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Abstract

In constancy experiments, humans report very small changes in appearance with substantial illumination changes. Hermann von Helmholtz introduced the term “*discounting the illuminant*” to describe 19th century thinking about underlying mechanisms of constancy. It uses an indirect approach. Since observers see objects as constant, observers “must” be able to detect the spatial and spectral changes in illumination and automatically compensate by altering the signals from the quanta catches of retinal receptors. Instead of solving the problem directly by calculating an object’s reflectance from the array of scene radiances, Helmholtz chose to solve the problem of identifying the illumination. Twentieth century experiments by Hubel and Wiesel, Campbell, Land, and Gibson demonstrate the power of mechanisms using spatial comparisons. This paper analyses a series of different experiments looking for unequivocal evidence that either supports “discounting the illuminant” or supports spatial comparisons as the underlying mechanism of constancy.

Do Humans “Discount the Illuminant”?

John J. McCann
McCann Imaging
Belmont MA 02478 USA

ABSTRACT

In constancy experiments, humans report very small changes in appearance with substantial illumination changes. Hermann von Helmholtz introduced the term “*discounting the illuminant*” to describe 19th century thinking about underlying mechanisms of constancy. It uses an indirect approach. Since observers see objects as constant, observers “must” be able to detect the spatial and spectral changes in illumination and automatically compensate by altering the signals from the quanta catches of retinal receptors. Instead of solving the problem directly by calculating an object’s reflectance from the array of scene radiances, Helmholtz chose to solve the problem of identifying the illumination. Twentieth century experiments by Hubel and Wiesel, Campbell, Land, and Gibson demonstrate the power of mechanisms using spatial comparisons. This paper analyses a series of different experiments looking for unequivocal evidence that either supports “discounting the illuminant” or supports spatial comparisons as the underlying mechanism of constancy.

1.0 INTRODUCTION

Many variations of ideas about our ability to recognize illumination are woven throughout our thinking about vision. Humans are very good at recognizing the location of light sources in complex scenes. The question addressed in this paper is whether there is any direct evidence that humans do in fact use information about illumination in arriving at the constant appearance of objects. The fact that we can calculate the location of the sun from an image is not the same as the assumption that we use that location to calculate a new post-receptor image of the scene.

The 1960s saw the start of three major bodies of work establishing that vision is controlled by a number of independent channels using spatial comparisons. Hubel and Wiesel’s neurophysiology of the visual cortex[1], Fergus Campbell’s psychophysics of spatial-frequency channels,[2] and Edwin Land’s Retinex theory[3] of color all established that vision works by spatial comparisons.

1.1 Black and White Mondrian

In 1967 Edwin Land first described the “Black and White Mondrian” experiment[4] in his Ives Medal Address at the Optical Society of America meeting. It consisted of an array of black and white papers illuminated with a single light bulb near the floor. By adjusting the position of the lamp, it was possible to measure identical radiances from a black paper near the lamp and a white paper near the top of the display. The white paper appeared white, and the black paper appeared black despite the fact that both papers sent identical radiances to the eye. The talk went on to describe a means of modeling human vision using spatial comparisons. This spatial model accounted for different appearances from identical radiances.

1.2 Checker Board Illusion

In 1995 Ted Adelson created a computer graphics experiment consisting of a cylinder on a checkerboard using simulated non-uniform illumination. This experiment is nearly identical to Land and McCann’s B&W Mondrian. The point of the experiment was the same, namely a square in “shadow” looked lighter than a square in “brighter illumination” despite the identical digital values for the centers of the two squares. The most significant difference between these experiments was their interpretation. Adelson reported “the visual system must take into account a great number of configural cues about what is paint and what is shadow” [5]. This is in sharp contrast to the Land and McCann’s conclusions from the same experiment. They reported that the result of spatial comparisons generate lightnesses consistent with what we see, without the need for calculating the actual pattern of illumination for the entire scene.

The goal of this paper is to discuss the existence of unequivocal evidence that humans "*must*" discount the illuminant. Can we prove that humans break retinal response into meaningful illumination and reflectance components so as to be able to recognize the constancy of objects? Alternatively, can we prove that human constancy mechanism are nothing more that the result of basic image processing by physiological spatial mechanisms? The paper will analyze a series of experiments with the intent of identifying any direct evidence for, or against, "discounting the illuminant".

