces in two very different illuminations. We used an illumination cube that attempted to provide uniform illumination. As seen in the measurements of watercolour reflectances (section 5), the departures from perfect uniformity of illumination caused soft shadows that were recorded small changes in perfect constancy. The harsh illumination used to make the HDR part of the display created edges in illumination. These edges superimpose on the reflectance edges of the blocks. These combined reflectance-illumination edges are equivalent to paint edges from new and different paints. If we take a meter and measure the light coming from two sides of an edge, we cannot separate the change in reflectance across that edge from the illumination change. If we cannot separate these reflectance and illumination components in measuring the scene, how can human vision do it?

Figure 9 illustrates this problem. We have here two photographs of 3-D Mondrian blocks all painted middle gray. The left image uses the illumination cube; the right image uses harsh side illumination.

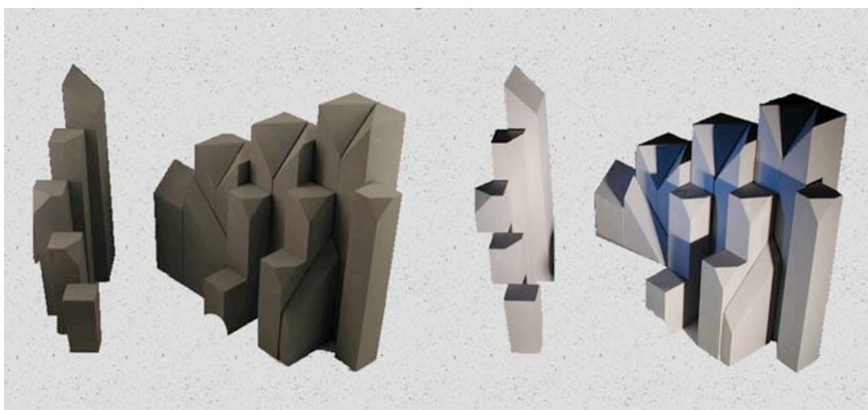

Figure 9 shows 3-D Mondrian blocks all painted middle gray. They are photographed using the illumination cube (left) and harsh nonuniform illumination (right). The rest of the image was removed.

The grey blocks in the LDR illumination (left) show small changes in appearance associated with small changes in luminance. The side illumination (right) creates sharp edges of high contrast along in top of the blocks. These are seen as blacks tin the HDR image . We also see less-sharp horizontal shadow edges in vertical grey surfaces. All the image structure in both images is illumination structure. It is difficult to explain how an algorithm could detect all this structure from an unknown scene. One has to detect it, that is, isolate it from changes due to reflectance, in order to discount it.

7. CONCLUSIONS

This paper describes an experiment that measures the appearance of over 200 colour segments in a pair of 3-D Colour Mondrians. The scene was made up of two identical sets of wooden blocks painted with six colour and five achromatic paints. One block set was illuminated by nearly uniform light (LDR), while the other used two directional white lights (HDR). The appearance information was recorded in two steps. First, an author made a watercolour painting of both LDR and HDR parts, viewed in the same room at the same time. Second, we measured the reflectances of the watercolour painting segments. The goal of the experiment was to measure the extent of colour constancy. If human colour appearance truly discounts illuminations to sense the reflectances of the objects, then the watercolours reflectances must match the reflectances of the painted blocks. The measured watercolour spectra show that colour constancy depends on both the reflectances of and the illumination on objects. Appearances in the watercolour painting are influenced differently by the different illuminants.

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