Color Constancy Under Changes in Reflected Illumination

Peter B. Delahunt
Department of Ophthalmology and Section of Neurobiology, Physiology and Behavior, University of California Davis, CA, USA

David H. Brainard
Department of Psychology, University of Pennsylvania Philadelphia, PA, USA

Abstract

Distinct physical processes can change the spectrum of the illumination that impinges on a surface. Here we consider two such changes. The first is a change in the spectrum of the light source that provides the scene illumination (*light source change*). The second is a change in the reflectance of a surface located near a test surface of interest (*reflected light change*). A color constant visual system must compensate for changes caused by both of these physical processes. We report measurements of constancy with respect to reflected light changes and compare them to results from a recent experiment that examines constancy across light source changes. Observers viewed synthetic images rendered from three-dimensional scene descriptions and displayed on a CRT-based stereoscope. They made achromatic adjustments to test surfaces embedded in the images. The degree of constancy varied with the color direction of the illuminant change, and the variation was similar for reflected light and light source changes. The overall level of constancy was lower for reflected light changes than for light source changes. A second experiment suggests that for our conditions constancy across reflected light changes is driven almost entirely by changes in the local surround of the test. In a third experiment, observers made asymmetric matches across both types of illuminant change. Here the matches were essentially identical across both types of illuminant change.

Introduction

The light reflected from an object to the eye depends both on the object's surface reflectance and the illuminant. The interplay between surface and illuminant properties produces ambiguity in the retinal image – many combinations of reflectance and illuminant result in the same reflected light. To provide an experience of color that yields reliable information about object properties, the visual system must separate the confounded contributions of reflectance and illuminant. When it does so successfully, the visual system has achieved *color constancy*.

Distinct physical processes can produce changes in the spectrum of the illumination that impinges on an object's surface. One is a change in the spectrum of the light source that provides the scene illumination. We refer to this as a *light source change*. A light source change typically affects many image locations in a correlated fashion.

The light impinging on an object's surface can change even when the light source is held fixed. If the illumination has a directional component, for example, then changing the position or pose of an object can modify its illumination. A second example occurs when there is a change in the reflectance of a surface in the scene. This can modulate illumination reflected indirectly onto an object of interest, and we refer to it as a *reflected light change*. Figure 1 illustrates reflected light changes.

It is important to distinguish between measurements of constancy with respect to various physical processes, since there is reason to suppose that different visual mechanisms may mediate constancy in the various cases. For example, recent theories (Adelson, 1999; Gilchrist et al., 1999; see also Ikeda, Shinoda, & Mizokami, 1998) posit that constancy is achieved in two stages, one that segments the scene into differently illuminated regions and a second that stabilizes appearance within each region. Computational analyses of constancy also suggest that different algorithms should be applied to detect and discount the effects of illumination changes that have distinct physical origins (compare e.g. Land & McCann, 1971; Maloney & Wandell, 1986; Funt, Drew, & Ho, 1991; Adelson & Pentland, 1996; Brainard & Freeman, 1997).

Color constancy across light source changes has been extensively studied (e.g. Helson, 1938; Helson & Jeffers, 1940; Helson & Michels, 1948; McCann, McKee, & Taylor, 1976; Burnham, Evans, & Newhall, 1957; Breneman, 1987; Brainard & Wandell, 1992) and it is well established that the human visual system can exhibit excellent constancy with respect to such changes, particularly when the stimuli are naturalistic and contain a wide variety of valid cues to the illuminant (e.g. Brainard, 1998; Kraft & Brainard, 1999; Delahunt & Brainard, 2004). Constancy with respect to object position within a scene (e.g. Arend & Reeves, 1986; Brainard, Brunt, & Speigle, 1997; Bauml, 1999) and object pose (e.g. Hochberg & Beck, 1954; Gilchrist, 1980; Boyaci, Maloney, & Hersh, 2003; Ripamonti et al., in preparation) have also received increasing attention.

Bloj, Kersten and Hurlbert (1999) showed that human color vision can exhibit constancy with respect to a reflected light change. Their experiment compared the appearance of a test region under two conditions. In the first, the perceived geometry supported the possibility that light from a nearby surface reflected onto the test. In the second, a pseudoscope was used to alter the perceived geometry and eliminate the perceptual possibility that light reflected from the nearby surface onto the test, without otherwise changing the stimulus. The color of the test region appeared different in the two conditions, in a manner indicating that the visual system discounted the reflected light in the first condition. Beyond this basic result, however, little is known about the range of conditions over which the visual system exhibits constancy across reflected light changes, nor about the mechanisms that support such constancy.

The experiments reported here measure color constancy across reflected light changes. The measurements explore the effect of varying the spectrum of the reflected light and were designed to allow comparison with constancy for light source changes.

We report three experiments. In the first two, observers set a test patch to appear achromatic, and the measured achromatic locus across changes in reflected light was used to assess color constancy (see Brainard, 1998; Delahunt & Brainard, 2004). The spectra of the reflected light changes in these experiments were chosen to allow comparison with our measurements of constancy across light source changes (Delahunt & Brainard, 2004). In Experiment 1, the stimuli were constructed so that the local surround of the test patch provided a valid cue to the illuminant change (valid-cue condition). In Experiment 2, this local-surround cue was silent (invalid-cue condition). The third experiment was designed to allow direct comparison of constancy across light changes caused by two different physical processes. In this experiment, observers set simultaneous asymmetric matches within the context of complex scenes. The scene contained multiple light sources with different spectra. From one scene location to another, the spectrum of the impinging light varied, either because of differences in reflected light or because a different source provided the illumination. Both valid- and invalid-cue conditions were investigated in Experiment 3.

Experiment 1 – Valid-Cue Conditions

Methods

All the experiments reported here employed computer-generated images of three-dimensional scenes, presented stereoscopically using a computer-controlled haploscope. The use of synthetic stereo imagery facilitated experimental manipulations while preserving a reasonable degree of naturalness. The apparatus, rendering procedures, and calibration methods used in these experiments are described in detail elsewhere (Delahunt & Brainard, 2004).

Briefly, we used the physics-based rendering software RADIANCE software package (Larson & Shakespeare, 1998) to produce stimulus images from scene descriptions. Left and right eye images were generated by re-rendering the same scene description from two horizontally separated viewpoints. The images were displayed on a haploscope that consisted of two 21” monitors (Hewlett Packard Model P1110) driven by an Apple PowerMac G3 computer equipped with two Radius 10-bit graphics cards. The monitors were placed at an optical distance of 36" from the observer’s eyes. To ensure spectral accuracy, custom software was used to drive RADIANCE. This software allowed specification of illuminant spectral power distributions and surface reflectance functions at equally spaced intervals across the visible spectrum (400 nm to 700 nm at 10 nm intervals). RADIANCE then rendered a separate image for each sample wavelength, and the resulting set of 31 monochromatic rendered images was used to compute L-, M-, and S-cone coordinates for each image location. The LMS images were transformed for monitor display using standard methods (Brainard, Pelli, & Robson, 2002). A few image locations were outside of the gamut of the monitor, and values at these locations were clipped to the edge of the monitor gamut.

Experiment 1 measured color constancy across four changes in reflected light. Observers adjusted the chromaticity of a test patch embedded in simulated images until it appeared achromatic. During an adjustment, the luminance of the test patch was held fixed.[1]

Figure 1 shows the five images used in Experiment 1. The images have the same spatial structure, but the surface reflectance near to the test patch varied across the images. We refer to this as the *reflecting surface*. The variation in reflecting surface modulated the light incident upon the test patch across the five images. Following the usage in our previous paper (Delahunt & Brainard, 2004), we refer to the images as the ‘Blue’, ‘Yellow’, ‘Green’, ‘Red’, and ‘Neutral’ images. The location of the test patch is indicated by the black rectangle in each image. It subtended 1.6° (width) by 3.8° (height) of visual angle. Table 1 provides the chromaticity and luminance local surround of the test patch for each image. Measurements of the local surround were made at the test patch location, with the test patch itself omitted from the simulation.

Insert Figure 1 about here

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[1] The adjustment procedure simulated a change in the spectral reflectance function of the test patch. This simulated reflectance function was spatially uniform across the test patch. Because there was a gradient in illumination across the test patch, chromaticity and luminance varied somewhat over the pixels in the test patch. Values reported in this paper are taken from the center of the test patch.

Insert Table 1 about here

In the scene description for 'Blue', 'Yellow', 'Red', and 'Neutral' images, two light sources were specified: a spotlight and a dim overhead source of diffuse light. The spotlight was positioned in the front right of the rendering space so that it shone directly on the surface to the left of the test patch, but did not directly illuminate the test patch. Both light sources had the relative spectral power distribution of CIE D65 (CIE, 1986). To maximize the relative contribution of the reflected light onto the test patch for the 'Green' image, the ambient light was not used. Most of the simulated surfaces in the scene had spectrally flat reflectance functions. The two exceptions were the simulated Macbeth Color Checker Chart (MCC) and the reflecting surface. The spectra of the MCC were chosen to match measurements of such a chart made in our lab, except for the reflectances of the six achromatic squares. These were simulated as spectrally flat. The spectra of the reflecting surface are provided as part of the supplementary material (http://trc.ucdavis.edu/psychophysics/delahunt/comparison.) The overall reflectance of the simulated surface surrounding the test patch was 75%.

Within each experimental session, four different test luminance values were selected to include values both above and below the luminance of the test local surround. The local surround was the area immediately surrounding the test patch and had a luminance value of approximately 5 cd/m^2 (see Table 1). The test patch luminance values were approximately 2.5, 4.0, 6.0, and 8.5 cd/m^2 for all valid-cue conditions, and also for the 'Blue' and 'Red' invalid-cue conditions. For the 'Yellow' invalid-cue condition, the test luminance values were approximately 1.5, 2.5, 4.0, and 6.0 cd/m^2 , and for the 'Green' invalid condition they were approximately 1.0, 1.8, 3.0, and 4.7 cd/m^2. Test luminance values varied across conditions because of variations in the luminance of the local surround of the test (see Table 1). Each test patch luminance was presented four times making a total of 16 settings per session. One session was typically run per observer per condition.

Other details of the experimental procedure were identical to those reported for Experiment 1 of Delahunt and Brainard (Delahunt & Brainard, 2004), and the same seven observers as participated in that experiment were used. Six were naïve as to the purpose of the experiment and one was author PBD.

Results

The left panel of Figure 2 shows the group data for Experiment 1. Each plotted achromatic chromaticity (open symbols) is the average for the seven observers. The color of the plotted points indicates the corresponding experimental image. The chromaticities of the illuminant impinging on the test patch are also shown (solid symbols).

Insert Figure 2 about here

If we take the achromatic setting for the 'Neutral' condition as a reference, then the achromatic settings in the other conditions generally shift in the same direction as the change in illuminant chromaticity. Such shifts are indicative of partial color constancy (Brainard, 1998; Brainard, Kraft, & Longère, 2003; Delahunt & Brainard, 2004). To quantify the degree of constancy, it is useful to re-center the data, so that the recentered achromatic settings for a reference condition coincide exactly with the chromaticity of the reference illuminant. We did this using the procedure reported by Brainard (1998; Delahunt & Brainard, 2004), with the results shown in the right panel of Figure 2.