2.0 SIMPLE VS. COMPLEX IMAGES

Figure 1 (right) shows a photograph of the Lighthouse at Hilton Head, SC at sunset. The lighthouse is a hexagonal tower painted white and red. Four vertical faces are visible in the image and the horizontal painted stripes create a checkerboard effect. The left vertical face is in sunlight, the next is a mixture of sunlight and skylight, the next is in skylight and the right is a specular reflection of skylight. The specular reflection is nearly the same for both red and white paints. It is easy to recognize that this scene has non-uniform sunset illumination. Clues like the shadow at the base of the lighthouse and differences in appearance of painted surfaces are apparent.

How much does our interpretation of illumination influence the color appearances of areas in the image? With Photoshop we can make a simplified checkerboard using the average value of the faces of the lighthouse. The twelve rectangular patches (Figure 1(left)) show the color appearances of these stimuli without the context of the recognizable illumination.

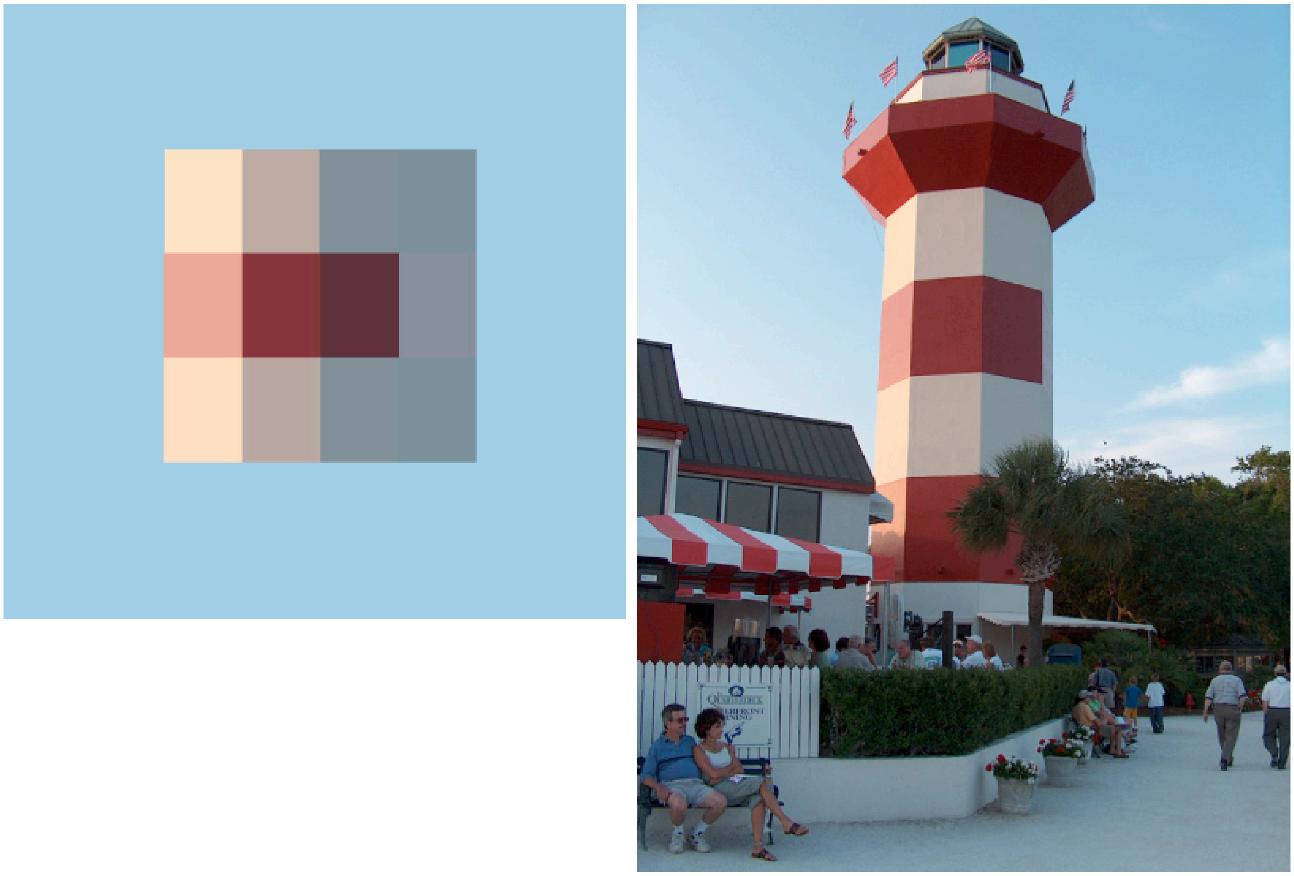

Figure 1 (left) shows an array of twelve color patches on a uniform blue background. The color of the rectangles and background were selected from average pixel values found in the corresponding areas in the photograph (right). The photograph contains a variety of cues to indicate that the illumination is spatially and spectrally non-uniform. The checkerboard on the left has none of these cues. The color appearances of both are very similar, suggesting that the configural information has no influence on this scene.

Despite a lack of difference in color appearances caused by recognizable illumination, this experiment is not unequivocal. The spatial-comparisons argument states that the appearance of the lighthouse is consistent with the array of edges common to both. An illumination argument states that illumination has no influence on this scene. This scene does not prove that another scene could not show that appearance is influenced by recognizable illumination. The absence of a difference does not disprove its possible existence.

3.0 SHADOW EDGES VS. REFLECTANCE EDGES

Figure 2 shows the stimulus in a matching experiment. A painted wooden cube was places on a piece of black velvet. It is viewed in non-uniform illumination. The observers' task was to match the three faces of the cube to the square patches in the standard display on the left. Three of the faces of the cube are painted white. The other three are painted different shades of gray. The observer was unaware of orientation of the cube and the reflectances visible for any of the matches. The observers made matches for all combinations of reflectances and illuminations.[6]

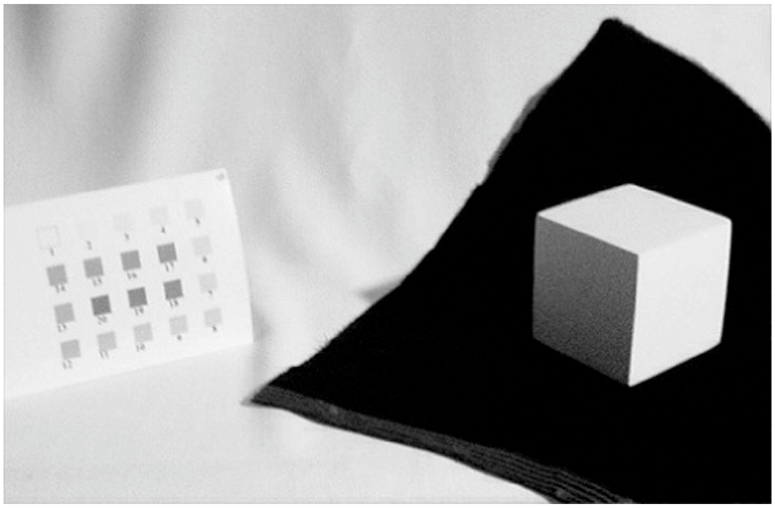

Figure 2(left) shows an array of twenty gray patches on a uniform white background. Observers matched the appearances of the three faces of the painted cube in non-uniform illumination. In some orientations of the cube, all three white faces were visible; so the observers reported on appearance changes due to illumination only. In other orientations faces with different reflectances were visible. The experiment compared the matches with and without reflectance changes.

Observers made the same matches for the same edge ratios of luminances. The observer matches were the same regardless of whether the edges were generated by illumination or reflectance and illumination. The observers were unable to differentiate the appearance generated by just illumination from the other orientations of the cube.

Despite the lack of difference in appearance of illumination and reflectance edges, this experiment is also not unequivocal. The spatial-comparisons argument states that the appearance of the cube is consistent with the array of edges and gradients regardless whether they were generated by illumination or reflectance. The illumination argument states that illumination edges have the same visual effect as reflectance edges.