We refer to the recentered settings as the equivalent illuminants. Perfect constancy, with respect to the reference illuminant, is indicated when the equivalent illuminant chromaticities coincide with the actual illuminant chromaticities, while the complete absence of constancy is indicated when the equivalent illuminant chromaticities all coincide with the chromaticity of the 'Neutral' illuminant. We used a constancy index, CI, to quantify the degree of constancy across illuminant changes:

$$CI = 1 - [| e2 - eeq| / | e2 - e1 |] \qquad (1)$$

where e1 is a two-dimensional vector specifying the chromaticity of the reference illuminant, e2 is a vector representing the chromaticity of the experimental illuminant, and eeq is a vector representing the chromaticity of the equivalent illuminant. A CI of 1 indicates perfect constancy, while a CI of 0 indicates no constancy. This is the same index we used previously (Delahunt & Brainard, 2004; also Brainard & Wandell, 1991; Arend, Reeves, Schirillo, & Goldstein, 1991; Brainard et al., 1997; Brainard, 1998).

The solid bars in Figure 3 show the constancy indices obtained from comparisons of the 'Blue', 'Yellow', 'Green', and 'Red' achromatic settings with the 'Neutral' achromatic settings. For each illuminant change, the reported indices were obtained by averaging an index obtained with the 'Neutral' illuminant playing the role of reference illuminant and one obtained with the chromatic illuminant playing the role of reference illuminant. Plotted indices are averaged over observers. Across the four illuminant changes, the average constancy index was 0.55. Clearly, the visual system exhibits a fair degree of constancy for reflected light changes under the stimulus conditions of Experiment 1.

Insert Figure 3 about here

Comparison with Light Source Changes

We have previously reported achromatic settings made in a series of images that differ because of light source changes (Delahunt & Brainard, 2004). Those experiments used the same apparatus, rendering methods, and observers as here. In addition, the chromaticities and luminances of the illuminants impinging on the test patch were fairly well-matched across the two studies. Figure 3 re-plots the CIs from Delahunt and Brainard's (2004) Experiment 1 for comparison with the present experiment. A plot of the light source change achromatic settings and equivalent illuminants is available in Delahunt and Brainard's (2004) Figure 6. Qualitatively, the data are very similar, but the CIs for the light source changes are systematically higher than those for the reflectance changes. A two-way ANOVA (Table 2) conducted on the CIs indicates that there was a significant effect of type of illumination change (light source vs. reflected) and also for the direction of the illuminant change ('Blue', 'Yellow', 'Red', or 'Green'). The interaction between the type of illumination change and the illuminant was not significant.

Effect of Color Direction of Illuminant Change

The constancy indices vary with the color direction of the illuminant change, with the degree of constancy being highest for the 'Blue' and 'Green' changes, followed by 'Yellow' and 'Red' respectively. A one-way ANOVA performed on the CIs indicates that this effect was statistically significant (F(3,24) = 3.01, p > .05). The observed effect of color direction is consistent with what we found in our study of constancy with respect to light source changes, possibly indicating that similar mechanisms mediate both types of constancy.

Insert Table 2 about here

Experiment 2 – Invalid-Cue Conditions.

Rationale and Methods

In Experiment 1, the reflected light changes produced a concomitant change in the chromaticity and luminance of the area immediately surrounding the test patch. Thus in Experiment 1 the action of simultaneous contrast on the test could support the constancy observed without any explicit processing of the scene geometry. In Experiment 2 we minimized any effect of simultaneous contrast. This was done by changing the simulated surface reflectance of the area surrounding the test patch to cancel, as much as possible, the effect of the reflected light change on the local surround of the test (see Kraft & Brainard, 1999; Kraft, Maloney, & Brainard, 2002; Delahunt & Brainard, 2004). Figure 4 shows the five experimental images used in Experiment 2. Stimulus measurements are provided in Table 1. The variation in local surround chromaticity across the five images was very small. There was some residual variation in local surround luminance. The methods in Experiment 2 were otherwise identical to those of Experiment 1. The same observers participated.

Insert Figure 4 about here

Results

Figure 5 plots the results of Experiment 2 in the same format as Figure 2. Silencing the contribution of local contrast greatly reduces constancy: the average CI in Experiment 2 was 0.02, compared with 0.55 in Experiment 1. The constancy indices in Experiment 2 were not significantly different from zero at the $p < 0.05$ level for any of the illuminant changes, although this difference approached significance for the 'Blue and 'Yellow' illuminant changes (Two-tailed t-tests on the constancy indices: 'Blue' $p = 0.065$; 'Yellow' $p = 0.059$; 'Green' $p = 0.256$; 'Red' $p = 0.301$). A drop in constancy when local contrast is held constant is consistent with previous results obtained in studies of constancy across light source changes (Kraft & Brainard, 1999; Kraft et al., 2002; Delahunt & Brainard, 2004), although here the residual constancy is minimal.

The results of Experiment 2 indicate that the effect of local contrast is the primary contributor to the constancy across reflected light changes observed in Experiment 1. If the visual system processes the scene geometry and uses the juxtaposed locations of the test patch and the reflecting surface (that is, the surface that modulates the reflected light) to help achieve constancy, the achromatic settings should vary as the reflectance of the reflecting surface was changed across our 'Blue', 'Yellow', 'Green', and 'Red' conditions. This prediction holds even when the local surround of the test is held constant. The prediction fails in the data. If geometry *per se* makes a contribution to the discounting of reflected light changes, our experiment does not reveal it.

Insert Figure 5 about here

Comparison with Light Source Changes

The data from Experiment 2 may be compared to Delahunt and Brainard's (2004) measurements of constancy across light source changes when local contrast is held silent. Figure 6 re-plots the CIs from their Experiment 2 for comparison with the present results. Again, constancy across the reflected light changes is systematically lower than constancy across the light source changes. A two-way ANOVA (Table 3) conducted on the CIs indicates that there was a significant effect of both type of illuminant change and direction of illuminant change, with no significant interaction.

Insert Figure 6 about here

Insert Table 3 about here

Experiment 3 – Asymmetric Matches.

Introduction

In Experiments 1 and 2, light source changes affect the image more globally than reflected light changes. In Experiment 3 we attempted to minimize this difference while preserving the light source/reflected light taxonomy.

Methods

Experiment 3 was an asymmetric matching experiment. Figures 7 and 8 illustrate the experimental images used in Experiment 3. They were rendered using the same methods and displayed on the same apparatus as in Experiments 1 and 2. The left side of the scene was illuminated by a light source with the relative spectrum of CIE D65. The right side of the scene was illuminated by a separate light source, and the scene contained a partition so that the illumination from the two light sources was separated.

Insert Figure 7 about here

There were 3 test patch locations. The central patch subtended 4.24° (width) by 3.18° (height) of visual, while the lateral test patches subtended 1.68° (width) by 3.91° (height). The illumination impinging on the central patch had the relative spectrum of CIE D65, as it originated primarily from the left light source. The illumination impinging on the left lateral patch differed from D65 because of reflected light from a nearby surface. The illuminant falling on the right lateral patch varied because of a light source change. The simulated surfaces of the wall, tables and the card placed in the center of the scene all had spectrally flat reflectance functions.

In each experimental condition, the reflected light and light source changes were arranged so that essentially the same illumination fell on each of the two lateral test patches. Two color changes were used (‘Blue’ and ‘Red’) and the scenes were presented in either valid- (Figure 7) or invalid-cue (Figure 8) configurations, giving a total of four conditions. In the valid-cue conditions, all the surfaces of the simulated cards containing the test patches had spectrally flat reflectance functions (see Figure 7). In the invalid-cue conditions, the light reflected from the surrounds of all three test patches were essentially equated by modifying the surfaces of the simulated cards containing the left and right test patches (see Figure 8). The chromaticity (CIE u’v’ coordinates) and luminance values of the light measured at the test patch locations are shown in Table 4.

Insert Figure 8 about here

Insert Table 4 about here.

On each trial of the experiment, observers adjusted the chromaticity and luminance of one of the lateral patches so that it matched the central patch in appearance. No special instructions were provided to define the perceptual criterion that should be used to make a match, so that the instructions were analogous to the 'Neutral' instructions employed in our previous paper (Delahunt & Brainard, 2004) and in Experiments 1 and 2 above. During the adjustment, the two test patches were presented in alternation, with each test patch on for 1 second and then off for 1 second. Observers were instructed to fixate on the central and lateral patch in synchrony with the presentation. When a test patch was off, it was removed from the scene description, so that the portion of the local surround surface that the test patch had occluded was revealed. Observers controlled the chromaticity and luminance of the lateral patch using buttons and the joystick on a Gamepad, with the axes of adjustment corresponding to the a*, b*, and L* coordinates of the CIELAB color space. A trial ended when the observer indicated that a satisfactory match had been obtained. On alternate trials, observers adjusted the left and right lateral test patch to match the central patch.

On each trial, the central patch was set to one of 10 predetermined test colors, obtained by crossing 5 test chromaticities with 2 test luminances. One luminance was lower than the local surround of the central patch, and the other was higher. The test chromaticities and luminances are provided in Table 5. Observers matched all 10 tests at both locations in a single session, and data were obtained for four sessions per observer for each of four conditions (‘Blue’ and ‘Red’ illuminant changes in both valid and invalid-cue conditions). The order of presentation of the tests was randomized in each experimental session.

Four observers participated in this experiment (three females, one male). Three were experienced at psychophysical observation (having participated in Experiments 1 and 2), but naïve as to the purpose of the experiment. The fourth observer was author PBD.

Insert Table 5 about here.

Results

Figure 9 shows results for the valid-cue conditions. The central tests are shown by asterisks, and the matches are shown by the circles (red for light source changes, green for reflected light changes). If there were no color constancy, the matches would have the same coordinates as the test patch coordinates (asterisks). The results show that the matches shift from the standards in the direction of the color shift (indicated by the arrows in Figure 9). Figure 10 shows the results for the invalid-cue conditions. Here the shift in matches from the standards is much smaller indicating very little constancy.

Clear from the plots is that there is essentially no difference in performance between the data from the reflected light and light source change conditions – the green and red points nearly superimpose in the plots. The measured shift is very small for the invalid-cue conditions, with match settings superimposing on test chromaticity for many (but not all) cases.

Insert Figure 9 about here

Insert Figure 10 about here

We also examined the luminances of the observers' matches, which are not shown in the plots. These were close to veridical and did not vary systematically with the chromaticity of the test patch. There was a slight tendency for the match luminances to be higher in the reflected light condition than in the light source condition. This may have been due to small differences in the local surround of the test between the two conditions (see Table 4).