There are a great many examples used to argue that humans use illumination to generate appearances.[7] In each case, there is also a mechanistic interpretation explaining that the same observation can be modeled by basic image processing found in the visual pathway from retina to primary visual cortex.[8,9,10,11] None of these demonstrations can be considered unequivocal. The problem is that both spatial-comparisons and illumination models are trying to explain the same experiment. In order to resolve this century old debate we need to identify experiments in which the spatial-comparisons approach and the illumination approach predict different appearances. Then the observer experiment can settle the debate. If observer data supports one hypothesis, and does not support the other, we can make progress.

4.0 DEPARTURES FROM PERFECT COLOR CONSTANCY

Color Constancy experiments show that the appearance of objects is almost constant with large spectral changes in illumination. Color is not uniquely determined by the quanta catch of cone receptors. As the explanation of constancy, von Kries suggested that changes in spectral illumination caused relative changes in receptor sensitivities (called adaptation).[12] McCann, McKee and Taylor[13] showed that the Land and McCann model of spatial comparisons predicted the color matches of observers by making spatial comparisons independently for the long-, middle- and short-wave cone receptors. They also pointed out that the departures from perfect constancy correlated with the spectral crosstalk between these broadband retinal receptors. In 1997 Nayatani proposed that incomplete-adaptation explained the departures from perfect constancy.[14] Nayatani's mechanism is illumination based; it is the result of imperfect adjustments to changed illumination. McCann, McKee and Taylor's mechanism is reflectance based. Cone response ratios of from two papers change with illumination because of crosstalk. Recent experiments[15] comparing the predictions made by illumination and reflectance mechanisms provide an unequivocal test of which mechanism controls color constancy.

4.1 Spatial Comparisons

Recent studies[15] of the departures from perfect constancy highlight the role of crosstalk. The experiment included four papers; white, yellow, purple and gray; illuminated by three narrow-band LEDs; 625, 530 and 455nm. The Total Long-wave Response (TLR)

$$\mathrm{TLR} = [\,(I_{625} * R_{625} * LS_{625}) + (I_{530} * R_{530} * LS_{530}) + (I_{455} * R_{455} * LS_{455})\,]$$

where I is the incident illumination, R is the % reflectance and LS is the long-wave channel's sensitivity for each wavelength used. The long-wave sensors' response to 625nm light is a primary response. The long-wave responses to 530nm and to 455nm are both crosstalk. The Total Mid-wave and Total Short-wave Responses are similar. The experiment used four identical LED for each wavelength. The experimenter switched on 1, 2 or 4 LEDs of each wavelength to vary the spectral content of the illumination. The I_{625} , $I_{530,}$ I_{455} values were: 4,4,4; 4,4,2; 4,4,1; 4,2,4; 4,2,2; 4,2,1; …1,2,1;, 1,1,4; 1,1,2; 1,1,1. In total 27 different combinations of 3 LEDs at 3 intensities were tested.

Spatial-comparison models hypothesize that human vision builds independent L, M and S lightness images by taking ratios of different image areas. The long-wave output calculation uses the ratio of the yellow paper to the white paper. This ratio changes with relative changes in 625, 530 and 455nm illumination because the proportions of crosstalk contributions change. This argument holds for colored papers, but not for achromatic ones. By definition a white and gray papers have the same reflectance for all wavelengths. When the crosstalk component is the same as the principle component the ratio of gray to white is constant for all changes in illumination. Consider the ratio of the TLR for the neutral gray paper (Reflectance Rn) to the TLR of the white paper (Reflectance Rw):

$$Ratio = \frac{\left(\left[I_{625} * Rn_{625} * LS_{625}\right] + \left[I_{530} * Rn_{530} * LS_{530}\right] + \left[I_{455} * Rn_{455} * LS_{455}\right]\right)}{\left(\left[I_{625} * Rw_{625} * LS_{625}\right] + \left[I_{530} * Rw_{530} * LS_{530}\right] + \left[I_{455} * Rw_{455} * LS_{455}\right]\right)}$$

$$when:\quad Rn_{625} = Rn_{530} = Rn_{455} = c1 \qquad and \qquad Rw_{625} = Rw_{530} = Rw_{455} = c_2$$

$$Ratio = \frac{\left(\left[I_{625} * c_1 * LS_{625}\right] + \left[I_{530} * c_1 * LS_{530}\right] + \left[I_{455} * c_1 * LS_{455}\right]\right)}{\left(\left[I_{625} * c_2 * LS_{625}\right] + \left[I_{530} * c_2 * LS_{530}\right] + \left[I_{455} * c_2 * LS_{455}\right]\right)}$$

$$Ratio = \frac{c_1}{c_2}\,\frac{\left(\left[I_{625} * LS_{625}\right] + \left[I_{530} * LS_{530}\right] + \left[I_{455} * LS_{455}\right]\right)}{\left(\left[I_{625} * LS_{625}\right] + \left[I_{530} * LS_{530}\right] + \left[I_{455} * LS_{455}\right]\right)}$$

$$Ratio = \frac{c_1}{c_2}$$

As shown in the above equations, crosstalk for the gray paper is canceled by the crosstalk from the white. The ratio of neutral gray papers to white is completely unaffected by the spectral composition of the illuminants. This is not true for colored papers. The ratio of yellow to white depends on the crosstalk contributions controlled by the overlap of sensitivity functions and variable proportions of spectral illuminants. The independence of grays and the dependence of colored papers on spectral illumination is an important signature of crosstalk.

4.2 Incomplete Adaptation Predictions

As the explanation of constancy, von Kries adaptation changes receptor sensitivities in response to spectral illumination changes. Incomplete-adaptation hypotheses assume that the departures from perfect constancy are the result of imperfect adjustments to changes in illumination. Figure 3 is a 3D diagram of incomplete adaptation in L*a*b* space. The 27 illuminants form a cloud of points. L*a*b* stretches the radiances into a football shape with a* as the longest axis. 33% incomplete adaptation shrinks the football to the volume shown by the solid balls in Figure 3.

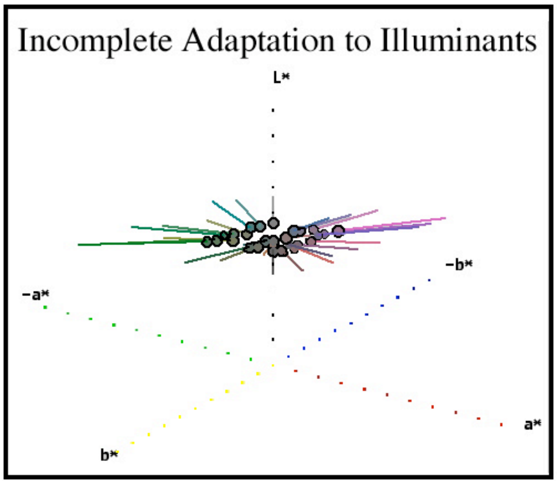

Figure 3 models the effect of incomplete adaptation. The XYZ chromaticities of the 27 different illuminants (combinations of 625, 530 and 455 LED illuminants) were converted to L*a*b* coordinates. L* is vertical dotted line rising up from the a*, b* plane. The ends of the lines represent the 3D colorimetric space occupied by the illuminants. Assuming a 33% incomplete adaptation compresses the color space to the volume occupied by the solid spheres. All lines converge towards theoretical perfect color constancy.

Since the incomplete adaptation hypothesis is controlled only by illumination changes, it predicts that gray and yellow papers will have identical constancy departures. In other words, the lack of complete adaptation should cause color shifts in the same direction in color space and they should have the same magnitude. Asking the observer to look at different paper in the same field of view does not change the illumination predictions. Figure 4 (left) shows L*a*b* plots of the incomplete adaptation predictions for three papers in the same field of view: Yellow (Sunburst), purple (Weeping Wisteria) and gray (Steel Gray). Each paper generates a cloud of 27 different points representing 33% incomplete adaptation for each illuminant.

4.3 Spatial-Comparisons Predictions

Let us analyze color constancy assuming that vision is controlled by a number of independent channels using spatial comparisons. Here we calculate the ratios of Total Responses: ($TLR_{yellow}/ TLR_{white}$); ($TMR_{yellow}/ TMR_{white}$); ($TSR_{yellow}/ TSR_{white}$) for all 27 illuminants. Similar calculations are made for the purple and gray papers. Figure 4 (middle) plots the spatial-comparisons predictions in L*a*b* for the three papers in 27 illuminants. Here the results of crosstalk fall along a long line for yellow, a shorter line for purple, and close to point for gray. (The measured reflectance values for the gray paper were 64%, 60%, and 56% (L, M, S); hence the departure from a single point.)