Constancy Index

For the achromatic adjustment data, we obtained a constancy index by comparing the measured shift in achromatic chromaticity with the physical shift in illuminant chromaticity. A similar strategy may be used for asymmetric matches, but the task is complicated by the fact that one must aggregate over the various test chromaticities. Figures 9 and 10 show that the measured shifts vary considerably across test chromaticities, which means that any overall summary will provide a rough indication at best.[2] None-the-less, such summaries are of some interest, and we computed CIs following the procedure described by Brainard et al. (1997). First we fit the mean matches from each condition with a simple cone gain change model (we fit the light source and reflected light matches separately). The parameters of this model are changes in multiplicative gain for

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[2] We have no explanation as to why the pattern of results varies across test chromaticities. In other work, we have found considerable regularity in this aspect of asymmetric matching data (Brainard et al, 1997). It may be that the small effect of illuminant change found here makes the data more susceptible to measurement variability. The data of Arend and Reeves (1986) exhibit variation similar to our current results for conditions where the illuminant change is small.

the three classes of cones. (Consistent with the discussion of the data above, the gain change model fit the data only marginally well, as it is unable to account for the large variations across test chromaticity) These gains were then applied to the standard illuminant (D65) to produce an equivalent illuminant. The CI was then calculated using Formula 1 above.[3]

Figure 11 shows the CIs obtained in Experiment 3. As expected from the raw data, there is very little difference between the light-source and reflected light conditions. The average rate of constancy for the valid-cue conditions of Experiment 3 were 0.28 ('Blue') and 0.34 ('Red'), while for the invalid-cue conditions the rates of constancy were essentially 0. These rates are lower than those obtained in Experiments 1 and 2. Such a difference between constancy indices obtained with asymmetric matching (simultaneous constancy) and with achromatic adjustment (successive constancy) has been reported previously (compare Brainard et al., 1997; Brainard, 1998; see also Speigle & Brainard, 1999) and may be related to differences in the observers state of adaptation in the two tasks. The level of constancy we obtained for the valid-cue conditions of Experiment 3 is lower than has been observed for measurements of simultaneous constancy obtained when the stimuli consist of real illuminated objects (~0.60 Brainard et al., 1997) but comparable to that reported for simple displays presented on CRTs (~0.28 Arend & Reeves, 1986, their unasserted-color task, index value reported in Brainard et al. 1997).

Insert Figure 11 about here

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[3] The equivalent illuminant and CI calculations are actually performed twice, the first time with the standard illuminant as eq1 and the test illuminant as eq2, and the second time with the test illuminant as eq1 and the standard illuminant as eq2 (see Formula 1). The CIs reported here are the means of these two CIs.

Discussion

Empirical Summary

In Experiments 1 and 2 we used an achromatic adjustment task to measure color constancy with respect to reflected light changes. A reasonable degree of constancy was found in Experiment 1, where both geometric and local surround cues to the light change were valid. Experiment 2 revealed little constancy. In this experiment the local surround of the test patch was held constant and thus the local surround of the test provided an invalid cue as to the illuminant change. We interpret this result to imply that one need not invoke geometric factors per se to explain the constancy with respect to reflected light changes found in Experiment 1.

Experiment 3 was designed as a more direct test of whether common mechanisms subserve constancy with respect to reflected light and light source changes. In this experiment, observers set asymmetric color matches across both reflected light and light source changes. Asymmetric matches provide more experimental power to distinguish the site of context effects, as the operation of different mechanisms can be revealed in the dependence of the effect on the chromaticity and luminance of the test stimuli. The results of Experiment 3 were essentially identical for the reflected light and light source changes, again suggestive of a common mechanism. As with Experiments 1 and 2, the results of Experiment 3 do not compel the idea that geometric factors play an important role in constancy with respect to reflected light changes.

Effect of the Color Direction of the Illuminant Change

We designed Experiments 1 and 2 so that the illuminant changes were matched to those used in our previous study of the dependence of constancy with respect to light source changes (Delahunt & Brainard, 2004). Our initial hypothesis was that constancy with respect to the two physically distinct types of illuminant change might well be subserved by different mechanisms, leading to a different dependence of constancy on the color direction of the illuminant change. This hypothesis was particularly attractive to us because one might expect that the statistics of light source and reflected light illumination changes would be quite different from each other, providing a rational basis for a dissociation. In the event, the effect of the color direction of the illuminant change was very similar in Experiments 1 and 2 here and in our earlier measurements of constancy with respect to light source changes. The similarity is consistent with the idea that common mechanisms subserve the two types of constancy.

The particular form of the dependence of constancy on the color direction of illuminant change is difficult to reconcile with what we currently know about the statistics of natural daylight (see Delahunt and Brainard, 2004). Not enough is currently known about the statistics of reflected light changes to compare the data to these, although we think this would be an interesting comparison to make.

Achromatic Adjustments Versus Asymmetric Matches

It is not entirely clear why our achromatic adjustment experiments indicate different levels of constancy between light source and reflected light changes, while our asymmetric matching experiments do not. Nor is it obvious why the asymmetric matching experiments lead to lower levels of constancy than the achromatic adjustment experiments. It is possible that these differences could be predicted by a low-level model that accumulated information about the illuminant by integrating information over time and space (see Smithson & Zaidi, 2004). In such a model, detailed differences in eye movement patterns between achromatic adjustment and asymmetric matching (Speigle & Brainard, 1999) may produce difference results. In addition, differences in how much of the image is affected by the illuminant change, as well as in the variety of surface colors present in the simulated scenes, are also likely to be important. Until we have a detailed model of the information integration process in hand, however, checking this type of prediction will remain elusive. In addition, instructions provided to observers (see below) could conceivably have had a different influence on the measurements for asymmetric matches than for achromatic adjustments.

Decrements Versus Increments

Previous studies have generally found higher rates of color constancy or greater adaptation for test stimuli with luminance values below that of their surround (decrements) than for test stimuli with higher luminances than their surround (increments) (Mausfeld & Niederee, 1993; Chichilnisky & Wandell, 1996; Mausfeld, 1998; Schirillo, 1999a, 1999b; Delahunt & Brainard, 2000; Bauml, 2001; Delahunt & Brainard, 2004). In the current experiments, we used test luminance values that were both below and above the local surround. We separated the settings into decrements and increments and analyzed the results separately.

Figure 12 shows the mean equivalent settings (open symbols) for decrements (circles) and increments (squares) for the achromatic settings experiments (Experiments 1 and 2). The solid circles show the chromaticities of the illuminant. Settings for the valid (top panel) and invalid (bottom panel) conditions are shown. The CIs are shown in Figure 13. Consistent with previous studies, rates of color constancy for valid-cue conditions are higher for the decrements than for increments. This effect is not apparent for the invalid-cue conditions, perhaps because the effects are generally small for this case. Two-way ANOVAs confirm that the differences are statistically significant for the valid-cue condition, but not for the invalid-cue condition (see Table 6).

Insert Figure 12 about here.

Insert Figure 13 about here.

Insert Table 6 about here.

The mean decrement and increment settings for the asymmetric matching experiment (Experiment 3) are shown for valid-cue conditions in Figure 14 and for invalid-cue conditions in Figure 15. The mean CIs are shown in Figure 16. Again, there is significantly greater constancy for decrements in the valid-cue conditions, and no significant difference in the invalid-cue conditions (see two-way ANOVA results in Table 7). The close agreement in the matches for light source and reflected light changes is seen both for increments and decrements.

Insert Figure 14 about here.

Insert Figure 15 about here.

Insert Figure 16 about here.

Insert Table 7 about here.

Instructional Effects

Previous authors have found that the instructions provided to observers in color appearance tasks can affect the results (Arend & Reeves, 1986; Bauml, 1999; Bloj & Hurbert, 2002). When observers are instructed to judge the low-level appearance of the stimuli, they show less constancy than when they are instructed to judge the reflectance properties of the stimuli. Our instructions were neutral, in the sense that observers were not told what aspect of color appearance they should judge. In our previous paper (Delahunt and Brainard, 2004) we report measurements of the effect of explicit instructional manipulations. These measurements employed achromatic adjustment and were with respect to light source changes. The instructional effects were reliable but small, and did not interact with the effect of our other experimental manipulations. We did not repeat this study for the current experiments, and it is possible that effects of geometry would emerge had we explicitly instructed observers to judge reflectance properties. On the other hand, in our recent study of lightness constancy with respect to object pose, we again found little effect of instructional manipulations (Ripamonti et al., 2004). The question of when instructional manipulations have an important effect remains open and interesting.

Effect of Geometry

Taken as a whole, our experiments confirm that the visual system exhibits constancy with respect to reflected light changes, but do not require a model in which the visual system takes the three-dimensional structure of the scene into account. Indeed, a low-level account in which the visual system uses the color statistics of the image, perhaps in a manner that weights the region of the test patch most heavily, could almost certainly explain our data. In this sense, our results appear at odds with the conclusions of the two other studies of constancy with respect to reflected light changes (Bloj et al., 1999; Doerschner, Boyaci, & Maloney, 2004).

Bloj, Kersten, and Hurbert (1999) published the first report of constancy with respect to reflected light changes. As discussed in the introduction, their experiment was designed to isolate the effect of geometry and indicated clearly that observers can use geometrical information to accomplish constancy with respect to reflected light changes. We find their experiment persuasive, and indeed it motivated our more parametric study. In trying to understand *ex post* why our data do not require a geometric account, some differences in design are worth considering.

First, Bloj et al. used real illuminated surfaces rather than graphics simulations. It is possible that real stimuli provide subtle cues that cause the visual system to act differently in their presence. Indeed, Bloj and Hurlbert (personal communication) have noted to us that they had difficulty replicating their result with simulated stimuli as they had difficulty obtaining a stable three-dimensional percept using graphics simulations. On the other hand, Doerschner, Boyaci, and Maloney (2004) studied the effect of reflected light changes using simulated stimuli and argue that their results indicate that the visual system does use geometric cues. The issue of how good simulations must be to yield results identical with those that would be obtained had analogous experiments been done with real stimuli remains open. We discuss this issue at more length elsewhere (Delahunt & Brainard, 2004). Our conclusion there was that for light source changes simulations like those used here lead to results quite similar to those obtained with stimuli consisting of actual illuminated surfaces. There is little data available, however, that speaks to whether simulations are adequate lab models when the interaction between scene geometry and object color is studied. It certainly remains possible that a replication of our experiment using actual illuminated surfaces would produce different results. Using simulated stimuli and methods similar to ours, however, Doerschner, Boyaci, and Maloney (2004) found constancy across reflected light changes mediated by changes in scene geometry (see discussion below). This suggests that the use of simulations *per se* is not the reason for the difference in results.

A second difference between our stimuli and those of Bloj et al. (1999) concerns the local surround of the test. Their stimulus conditions differed from ours in that only two surfaces other than a black enclosure were visible to the observer: the test region and a juxtaposed surface that provided the reflected light. In terms of the effect of local surround, their conditions were thus intermediate between our valid- and invalid-cue conditions, as there was no separate surface surrounding the test region. It is possible that in our experiments the effect of the local surround swamped the geometric effect demonstrated by Bloj et al., and that had we used a design in which the test was presented in isolation we would have been able to tease out an effect of geometry. This result would make sense if under most natural viewing conditions, the local surround is a more reliable indicator of the local illuminant than inferences made from processing scene geometry.