4.4 Observed Results

Since incomplete adaptation hypothesis is controlled only by illumination changes, it predicts that all papers will have identical constancy departures, as long as the field of view is constant. Since the crosstalk hypothesis is based on the ratio of radiances sensed by broadband retinal receptors it is paper dependent. Here the model predictions are unequivocally different.

The predictions and matching data were displayed and analyzed using 3D rotating plots of all 27 illumination points for yellow, purple and gray papers. Illumination prediction plots show three nearly identical football-shaped clouds of data. These clouds are the compressed colorimetric distribution of the 27 illuminations. The purple and gray illumination predictions partially overlap. The spatial-comparisons predictions show no resemblance to the colorimetric distribution of illuminants. They fall on lines for yellow and purple, and occupy a very small volume for gray. The observer matches are very similar to the spatial-comparisons predictions.

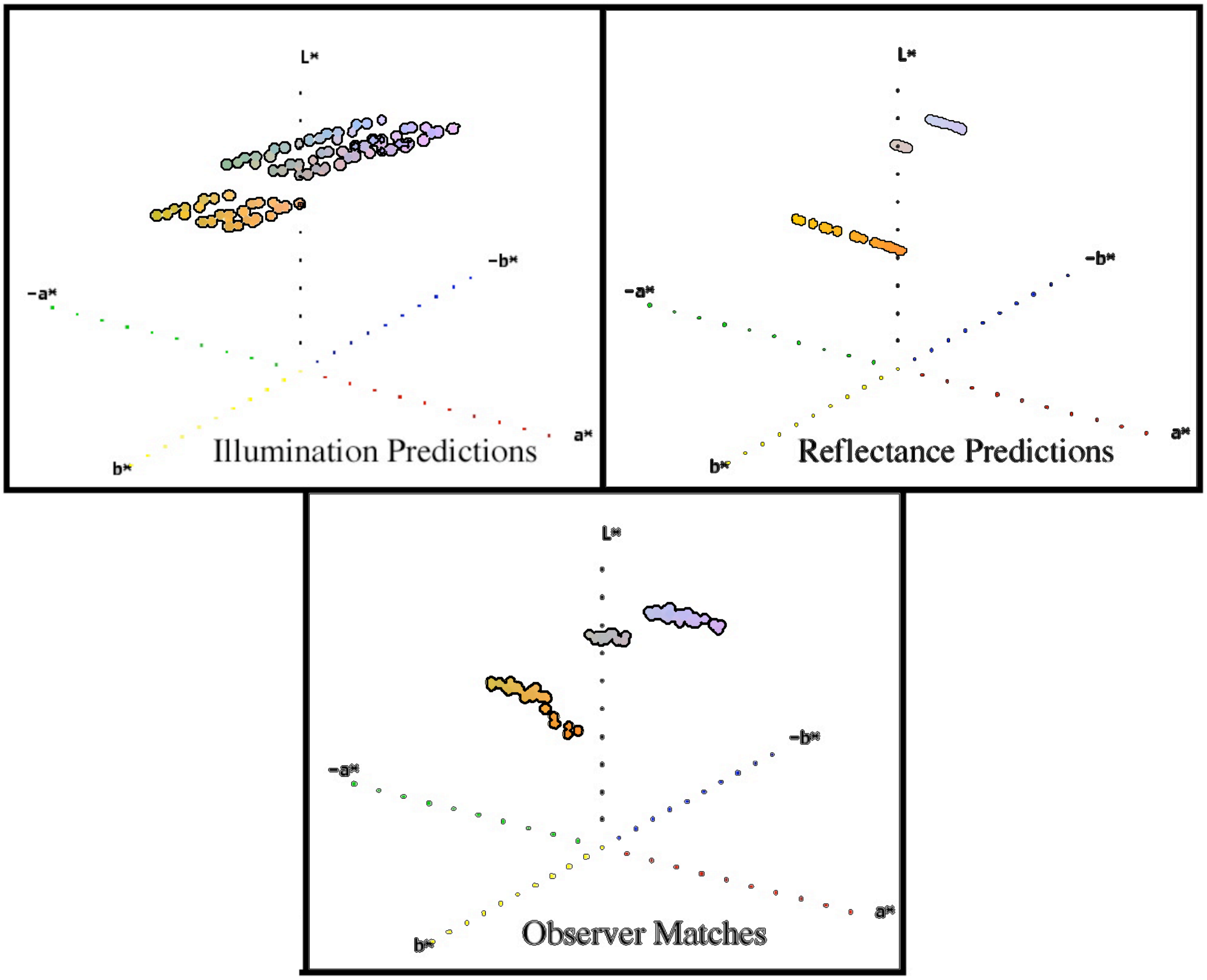

Figure 4 (top left) shows predicted matches based on illumination. It plots the projections of three very similar football shaped clouds of predictions of 27 different results for each illuminant. Figure 4(top right) shows the predictions based on crosstalk of receptors. It plots different loci of matches for yellow (a long line in front of L*axis) purple (a shorter line behind L* axis) and gray (a very small volume close to L* axis). Figure 4 (lower middle) shows observers' matches. The matches are consistent with the reflectance crosstalk predictions. Yellow matches are the long line in front of L*axis, purple matches are the shorter line behind L* axis and gray matches are the small volume close to L* axis. Incomplete adaptation predictions of 33% have a smaller maximum range than that for yellow matches and a much bigger maximum range for gray matches. These matches are inconsistent with incomplete adaptation predictions.

Figure 4 is a plot of a single perspective view of the 3D data. Figure 4 (top left) shows a cross-section of the illumination-prediction clouds. Gray paper predictions have the same volume and shape as those of the other papers. Figure 4 (top right) shows that the predictions for spatial-comparisons are very different from those for illumination. Here, the crosstalk-based predictions vary with the papers reflectances. The yellow paper data show an extended linear track at high saturation. The purple data form a shorter less-saturated linear track. The gray paper predictions occupy a very small volume near the L* axis. Figure 4 (lower middle) shows that papers have very different changes in appearance consistent with