Doerschner, Boyaci, and Maloney (2004) have also studied constancy with respect to reflected light changes. They used simulated stimuli similar to ours and studied the dependence of color appearance on the angle between a test and nearby surface that reflected light onto it. They account for their results using a parametric model based on the idea that the visual system computes surface color through an inverse-optics calculation that takes scene geometry explicitly into account. The support provided by their experiment for an explicit role of geometry is thus more indirect than that provided by Bloj et al. (1999), but it cannot be denied that their results are suggestive of a role of perceived geometry in mediating constancy with respect to reflected light changes. As with our study, Doerschner et al. employed a stimulus that included a surface surrounding the test patch, and their analysis does not explicitly rule out the possibility that their effects were mediated by changes in the contrast of the test that covaried with the geometry. They argue, however, that this interpretation is unlikely because the very low simulated reflectance of the local surround (0.01) in their experiments silenced its role as a cue to the reflected light change.

A third difference between our experiments and the previous studies is one of experimental design. In our experiments, the primary independent variables were the color direction of the illuminant change and whether the local surround provided a valid cue to the illuminant. We found that there was essentially no residual constancy when the local surround was silenced as a cue, and for this reason our data do not argue for an explicit role for geometry. In the previous studies, the primary independent variable was geometric, a manipulation of either perceived or simulated scene geometry. It is possible that had we explicitly manipulated scene geometry while holding the local surround constant, we would have found a measurable effect.

Finally, the color directions of our illuminant changes were not matched to those used in the prior studies. In our achromatic adjustment experiments, the invalid-cue constancy indices for the 'Blue' condition approached statistical significance. It is possible that by running more subjects or in some other manner increasing experimental power, one could establish a degree of residual constancy after silencing the local surround. Such residual constancy might then be attributed to some form of geometric processing. Bloj et. al. (1999) and Doerschner et al. (2004) however, used reddish or orangish reflected light changes, where we see no evidence for an effect in our invalid-cue conditions. Thus the color direction of the illuminant change seems unlikely to be a variable that can reconcile the results from the different labs.

Our current view is that there is good reason from other studies to believe that three-dimensional scene geometry plays a role in constancy with respect to reflected light changes, but that this effect is either small or fairly fragile. In particular, the interaction between geometrical manipulations and the changes in the local surround of the test seems likely to be an important factor in understanding why different experiments lead to different conclusions about the role of geometry. Such interaction has received limited attention in a related literature on how object pose effects perceived surface lightness (Gilchrist, 1980) and is an issue ripe for further investigation.

Acknowledgments

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Table Captions

Table 1. Image measurements for the stimuli used in Experiments 1 and 2. The table provides the chromaticity (CIE u'v' coordinates) and luminance for the local surround of the test patch. The 'Neutral' image was used in both experiments. The valid-cue images were used in Experiment 1, while the invalid-cue images were used in Experiment 2.

Table 2. Valid-Cue conditions. Two-way ANOVA on constancy indices. Data from Experiment 1 of this paper and Experiment 1 of Delahunt and Brainard (2004).

Table 3. Invalid-Cue conditions. Two-way ANOVA on constancy indices. Data from Experiment 2 of this paper and Experiment 2 of Delahunt and Brainard (2004).

Table 4. The chromaticity (CIE u'v' coordinates) and luminance values for the local surround of the test locations for Experiment 3. The light source values were measured at the test patch location on the right side of the scene that received colored illumination. The reflected light values were measured at the test patch location on the left side of the scene that received colored reflected light. The neutral values were measured at the test patch location in the center of the scene.

Table 5. This table provides the chromaticities and luminances of the test patches used in Experiment 3.

Table 6. Two-way ANOVAs for the achromatic settings made in Experiments 1 and 2 for valid- and invalid-cue conditions. The two factors were decrements/increments and direction of the illuminant change ('Blue', 'Yellow', 'Red' and 'Green') .

Table 7. Two-way ANOVAs for the asymmetric settings made in Experiment 3, for types of illuminant change (light source/reflected light) for both valid- and invalid-cue conditions. The two factors were decrements/increments and the direction of the illuminant change ('Blue' and 'Red').

Figure Captions

Figure 1. Experimental images from Experiment 1. Each image shows a rendering of one experimental scene, all of which embody valid-cue conditions. Top left: 'Green'; top right: 'Yellow'; middle: 'Neutral'; bottom left: 'Blue'; bottom right: 'Red'. These images show renderings from a single viewpoint. For the experiment, stereo pairs were generated for each scene. The images shown here and elsewhere in this paper have been converted from LMS values to the sRGB monitor color space and gamma corrected according to the sRGB standard (http://www.srgb.com/). They are intended only to provide the reader with a visual sense for the stimuli - the conversion of the images into the published format introduces small distortions in the sRGB values we computed. There is a free scale factor in the sRGB rendering process. This was chosen so that the rendered images clipped at output digital value 255 for approximately the same input luminance values as the actual experimental images.

Figure 2. Experiment 1 (valid-cue) results. Left panel: Achromatic chromaticities averaged over data from seven observers (open squares) and chromaticities of corresponding experimental illuminants (solid circles). Right panel: Equivalent illuminants derived from the achromatic chromaticities (open circles) and chromaticities of corresponding experimental illuminants (solid circles). Where visible, error bars show +/- 1 SEM.

Figure 3. Experiment 1 (valid-cue) constancy indices. The mean CIs obtained in Experiment 1 (solid bars) are compared to light source CIs (patterned bars) obtained by Delahunt and Brainard (2004). The error bars show +/- 1 SEM.

Figure 4. Experimental images from Experiment 2. Same format as Figure 1. These are the images from the invalid-cue conditions. The thin colored bands at the right edge of the test patch surrounds are not artifacts. For the invalid-cue conditions, the surround surface is not neutral. Its right edge (which is not infinitely thin) does not receive reflected light, and thus is rendered under the global scene illuminant. This effect may also be seen in Figure 8.

Figure 5. Experiment 2 (invalid-cue) results. Left panel: Achromatic chromaticities averaged over data from seven observers (open squares) and chromaticities of corresponding experimental illuminants (solid circles). Right panel: Equivalent illuminants derived from the achromatic chromaticities (open circles) and chromaticities of corresponding experimental illuminants (solid circles). Where visible, error bars show +/- 1 SEM.

Figure 6. Experiment 2 (invalid-cue) constancy indices. The mean CIs obtained in Experiment 2 (solid bars) are compared to light source CIs (patterned bars) obtained by Delahunt and Brainard (2004). The error bars show +/- 1 SEM.

Figure 7. Experimental images used in the valid-cue conditions of Experiment 3. The left side of the scene produced reflected light on the left test patch. The right side of the scene contained a card with a test patch that received colored light

Figure 8. Experimental images used in the invalid-cue conditions of Experiment 3. Same format as Figure 7.

Figure 9. Experiment 3, results for valid-cue conditions. The results are shown for the two color changes (‘Blue’ and ‘Red’). The asterisks show the chromaticities of the tests placed in the center of the scene. The mean settings for the light source matches (red circles) and the reflected light matches (green circles) are shown. The errors bars are +/- 1 SEM. The arrows show the shift in chromaticity between the local surround of the test and match. For each test chromaticity, data are averaged over the two luminance levels used at that chromaticity.

Figure 10. Experiment 3, results for invalid-cue conditions. Same format as Figure 9.

Figure 11. CIs for the four conditions in Experiment 3 for light source (plain bars) and reflected light conditions (patterned bars). The error bars show +/- 1 SEM.

Figure 12. Experiment 1 and 2 equivalent illuminants for decrements (open circles) and increments (open squares) for valid-cue conditions (Experiment 1, left panel) and invalid-cue conditions (Experiment 2, right panel). The closed circles show the chromaticities of the illuminant. Where visible, error bars show +/- 1 SEM.

Figure 13. Experiment 1 and 2 CIs for decrements (horizontally striped bars) and increments (vertically striped bars) for valid-cue conditions (Experiment 1, top panel) and invalid-cue conditions (Experiment 2, bottom panel). The error bars show +/- 1 SEM.

Figure 14. Experiment 3 results for decrements (top panels) and increments (bottom panels) for valid-cue conditions (‘Blue’, left panels; ‘Red’, right panels). The mean settings for the light source matches (red circles) and the reflected light matches (green circles) are shown. The asterisks show the chromaticities of the tests placed in the center of the scene . The errors bars are +/- 1 SEM. The arrows show the shift in chromaticity between the local surround of the test and match.

Figure 15. Experiment 3 results separated into decrements and increments for invalid-cue conditions. Same format as Figure 14.

Figure 16. Experiment 3 CIs for decrements (horizontally striped bars) and increments (vertically striped bars) for valid-cue conditions (top panel) and invalid-cue conditions (bottom panel). The error bars show +/- 1 SEM.

Table 1.

Condition	Cue type	u'	v'	Lum (cd/m2)
‘Neutral’	Valid-cue	0.195	0.470	4.79
‘Blue’	Valid-cue	0.178	0.427	4.86
‘Yellow’	Valid-cue	0.218	0.508	4.85
‘Red’	Valid-cue	0.237	0.458	4.85
‘Green’	Valid-cue	0.159	0.487	4.45
‘Blue’	Invalid-cue	0.192	0.469	4.66
‘Yellow’	Invalid-cue	0.194	0.472	3.34
‘Red’	Invalid-cue	0.197	0.470	4.79
‘Green’	Invalid-cue	0.196	0.470	2.49

Table 2.

Source of Variation	SS	df	MS	F	p-value
Type of illum. change	0.443	1	0.443	14.656	0.000
Direction of illum. change	0.394	3	0.131	4.352	0.009
Interaction	0.041	3	0.014	0.455	0.715

Table 3.

Source of Variation	SS	df	MS	F	p-value
Type of illum. change	0.559	1	0.559	27.028	0.000
Direction of illum. change	0.423	3	0.141	6.830	0.001
Interaction	0.069	3	0.023	1.110	0.354

Table 4.

Condition	Location	u'	v'	Lum (cd/m2)
‘Blue' valid-cue	Light source	0.182	0.422	4.67
	Reflected light	0.182	0.422	4.68
	Test BG	0.195	0.466	4.87
‘Blue' invalid-cue	Light source	0.193	0.468	4.79
	Reflected light	0.196	0.467	4.73
	Test BG	0.195	0.468	4.88
‘Red' valid-cue	Light source	0.245	0.455	4.85
	Reflected light	0.247	0.452	4.98
	Test BG	0.196	0.468	4.87
‘Red' invalid-cue	Light source	0.196	0.472	4.81
	Reflected light	0.199	0.468	4.98
	Test BG	0.196	0.468	4.87

Table 5.

u'	v'	Lum (cd/m2)
0.183	0.429	2.49
0.228	0.512	2.51
0.245	0.462	2.48
0.156	0.494	2.49
0.199	0.475	2.48
0.183	0.424	8.54
0.226	0.508	8.48
0.244	0.456	8.52
0.155	0.488	8.55
0.199	0.470	8.51

Table 6.

Source of Variation	SS	df	MS	F	p-value
Valid-cue					
Dec/Inc	0.186	1	0.186	6.578	0.014
Direction of illum. change	0.714	3	0.238	8.425	0.000
Interaction	0.015	3	0.005	0.178	0.911
Invalid-cue					
Dec/Inc	0.002	1	0.002	0.110	0.742
Direction of illum. change	0.595	3	0.198	8.774	0.000
Interaction	0.025	3	0.008	0.362	0.781

Table 7.

Source of Variation	SS	df	MS	F	p-value
Light source valid					
Dec/Inc	0.100	1	0.100	15.288	0.002
Illuminant	0.002	1	0.002	0.352	0.564
Interaction	0.001	1	0.001	0.078	0.785
Reflected light valid					
Dec/Inc	0.081	1	0.081	10.772	0.007
Illuminant	0.004	1	0.004	0.584	0.460
Interaction	0.013	1	0.013	1.724	0.214
Light source invalid					
Dec/Inc	0.000	1	0.000	0.191	0.670
Illuminant	0.006	1	0.006	2.970	0.110
Interaction	0.002	1	0.002	0.853	0.374
Reflected light invalid					
Dec/Inc	0.000	1	0.000	0.204	0.660
Illuminant	0.005	1	0.005	2.627	0.131
Interaction	0.004	1	0.004	1.734	0.213

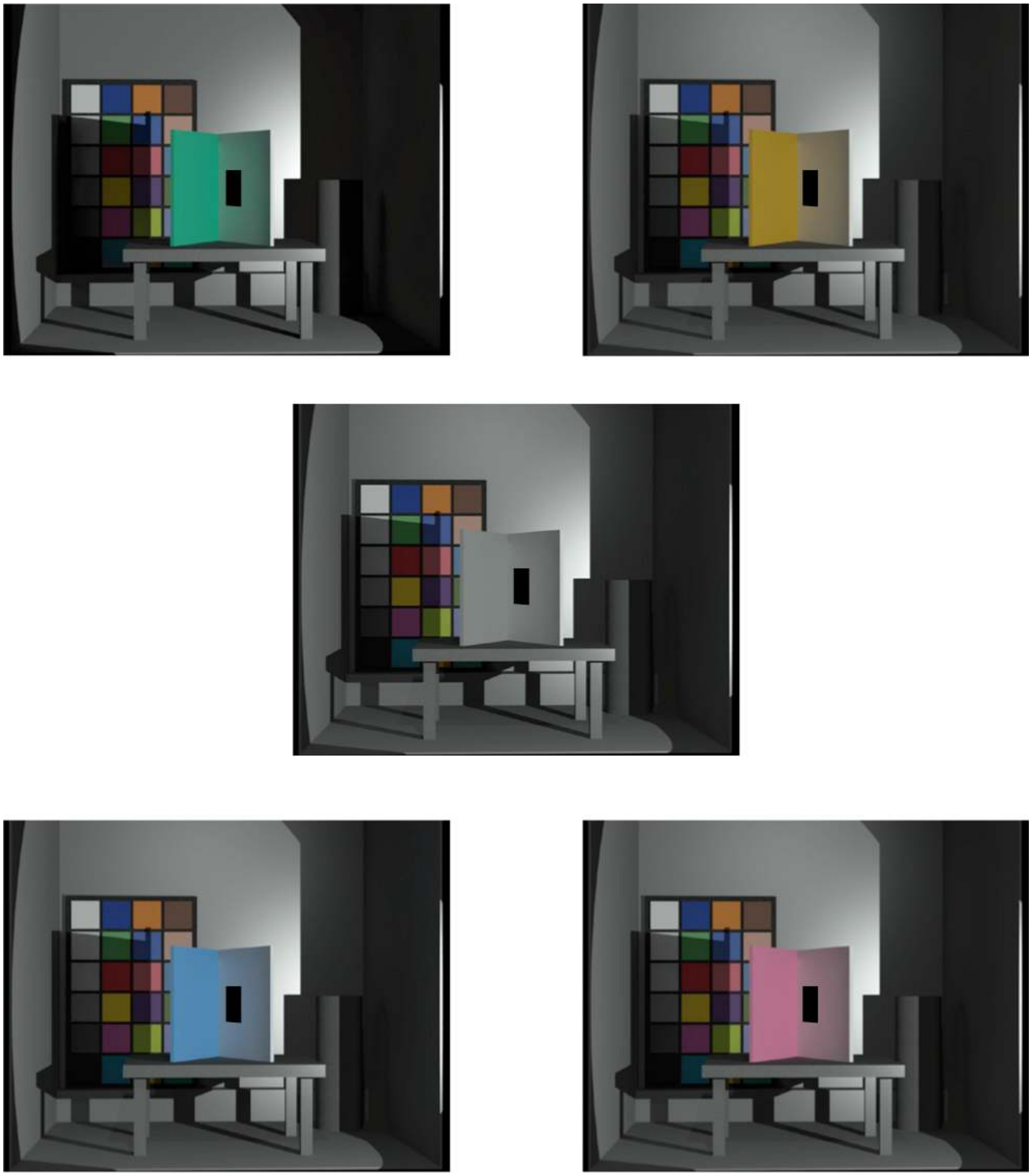


Figure 1

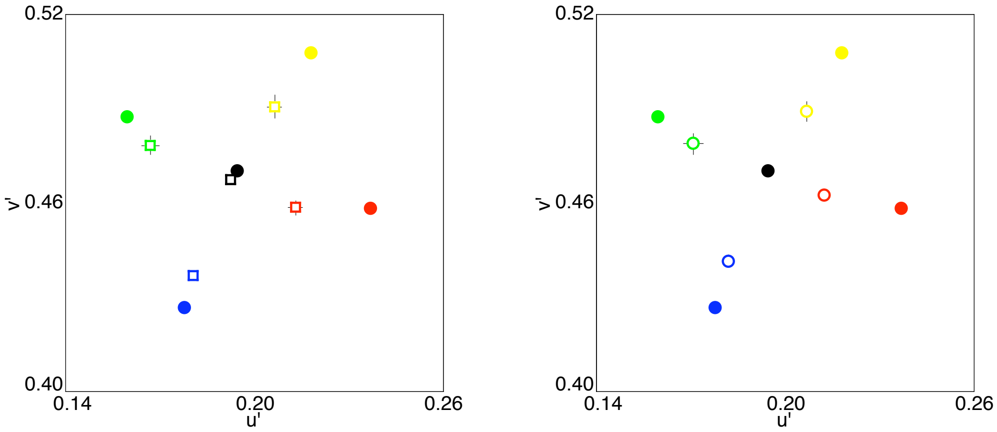


Figure 2

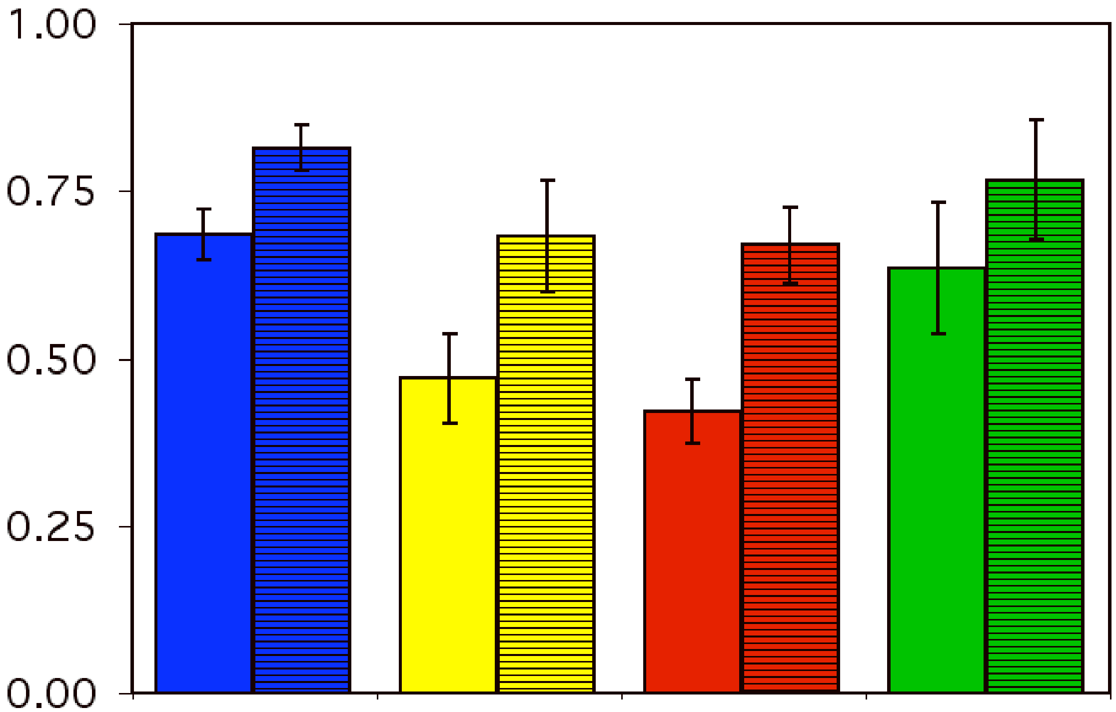
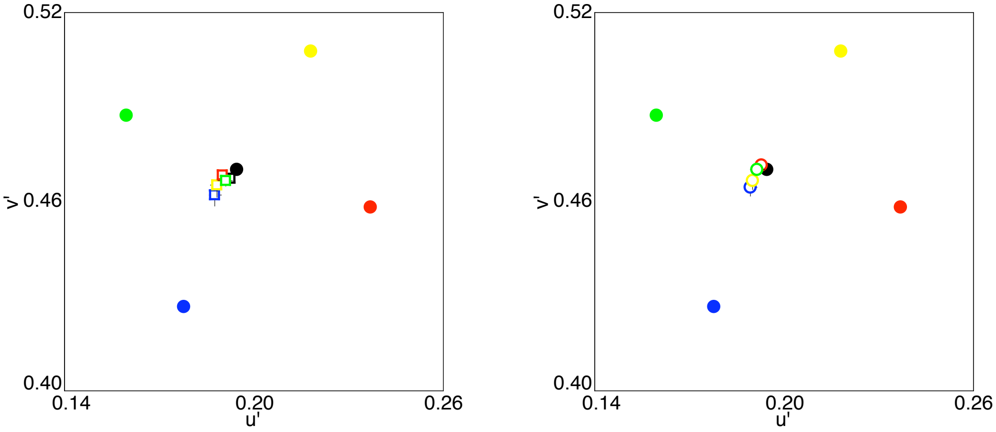