crosstalk. The gray paper matches occupy a small volume again consistent with crosstalk predictions. The yellow and purple matches form linear tracks similar to spatial predictions. Discrepancies from perfect constancy are consistent with three-channel crosstalk in spatial comparisons. The spatial predictions correlate with matches both in their locations and their distributions in color space. The matches are inconsistent with incomplete-adaptation predictions that gray-paper matches must change as much as colored ones

5. DISCUSSION

Color appearances are nearly independent of the spectral content of the illumination, and hence the quanta catch of the cones. Color constancy generates a set of visual responses independent of the overall intensity and spectral composition of the illumination. Spatial comparisons of cone responses provide a mechanism for illumination independence. The ratio of responses of two adjacent cones having the same spectral sensitivity is independent of overall changes in illumination, because the numerator changes by the same factor as the denominator. If the cone sensitivity curves had no crosstalk, then color constancy would be perfect. As we have seen here, there is considerable crosstalk and the departures from perfect constancy correlate with that crosstalk. Colored papers show color shifts and gray papers do not.

The above color constancy experiments are unusual in that they provide clearly different predictions for illumination models and spatial-comparison models. We need a number of such experiments with unequivocally distinct predictions if we are to make progress in our understanding of the mechanisms of vision. We need unambiguous analysis of appearance to move forward in the field.

6. CONCLUSIONS

Discrepancies from perfect color constancy were used as the experimental signature of the underlying mechanism of illumination constancy. Spatial-comparison models predict that departures from perfect constancy are the result of crosstalk between the LMS spectral channel with very broad spectral sensitivities. This hypothesis predicts minimal change for gray papers and considerable change for colored papers. Incomplete adaptation models predict equal departures for all papers that mimic the variations in illumination. Experiments, using 27 different combinations of 625, 530 and 455 narrow-band light, show that a gray paper has little change in matches, while colored papers show significant changes in appearance. Discrepancies from perfect constancy are consistent with sensor crosstalk in spatial comparisons. They are inconsistent with incomplete adaptation. Humans do not discount the illuminant in color constancy.

7. ACKNOWEDGEMENTS

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