Figure 3

Figure 4



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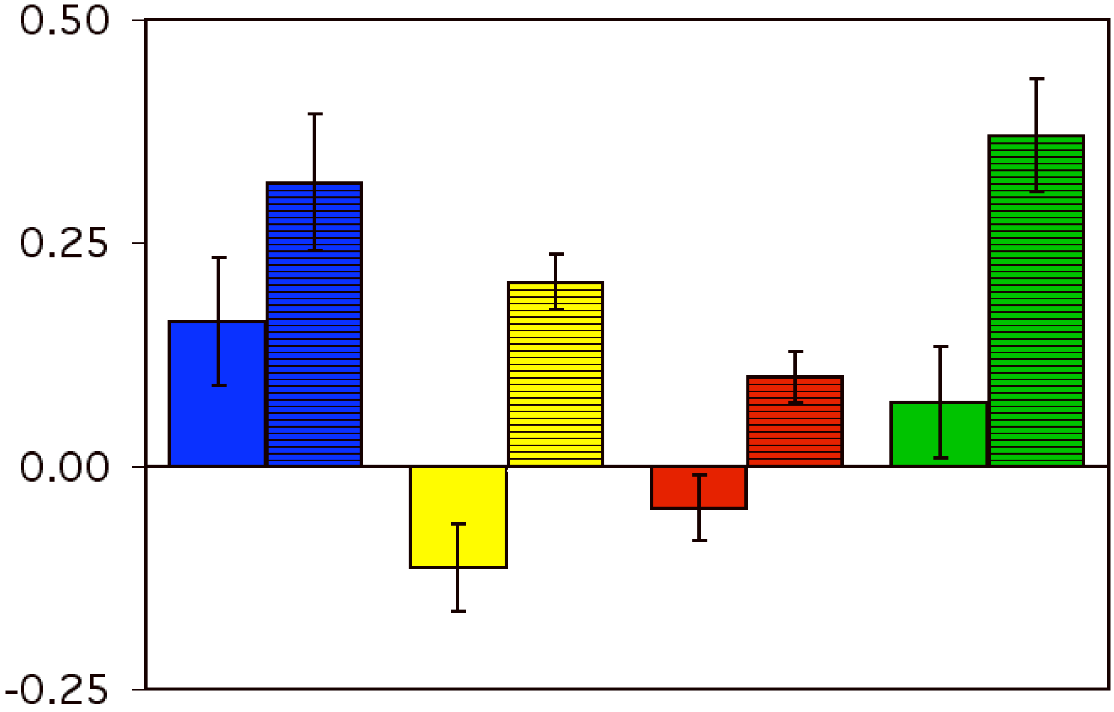

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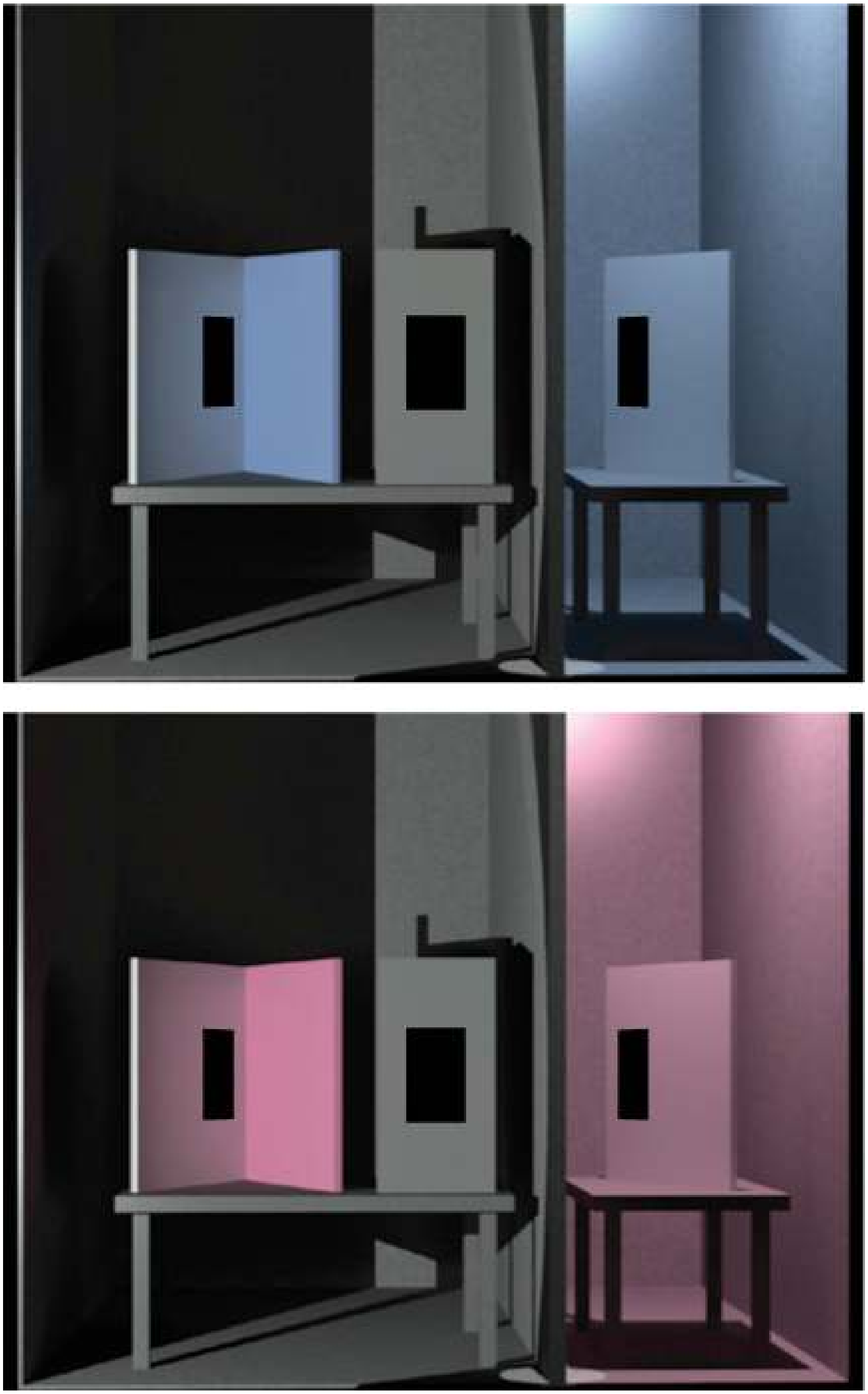

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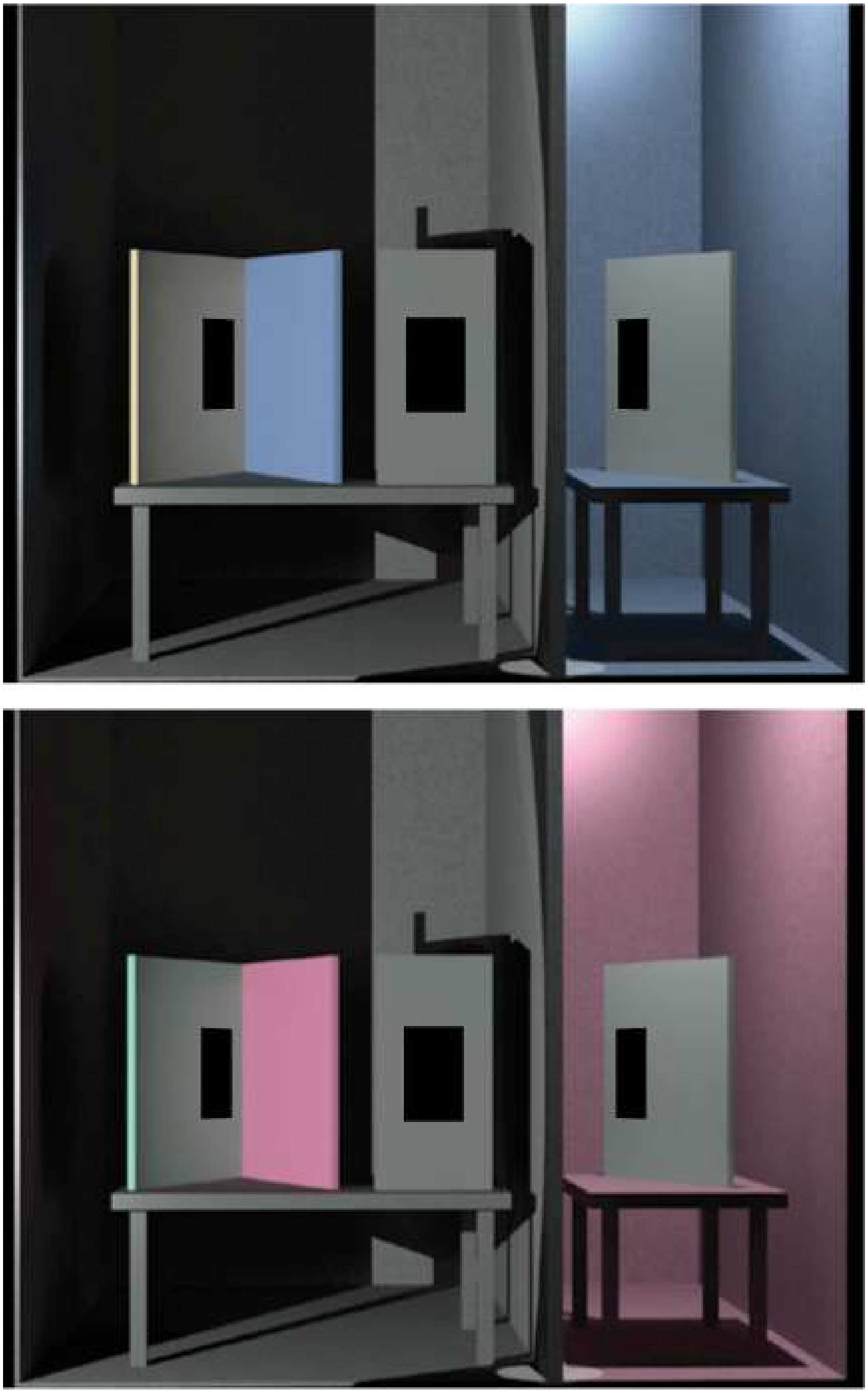

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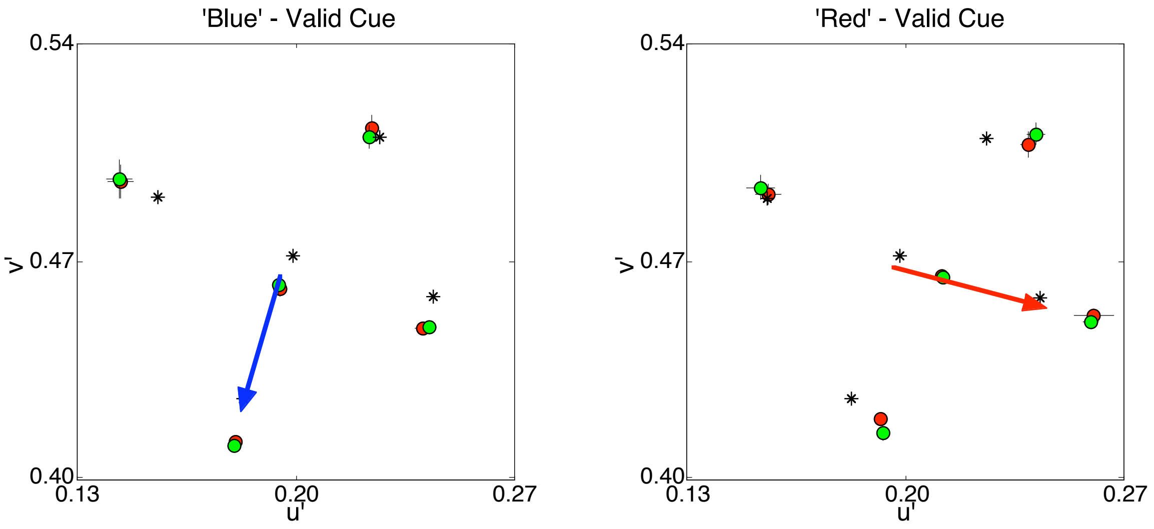


Figure 9

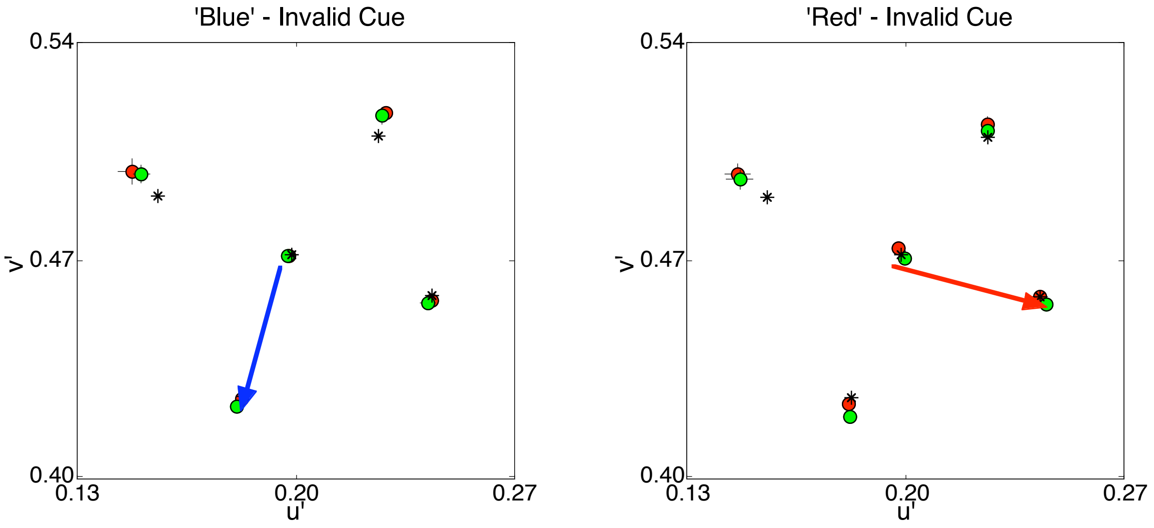
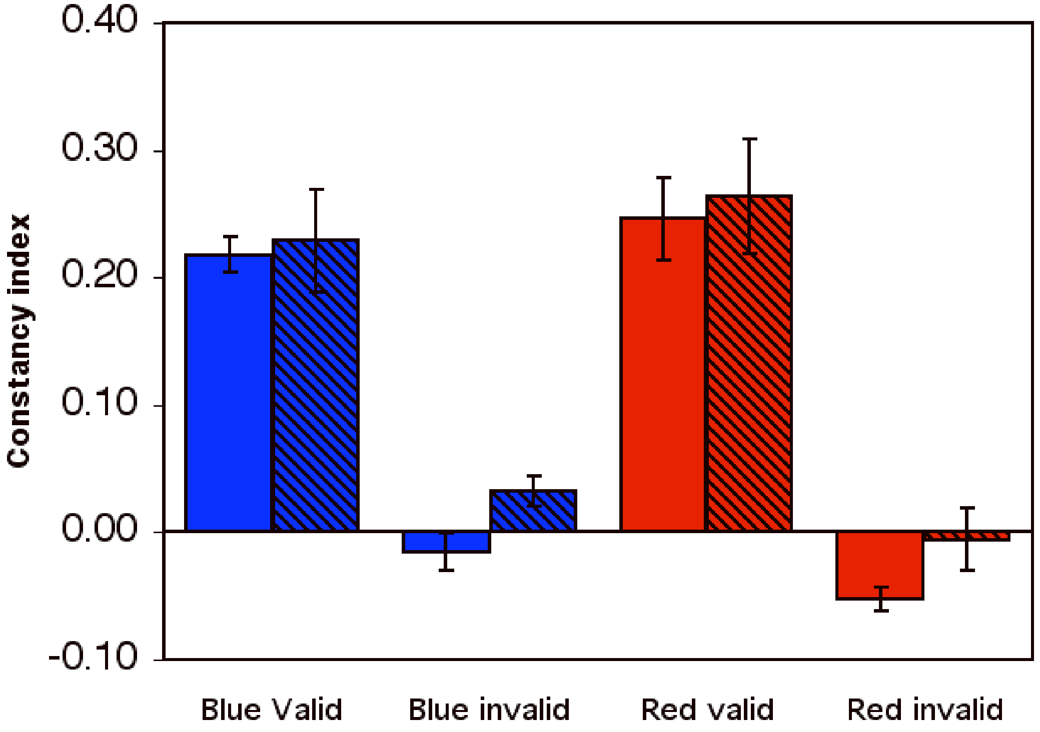


Figure 10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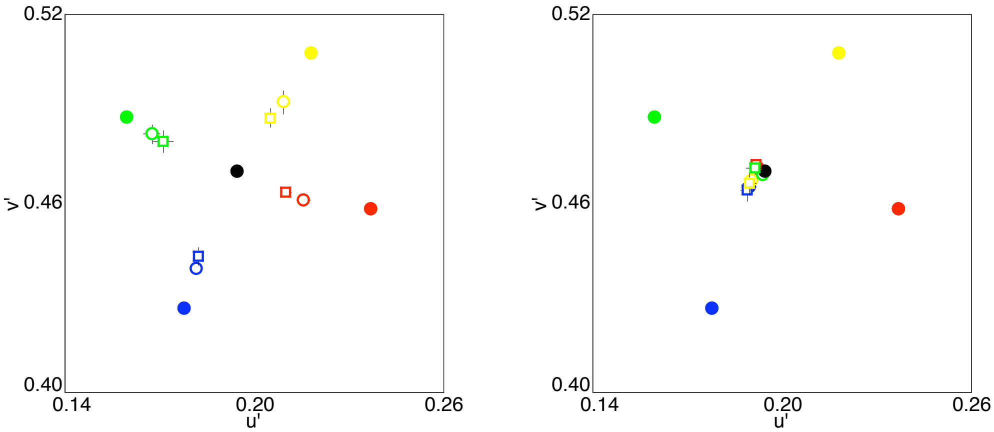
Blue invalid
Red valid
Red invalid

Figure 11



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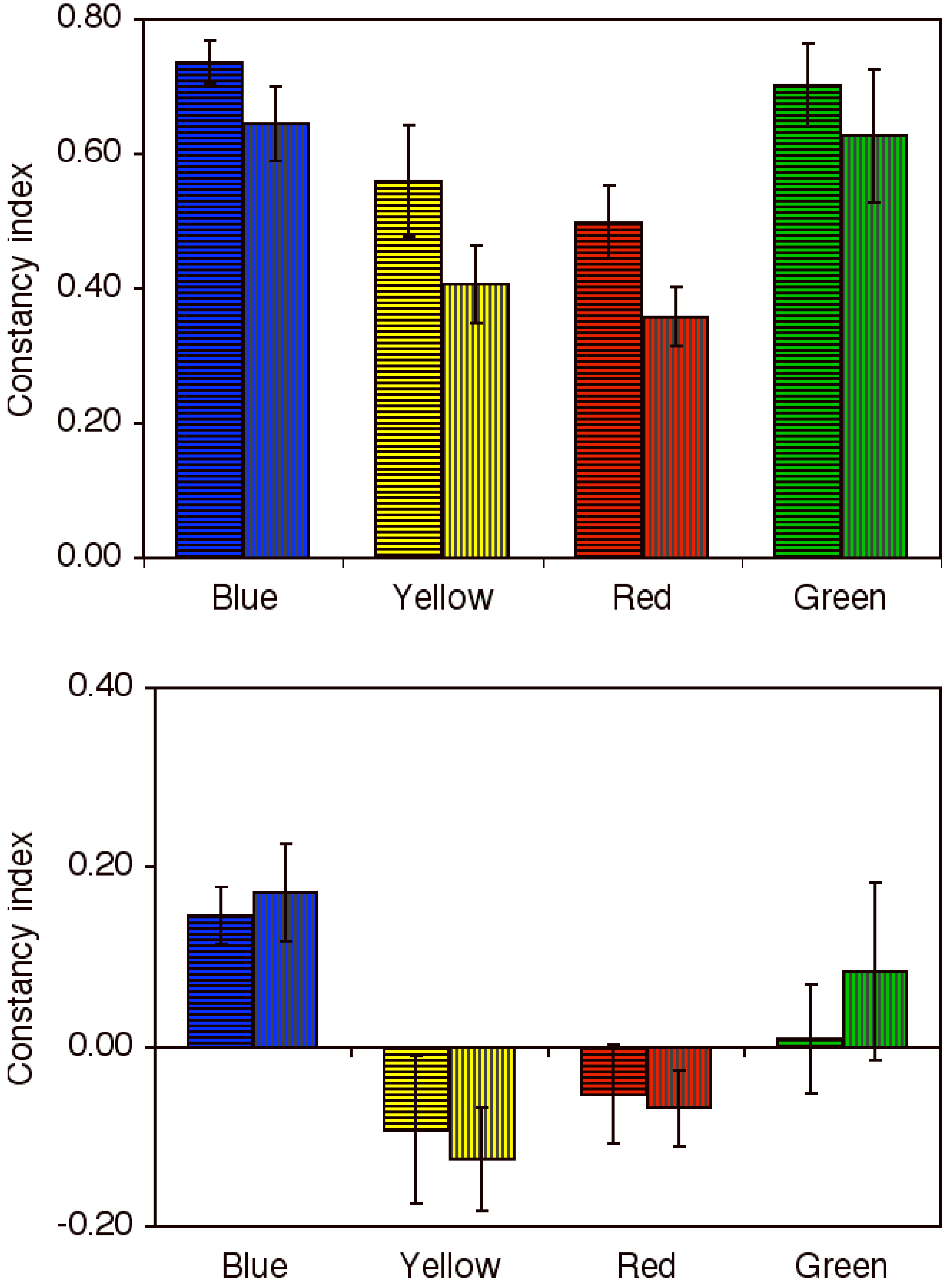
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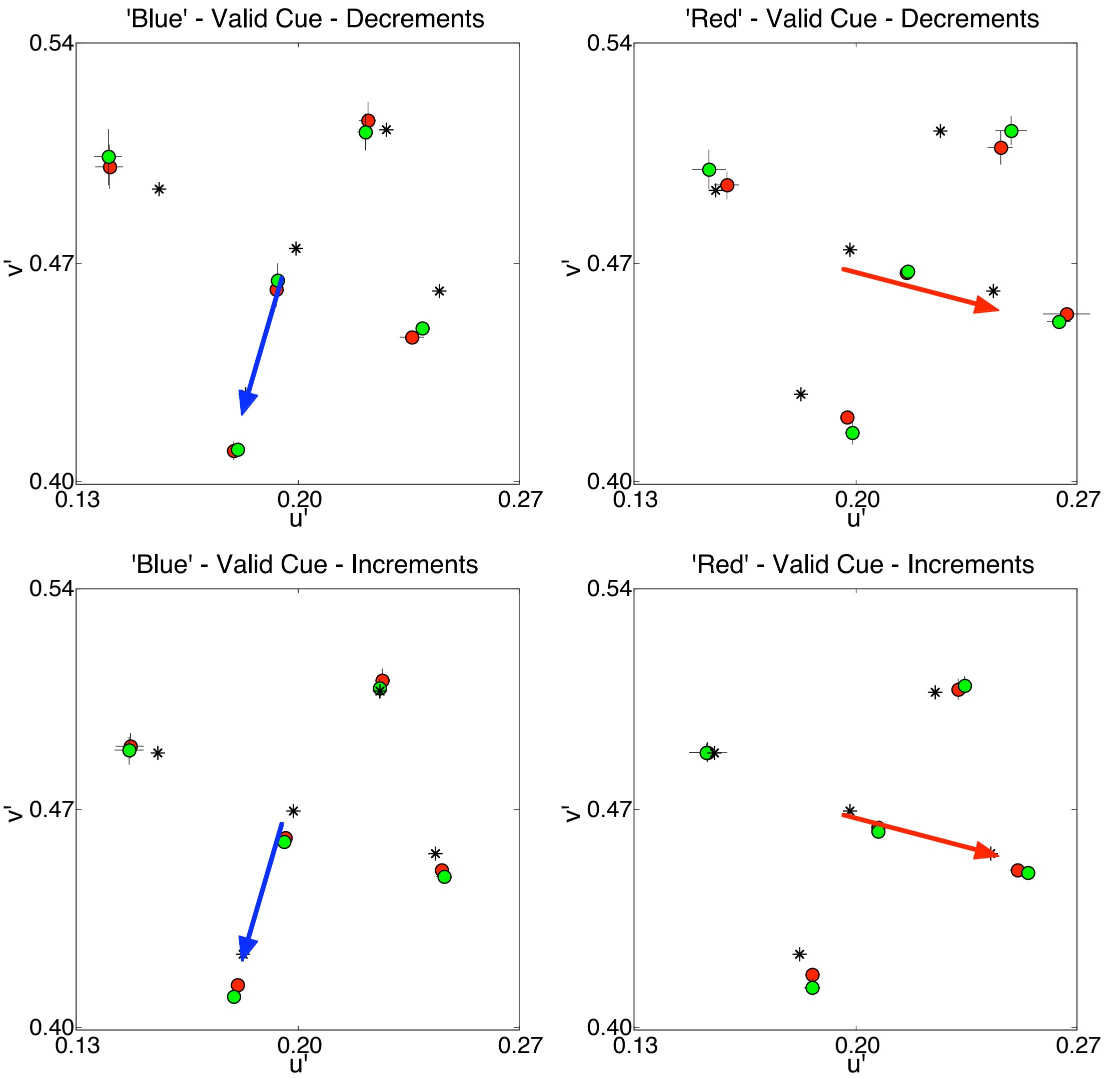
Constancy index
Blue
Yellow
Red
Green
0.40
0.20
0.00
-0.20
Constancy index
Blue
Yellow
Red
Green

Figure 13.



'Blue' - Valid Cue - Decrements
'Red' - Valid Cue - Decrements
'Blue' - Valid Cue - Increments
'Red' - Valid Cue - Increments
0.54
0.47
0.40
v'
0.13
0.20
0.27
u'

Figure 14.

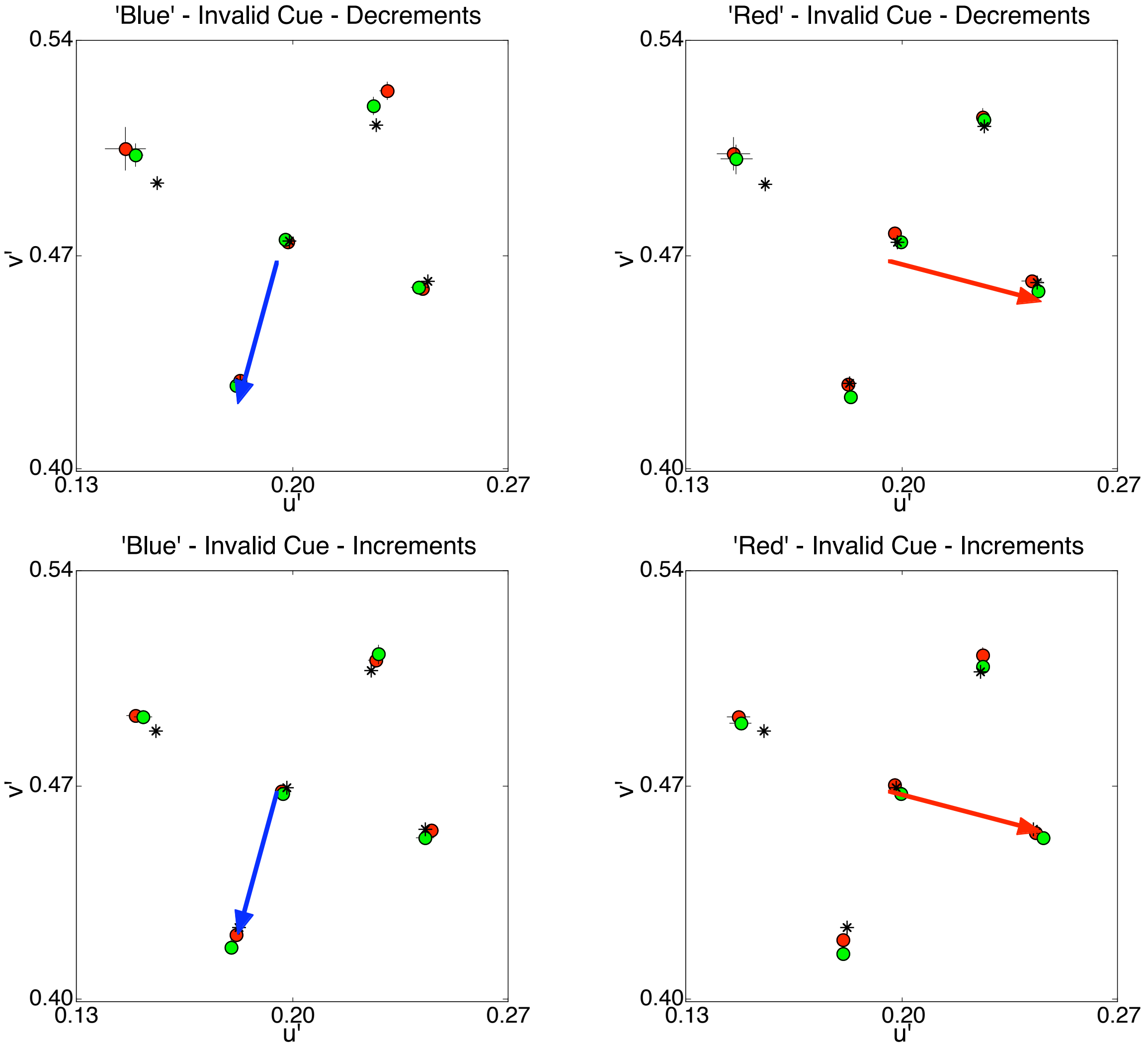

'Blue' - Invalid Cue - Decrements
'Red' - Invalid Cue - Decrements
'Blue' - Invalid Cue - Increments
'Red' - Invalid Cue - Increments
0.54
0.47
0.40
v'
0.13
0.20
0.27
u'

Figure 15.

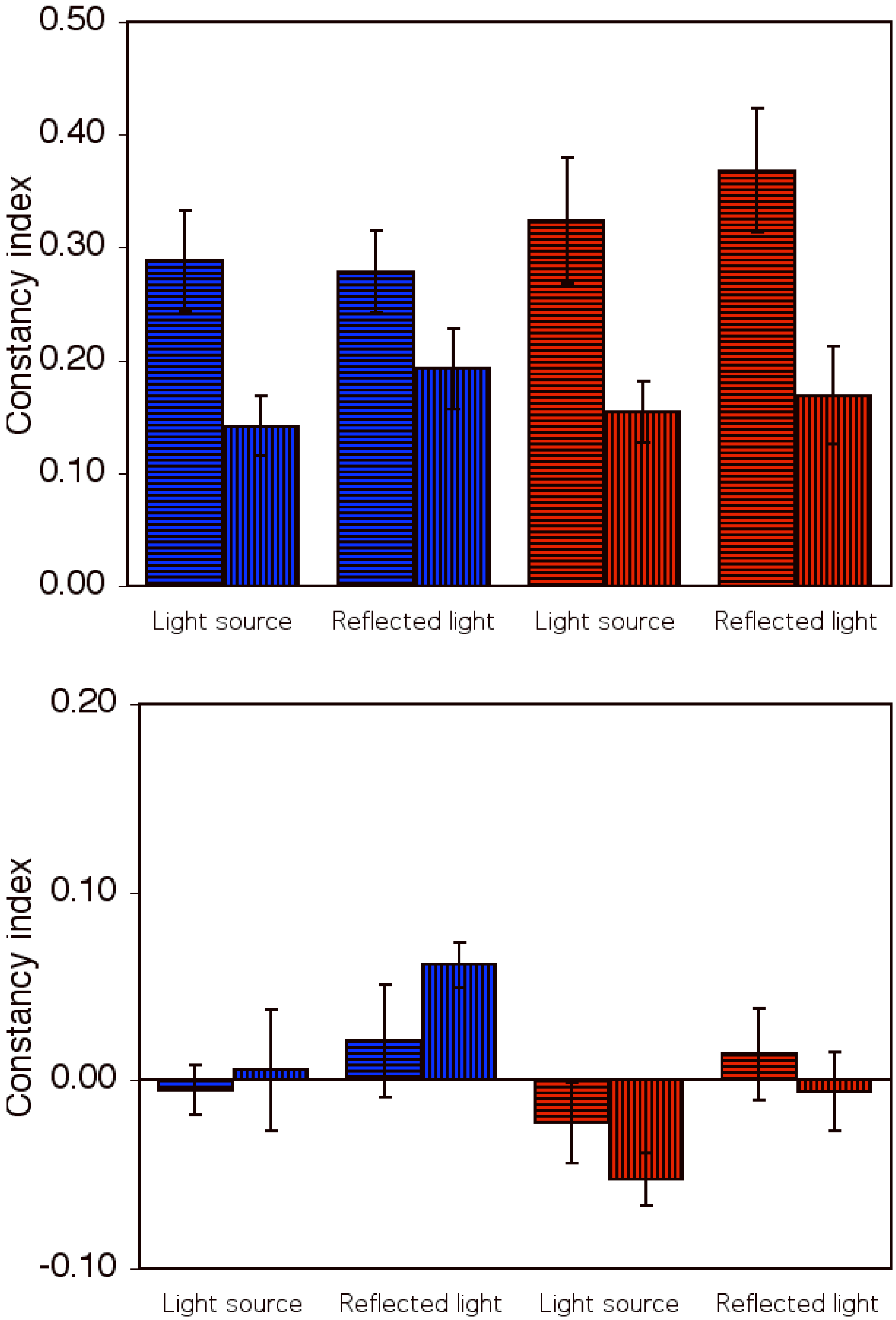

0.50
0.40
0.30
0.20
0.10
0.00
Constancy index
Light source
Reflected light
Light source
Reflected light
0.20
0.10
0.00
-0.10
Constancy index
Light source
Reflected light
Light source
Reflected light

Figure 16.